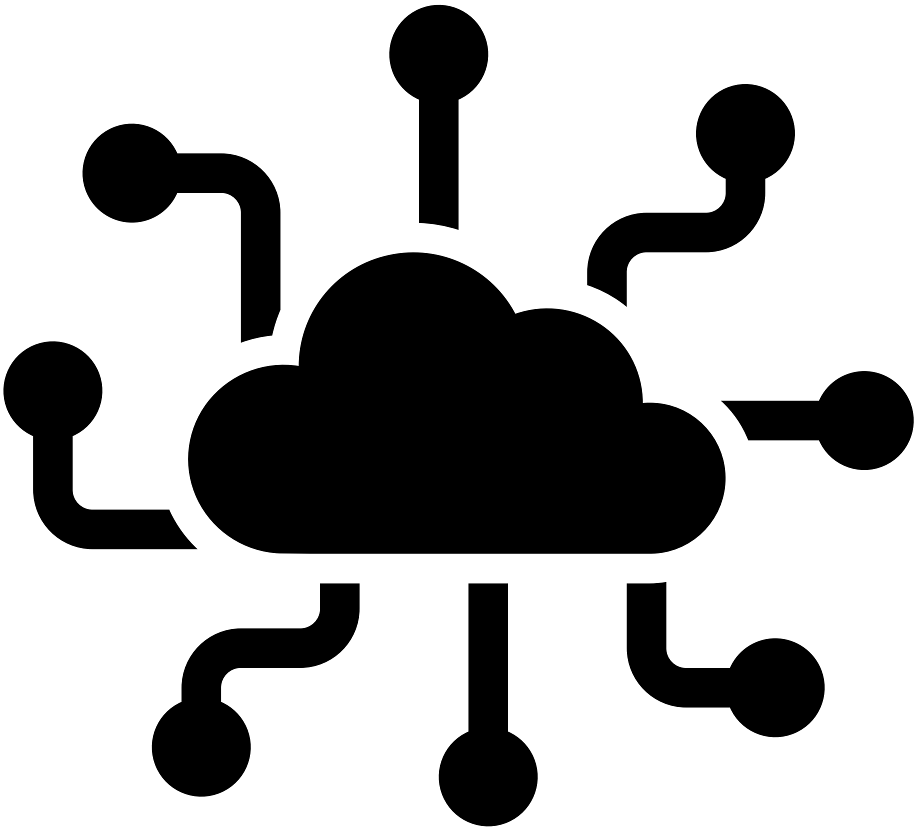
City of Things prototyping kit

ROTTERDAM UNIVERSITY OF APPLIED SCIENCES, PROJECT 7/8
LITERATURE RESEARCH – SENSORS



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1. Summary

The clients, Cities of Things Lab010 and Knowledge Center Creating 010, want to research how smart, initiative-driven connected objects in the smart city change daily life and whether they have a positive or negative impact on society. Therefore, this project requires the creation of a prototype in the form of, for example, a robot that can drive autonomously or remotely.

A proposal has been made to create a food serving robot destined for the catering industry that can be used as an example of what is possible, and what smart objects and possibilities there are in everyday life. This robot could be used in a restaurant to bring around food and drinks. In order to accomplish this, our robot must have a way of knowing where it is, and how it will need to move to a specific point. Our robot must also be able to detect moving obstacles. That these requirements can only be accomplished with the help of sensors is quickly apparent. Thus, research has been done to determine the best sensor for a food serving robot.

In this research, four different techniques for object detection have been researched: Ultrasonic, LIDAR, IR, and Stereo Depth Camera. To determine which sensor is the best for a food serving robot, research has been conducted on how the chosen sensors work. Then, the major (dis)advantages have been researched. As a result, the best sensor for room mapping and object detection can be determined.

Ultrasonic sensors use sound to calculate the distance between an object and the sensor. The sensor sends out a sound wave at a certain frequency and then listens to see if the sound wave comes back. If the emitted sound wave falls back on the sensor, it is possible to calculate the distance between the sensor and the object reflecting the sound wave, by keeping track of the time between sending and receiving the sound wave.

LIDAR, Light Detection and Ranging, sensors work almost the same way as ultrasonic sensors, but with light. A LIDAR uses a laser and then looks to see if the laser comes back. If this laser falls back on the sensor, then there is an object that has reflected this laser. As a result, the distance between the sensor and the object can be calculated by keeping track of the time between sending and receiving the laser.

An IR sensor will emit light and, if the light is reflected on an object, will receive it again. Since IR light is not as concentrated as laser, this light will attenuate itself the further it travels. This way, the distance between the sensor and the object reflecting the light can be calculated. The weaker the light received, the further away the object is.

Stereo Depth Cameras have two sensors that are close together. A Stereo Depth Camera uses the two images that the sensors create and compares them. Since the distance between these two sensors is known, this comparison gives depth information. An object that is close by will move around a lot when you compare the two images. An object that is far away will not move as much.

Without room mapping, there is no way for the robot to know its position in a restaurant, let alone move through one. For this reason, the food serving robot needs a fast and reliable way to get a map of the restaurant.

Ultrasonic sensors can only detect in a straight line. A robot with an ultrasonic sensor would have to move a few meters, completely circle around, and repeat. This process would take forever, and the chance of missing a spot in the room would be a lot bigger than with other sensors. LIDARs have a major advantage over ultrasonic sensors. Namely, they already look around themselves. This means that a robot with these sensors can drive across a room without having to stop to turn around. This increases the mapping speed and makes a robot with these sensors many times faster compared to ultrasonic sensors. However, one huge disadvantage of these sensors is the inability to see through transparent objects such as glass.

In terms of room mapping, IR-sensors are comparable to Ultrasonic sensors. Both have the disadvantage of a linear detection range, making them very slow to map a room. Stereo depth cameras are a bit slower than, for example, LIDARs, as a robot with a stereo depth camera would also have to turn around. However, this is not as big as a problem as with Ultrasonic sensors because the viewing angle of a stereo depth camera is a lot larger. Also, these cameras have great advantages over LIDARs. For example, these sensors can detect glass. These sensors are also very reliable because they do not look linear. Something that can be seen above or below the sensor will also be seen by this sensor.

If a fast sensor is the goal, the LIDAR or the Stereo Depth Camera would be a good choice. However, there is only one sensor with a great reliability: the Stereo Depth Camera. Therefore, the Stereo Depth Camera is the best sensor for room mapping. However, the food serving robot also needs a way to constantly check for moving objects in its path.

Because ultrasonic sensors only detect directly in front of the sensor, there is no way for the sensor to predict a collision. This means that in a situation where a moving human is coming at an angle, our robot will only detect the moving human when it is directly in front of it. LIDARs solve this issue by detecting 360° around itself. This means that the robot will detect the moving human before it moves directly in front of the robot. As a result, the robot can predict a collision and stop moving before it will hit the human.

In terms of dynamic object detection, IR-sensors are comparable to Ultrasonic sensors, making them unreliable at dynamic object detection in situations as the example in the last paragraph. Stereo Depth Cameras have a very wide, though not as wide as that of a LIDAR, detection range. Therefore, Stereo Depth Cameras will be able to predict a collision in a situation where a moving human is coming at an angle.

Looking at the previous results, all sensors have their own up -and downsides, making these sensors fit better in different environments. The goal, however, is to use these sensors in the catering industry. As a result, the requirement for a fitting sensor is very clear. Namely, speed and reliability in dynamic environments is desirable. Therefore, a Stereo Depth + IR-Camera is the best choice for this project.

2. Introduction

The clients, Cities of Things Lab010 and Knowledge Center Creating 010, want to research how smart, initiative-driven connected objects in the smart city, like automatic delivery vehicles or safety robots, change daily life and whether they have a positive or negative impact on society. Therefore, this project requires the creation of a prototype in the form of, for example, a robot that can drive autonomously or remotely.

This prototype is intended for researchers and non-expert citizens with limited programming knowledge. Thus, the prototype should be easy to operate and set up. We have come up with the proposal to create a food serving robot destined for the catering industry that can be used as an example of what is possible, and what smart objects and possibilities there are in everyday life. This robot could be used in a restaurant to bring around food and drinks. Therefore, the robot will need to be able to move autonomously to a specific table.

In order to accomplish this, our robot must have a way of knowing where it is, and how it will need to move to a specific point. Our robot must also be able to detect moving obstacles. Think of tables that can be moved, but also people walking around or even other serving robots. That these requirements can only be accomplished with the help of sensors is quickly apparent. This brings us to the next question:

<u>Which sensor(s) is/are best for a food serving robot?</u>

3. Theoretical Framework

To answer the main question, we will focus on four different techniques for object detection: Ultrasonic, LIDAR, IR and Stereo Depth Camera.

Because there are different requirements that our serving robot must meet, we will answer this main question through the following sub-questions:

- How do the chosen sensors work?
- What are the advantages and disadvantages of the chosen sensors?
- Which sensor is best for room mapping?
- Which sensor is best for dynamic object detection?

These sub-questions were chosen to arrive at a logical choice for our sensor step by step. To understand the differences between the chosen sensors, we must first know how our sensors work. Knowing the difference between the sensors, we can then list the advantages and disadvantages. These (dis)advantages make the sensors best suited for different environments. Therefore, we can determine which sensor is better for dynamic object detection as this comes with its own requirements. Finally, we can determine which sensor is better for room mapping.

4. Methodology

In this study, qualitative research was conducted on sensors. This paper includes research on what sensors are, how they work, and what the advantages and disadvantages of these sensors are. It also includes research on what the best sensor might be for our purpose. To answer these questions, literature research has been written.

Used sources have mainly been searched in Google Scholar. Many of these sources come from scientific studies on sensors, newspaper articles or blogs on the use of sensors. For this research, data from 2010 to 2022 of Dutch or English language was used.

To keep this research clear for any reader, a logical order of information has been maintained. For example, we first examined how our sensors work. To find out which sensors are best for the project, we'll also need to know how the sensors work exactly. Now that we know how the sensors work, we investigate the advantages and disadvantages of these techniques. Once we know all the pros and cons, we can make the consideration between sensors and choose a sensor that best fits the project.

To maintain validity of this research, Google Scholar was used, as mentioned earlier. The advantage of this platform is that Google Scholar displays the number of citations per document. Thus, it is easy to see if a document is a reliable source. For books, literature with a good reputation was used. Unknown or unquoted literature was not used in this study.

5. Research

5.1 How do the chosen sensors work?

5.1.1 Ultrasonic

Ultrasonic sensors use sound to calculate the distance between an object and the sensor. This sound has a frequency between 25 and 50kHz: always above the perceptible frequency range for humans. The sensor sends out a sound wave at a certain frequency and then listens to see if the sound wave comes back. If the emitted sound wave falls back on the sensor, the distance between the sensor and the object reflecting the sound wave can be calculated by keeping track of the time between emitting and receiving the sound wave. Then, the distance can be calculated with a simple formula:

$$d = \frac{v * t}{2}$$

Whereby:
d = distance traveled in meters (m).
v = speed of the sound wave in meters per second (m/s).
t = time between 2 measurements in seconds (s).
The distance is divided by 2 to compensate for the distance to the object and the distance back from the object.

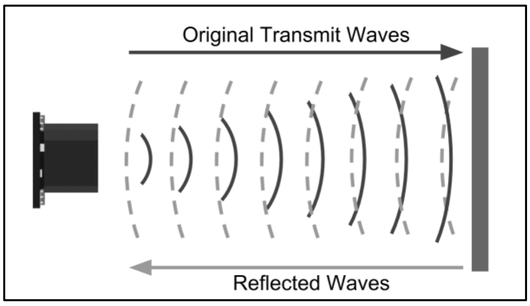


Figure 1 – Working principle of an Ultrasonic sensor. (How Ultrasonic Sensors Work, 2021)

Suppose an ultrasonic sensor sends a sound wave and receives it 0.1 seconds later. Assuming a speed of sound of 343 m/s. (External influences like ambient temperature influence the speed of sound. This is, for this research, negligible. A speed of sound of 343 m/s will also be assumed in this paper).

$$d = \frac{343 * 0.1}{2} = 17{,}15m$$

This way, the distance between the sensor and the reflecting object has been calculated the same way an ultrasonic sensor does.

(Morgan, 2014)

5.1.2 LIDAR

LIDAR, Light Detection and Ranging, sensors work almost the same way as ultrasonic sensors, but with light. A LIDAR uses a, for the human eye, invisible laser and then looks to see if the laser comes back. If this laser falls back on the sensor, then there is an object that has reflected this laser. As a result, the distance between the sensor and the object can be calculated by keeping track of the time between sending and receiving the laser. The distance between the sensor and the reflective object can be calculated using the same formula as for the ultrasonic:

$$d = \frac{v * t}{2}$$

Whereby:
d = distance traveled in meters (m).
v = speed of the sound wave in meters per second (m/s).
t = time between 2 measurements in seconds (s).
The distance is divided by 2 to compensate for the distance to the object and the distance back from the object.

Suppose a LIDAR sensor sends a laser and receives it 65 microseconds later:

$$d = \frac{(39{,}2 * 10^{7}) * (6{,}5 * 10^{-5})}{2} = 12740m$$

This way, the distance between the sensor and the reflecting object has been calculated the same way a LIDAR sensor does.

(Sharma, 2021)

5.1.3 IR

IR, Infra-Red, sensors work almost the same as LIDAR sensors. Where a LIDAR uses a laser, an IR sensor uses Infrared light. This light falls outside the, to the human eye, visible light spectrum. A major difference between LIDAR and IR is calculating the distance between the sensor and an object. The IR sensor will emit light and, if the light is reflected on an object, will receive it again. Since IR light is not as concentrated as a laser, this light will attenuate itself the further it travels. As a result, the distance between the sensor and the object reflecting the light can be calculated. The weaker the light received, the further away the object is.

(Wadhahi, Hussain, & Yosof, 2018)

5.1.4 Stereo Depth Camera

There are several techniques for using cameras to detect depth, and therefore obstacles. For this project, investigation of the Stereo Depth Camera has been chosen. This is because this camera is not affected by different types of light, such as sunlight. This is important for use on, for example, a terrace where sunlight can cause problems for other types of cameras.

Stereo Depth Cameras work on the same principle as human depth perception. These cameras have two sensors that are close together. A Stereo Depth Camera uses the two images that the sensors create and compares them. Since the distance between these two sensors is known, this comparison gives depth information. As seen on Figure 2, an imaginary triangle can be drawn between the two sensors and a random point represent in both images. Then, when drawing another imaginary line between the point and the middle of the two sensors, two right-angled triangles form. As a result, the length of the last drawn line can be calculated using the Pythagorean theorem. More in-depth information can be found here.

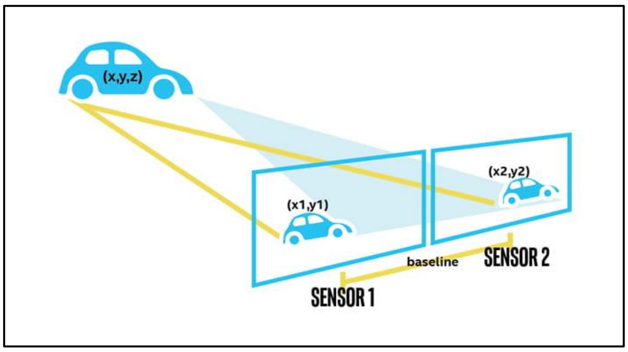


Figure 2 – Working principle of a Stereo Depth Camera. (Beginner's guide to depth (Updated), 2019)

(Beginner's guide to depth (Updated), 2019)

(Sinha, Murez, Bartolozzi, Bradrinarayanan, & Rabinovich, 2020)

5.2 What are the advantages and disadvantages of the chosen sensors?

5.2.1 Ultrasonic

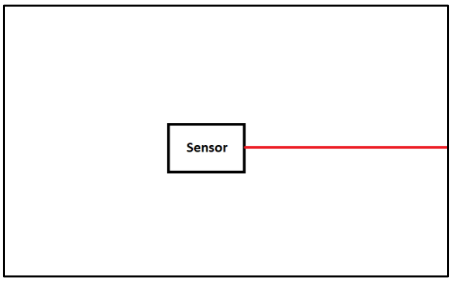


Figure 3 – Detection direction of an Ultrasonic sensor.

Average detection range: 2 - 400cm
Entry-level price: €3.95 (HC-SR04)
Detection: 2D Linear.
Working voltage / current: DC 5V / 15mA.
Weight: 8.5g.
Dimensions: 45x20x15mm.
Ranging accuracy: ≥3mm.

Ultrasonic sensors have several important advantages. These advantages are mainly related to the fact that these sensors use sound. But this advantage also has some disadvantages. Namely:

Advantages

- **These sensors are not affected by color or transparency of objects.**
  This allows these sensors to be used in dark environments, or in environments surrounded by glass [Figure 4].
- **These sensors are robust.**
  Due to the simple design of ultrasonic sensors, these sensors are quite robust. This makes these sensors easy to use in harsher environments.
- **These sensors are very cheap.**
  The working principle of these sensors is very simple, making these sensors very cheap.

Figure 4 – Environment surrounded by glass.

Disadvantages

- **These sensors can only detect linear forward.**
  These sensors can only detect in one line, straight ahead. This means that a lot of sensors are needed to properly detect obstacles.
- **These sensors are sensitive to external factors.**
  Because these sensors work with sound, they can deviate due to external factors. For example, the speed of the emitted sound waves changes by about 0.17% per degree Celsius. However, this can be solved with models that compensate for measured temperature. These models, however, are also slightly more expensive. Furthermore, these sensors are also affected, although most of these are negligible, by humidity, air pressure, wind, and fog.
- **These sensors are relatively slow.**
  Compared to, for example, a LIDAR, these sensors are relatively slow. This is because these sensors use sound, which is many times slower than light.
- **These sensors cannot detect sound absorbing materials.**
  Sensors that use sound cannot detect objects that absorb sound.

(Electrical Terminology, 2021)
(Senix, n.d.)

5.2.2 LIDAR

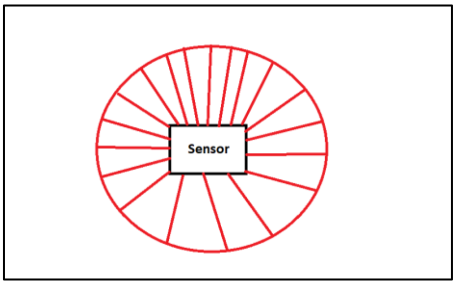


Figure 5 – Detection direction of a LIDAR sensor.

Average detection range: 12 - 800cm.
Entry-level price: €71.96 (YDLIDAR X2 Lidar).
Detection: 2D 360°.
Working voltage / current: DC 5V / 300-500mA (1A Instantaneous peak current at start-up).
Weight: 126g.
Dimensions: 60.5x50.3x96mm.
Ranging accuracy: Range ≤ 1m.

LIDAR sensors use laser, giving these sensors many advantages. Again, we list some of these advantages, as well as disadvantages:

Advantages

- **These sensors detect 360° around the sensor.**
  Because LIDARs are so fast, these sensors can measure distance in 360°. This allows you to get a good overview of what is happening in front, to the side and behind.
- **These sensors are accurate and reliable.**
  Because LIDAR sensors work with a laser, these sensors are very precise. A LIDAR is accurate to the centimeter.
- **These sensors are not affected by ambient light.**
  Because these sensors use their own very small and precise light source, they will not be affected by external light sources. This makes it easier, unlike ultrasonic, to use multiple sensors at the same time. You can also use this sensor in a place with little ambient light.
- **These sensors are very fast.**
  Because these sensors operate at the speed of light, these sensors are many times faster than ultrasonic sensors.

Disadvantages

- **These sensors can only see 2D.**
  Because these sensors can only see 2D, the placement of this sensor must be very well thought out. A perfect spot will not exist, and so multiple sensors will need to be used.
- **These sensors do not work well in extreme weather conditions.**
  These sensors do not work well when it is raining hard, snowing, or hailing.
- **These sensors cannot detect non-reflective objects or angled super reflective objects.**
  Because these sensors rely on reflection from the laser, these sensors cannot detect non-reflective objects, such as an environment surrounded by glass as in [Figure 4]. If the laser would reflect of an angled super reflective object such as an angled mirror, the laser would deflect off and give bad readings [Figure 6].
- **These sensors need to be kept horizontal.**
  Because a LIDAR rotates around its own axis, the readings of one can distort if not kept straight. This means that as soon as a LIDAR is tilted, the read values may no longer be correct.

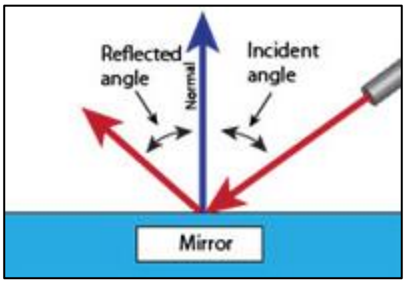
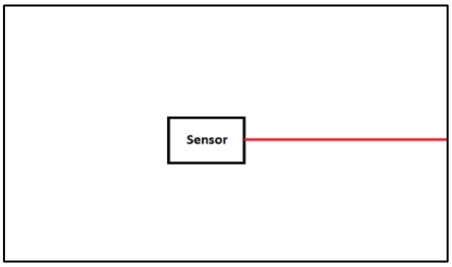


Figure 6 – A laser getting deflected by an angled mirror. (Physics, 2022)

(Ivankov, 2020)

5.2.3 IR



Average detection range: 10 - 80cm
Entry-level price: €9.88 (Sharp GP2Y0A21YK0F)
Detection: 2D Linear.
Working voltage / current: DC 4.5 - 5.5V / 30mA.
Weight: 3.5g.
Dimensions: 44.45x19.05x13.462mm.

Figure 7 – Detection direction of an IR sensor.

Infrared sensors use a different type of light than LIDAR sensors. The method used to calculate the distance between the sensor and an object is also different. This allows us to list some of the additional advantages and disadvantages:

Advantages

- **These sensors are not affected by sound.**
  Because these sensors work with light, they will not be affected by ambient noise.
- **These sensors use very little power.**
  Because these sensors have very low power consumption, they also require a smaller battery. This increases the battery life of the serving robot or gives room for a smaller battery.
- **These sensors are affected by non-transparent objects.**
  Because these sensors use Infra-Red light, which does not pass-through transparent objects, they are able to see materials such as glass.

Disadvantages

- **These sensors are affected by ambient light.**
  These sensors are very sensitive to changing light, heat, or sunlight. As a result, these sensors react differently in different environments.
- **These sensors can only detect linear forward.**
  These sensors can only detect in one line, straight ahead. This requires a large number of sensors to detect obstacles properly.
- **These sensors are affected by non-transparent objects.**
  Because these sensors do not work well in non-transparent conditions, they can give errors in measurement in a situation with, for example, smoke or fog.

(Garwal, 2020)

5.2.4 Stereo Depth Camera

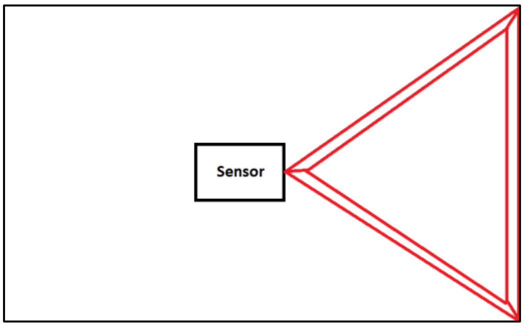


Figure 8 – Detection direction of a Stereo Depth Camera.

Average detection range: 30 - 300cm
Entry-level price: €235.30 (Intel Realsense D415)
Detection: 3D Forward.
Working voltage / current: DC 4.5-5.5V / 442mA
Weight: 55g.
Dimensions: 99x20x23mm.
Ranging accuracy: <2% at 2m.

Stereo Depth Cameras are very different compared to the other sensors. This gives another set of significant advantages and disadvantages:

Advantages

- **These sensors detect in 3D.**
  Because these sensors can detect in 3D, there is almost no possibility of missing an obstacle. Thus, placement of this sensor is less important than other sensors.
- **These sensors are accurate and reliable.**
  Because these sensors use photos, there is little that these cameras will not notice.
- **These sensors are not affected by ambient light.**
  Because these sensors use photos, these cameras can see anything in good light. If this is not the case, there are many cameras that can switch to internal IR sensors. The combination of these two sensors can capture just about anything.

Disadvantages

- **These sensors detect forward.**
  Because these sensors detect forward, it is not possible to see what is happening next to or in front of this sensor.
- **These sensors do not handle reflections well.**
  These sensors can give bad values when reflections occur, like in [Figure 9]. This is because these sensors use image and have no awareness of reflection.
- **These sensors are very expensive.**
  The price of these sensors, for an entry-level model, is between €200 and €400.
- **These sensors do not work well at high speeds.**
  These sensors are, compared to the other sensors, very slow. As a result, artifacts can occur when detecting fast moving objects. These sensors will not be able to properly detect a car driving at 100 km/h. However, these sensors would be able to properly detect a person running.

(Kadambi, Bhandari, & Raskar, 2014)

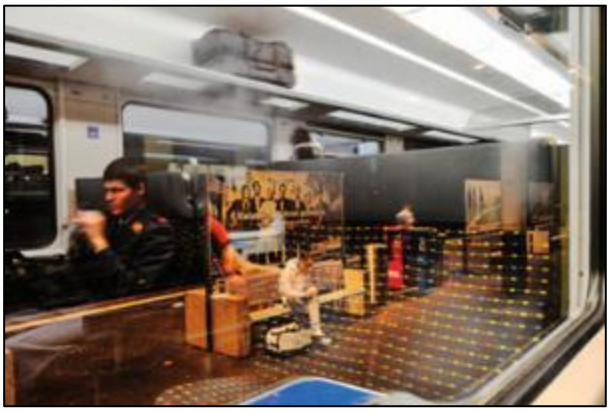


Figure 9 – A situation with many reflections. (Kadambi, Bhandari, & Raskar, 2014)

5.3 Which sensor is best for room mapping?

Room mapping is fundamental part of the food serving robot. Without room mapping there is no way for the robot to know its position in a restaurant, let alone move through one. For this reason, the food serving robot needs a fast and reliable way to get a map of the restaurant. We'll again list the sensors one by one:

Ultrasonic

Ultrasonic sensors are generally fast sensors in terms of response time. This, however, does not mean that these sensors are fast at mapping a room. The reason for this is one major disadvantage: the detection range. Ultrasonic sensors can only detect in a straight line. A robot with an ultrasonic sensor would have to move a few meters, completely circle around, and repeat. This process would take forever, and the chance of missing a spot in the room would be a lot bigger than with other sensors.

LIDAR

LIDARs, like ultrasonic sensors, are very fast sensors. However, these sensors have a major advantage over ultrasonic sensors. Namely, they already look around themselves. This means that a robot with these sensors can move across a room without having to stop to turn around. This increases the mapping speed and makes a robot with these sensors many times faster compared to ultrasonic sensors. This does not mean these sensors are without flaws, as one huge disadvantage of these sensors is the inability to see through transparent objects such as glass. This renders LIDARs completely useless in environments containing big windows, as most restaurants do have.

IR

In terms of room mapping, IR-sensors are comparable to Ultrasonic sensors. Both have the disadvantage of a linear detection range, making them very slow to map a room.

Stereo Depth Camera

Stereo depth cameras look forward. As a result, these sensors are a bit slower than, for example, LIDARs, as a robot with a stereo depth camera would also have to turn around. However, this is not as big as a problem as with Ultrasonic sensors because the viewing angle of a stereo depth camera is a lot larger. Also, these cameras have great advantages over LIDARs. For example, these sensors can detect glass. These sensors are also very reliable because they do not detect linear. Something that can be seen above or below the sensor will also be seen by this sensor.

Looking at the results above there isn't really a clear winner. All these sensors have their own (dis)advantages. However, the main goal is speed and reliability. If a fast sensor is the goal, the LIDAR or the Stereo Depth Camera would be a good choice. However, there is only one sensor with a great reliability: the Stereo Depth Camera. Therefore, the Stereo Depth Camera is the best sensor for room mapping.

5.4 Which sensor is best for dynamic object detection?

A restaurant is a dynamic environment. Therefore, the food serving robot needs a way to constantly check for moving objects in its path. Not hitting moving objects such as guests, chairs and even other robots is critical to successfully move to a waypoint in a mapped environment. To achieve this, a sensor that is quick and reliable is required to detect moving objects in front of itself. We'll once again list the sensors one by one:

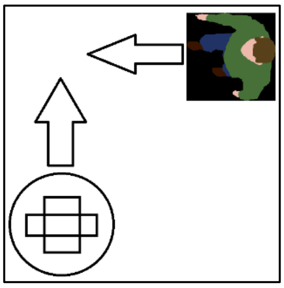


Figure 10 – A human and serving robot's trajectories colliding.

Ultrasonic

Ultrasonic sensors are generally great at reliably detecting objects in front of itself. However, because ultrasonic sensors only detect directly in front of the sensor, there is no way for the sensor to predict a collision. This means that in a situation such as in [Figure 10], the robot will only detect the moving human when it is directly in front of it. Which could be too late. This means that the reliability of using an ultrasonic sensor for dynamic object detection is not great.

LIDAR

LIDARs solve this issue by detecting 360° around itself, although it doesn't need the back 180°. This means that in a situation such as in [Figure 10], the robot will detect the moving human before it moves directly in front of the robot. As a result, the robot can predict a collision and stop moving before it will hit the human. LIDARs are also very fast sensors, making these sensors great for dynamic object detection.

IR

In terms of dynamic object detection, IR-sensors are comparable to Ultrasonic sensors. Both have the disadvantage of a linear detection range, making them unreliable at dynamic object detection in situations as in [Figure 10].

Stereo Depth Camera

Stereo Depth Cameras have a very wide, though not as wide as that of a LIDAR, detection range. Therefore, Stereo Depth Cameras will be able to predict a collision in a situation as in [Figure 10]. These sensors are a bit slower, though not too slow. A Stereo Depth Camera will be able to detect moving objects more than fast enough to not cause any problems. These sensors also come with the benefit of looking in 3D. Something that can be seen above or below the sensor will also be seen by this sensor, giving them an even greater reliability compared to LIDARs.

For the food serving robot to stop in time and avoid a collision, the robot needs to be able to predict a collision before the moving object is in front of it. If the robot is only able to detect objects directly in front of it, then the robot will generally stop too late in situations as in [Figure 10]. Therefore, sensors that are not able to predict such collisions, will automatically be a bad choice for dynamic object detection.

Just like when determining the best sensor for room mapping, the choice comes down to two sensors: using a LIDAR or using a Stereo Depth Camera. LIDARs tend to be faster than Stereo Depth Cameras, but the reliability of a Stereo Depth Camera is greater than the reliability of a LIDAR. However, since both sensors are fast enough to detect moving objects, the choice comes down to the sensor with the best reliability. Namely, the Stereo Depth Camera. Therefore, the Stereo Depth Camera is the best choice for dynamic object detection.

6. Conclusion

Looking at the previous results, all sensors have their own up -and downsides, making these sensors fit better in different environments. The goal, however, is to use these sensors in the catering industry. As a result, the requirement for a fitting sensor is very clear. Namely, speed and reliability in dynamic environments is desirable.

In previous chapters, research had been conducted on the best sensor for room mapping and object detection. Based on this research, the Stereo Depth Camera was the sensor to go for. This sensor does have its flaws, though. For example: the stereo depth camera is not great at detecting mirrors because it just sees more room. It doesn't know what a mirror is, like humans do know. However, what if there is a way to combine this sensor with a different kind of sensor to compensate for its flaws? What if we combine a Stereo depth camera with an IR-Sensor? The IR-Sensor is able to detect mirrors, as it does not rely on visibility. Thankfully, solutions like this already exists. For example: The Intel Realsense D415.

6.1 Recommendations

To make sure the right sensor will be chosen for the robot, a 'Consideration of alternatives and choice' table has been made. This table will paint a clearer picture about the alternatives considered and which sensor will be the best sensor for this project.

	Importance	Research type	IR-Camera (XBOX Kinect)		Stereo-Depth + IR-Camera (Intel Realsense D415)		Ultrasonic		IR		LIDAR	
			Value	Score	Value	Score	Value	Score	Value	Score	Value	Score
Field of View	3	Literature	3D	3	3D	3	Linear	1	Linear	1	360 degrees linear	2
Transparent object detection	3	Literature & experimental	80%	3	99%	3	99%	3	70%	2	20%	1
Datastream size	3	Literature & experimental	> 3GB/s	1	500MB/s - 3GB/s	2	< 500 MB/s	3	< 500 MB/s	3	< 500 MB/s	3
Detection speed	1	Literature	> 5 km/h	3	> 5 km/h	3	> 5 km/h	3	> 5 km/h	3	> 5 km/h	3
Detection changes at change of environment lighting	2	Literature & experimental	1 - 500 lux	2	< 1 lux	3	< 1 lux	3	> 500 lux	1	1 - 500 lux	2
Interference of other sensors	2	Literature	No chance	3	No chance	3	Moderate chance	1	Small chance	2	Small chance	2
Result			34		39		32		27		29	

Table 1 – Consideration of alternatives and choice.

	Score 1	Score 2	Score 3
Field of View	Linear	360 degrees linear	3D
Transparent object detection	Detects 0 - 50% transparency	Detects 50 - 75% transparency	Detects > 75% transparency
Datastream size	> 3GB/s	500MB/s - 3GB/s	< 500MB/s
Detection speed	Detects static objects	Detects objects at a speed of < 5 km/h	Detects objects at a speed of > 5 km/h
Detection changes at change of environment lighting	Change of detection values at a change of lighting at > 500 lux	Change of detection values at a change of lighting at 1 - 500 lux	Change of detection values at a change of lighting at < 1 lux
Interference of other sensors	Multiple sensors have at least a moderate chance of interfering with each other	Multiple sensors have a small chance of interfering with each other	Multiple sensors have no chance of interfering with each other

Table 2 – Score definition of Table 1, "Consideration of alternatives and choice."

According to Table 1, the Stereo-Depth + IR-Camera is the best choice for the robot, followed by the IR-Camera. As a result, we can answer the main question of this research: <u>Which sensor(s) is/are best for a food serving robot?</u> Namely, a Stereo-Depth + IR-Camera.

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Changelog

Version number	Date	Change	Author
2.0	30/05/22	Updated chapter 5.1.4	I. Zuiderent
1.9	23/05/22	Summary written.	I. Zuiderent
1.8	16/05/22	Written chapter 6	I. Zuiderent
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