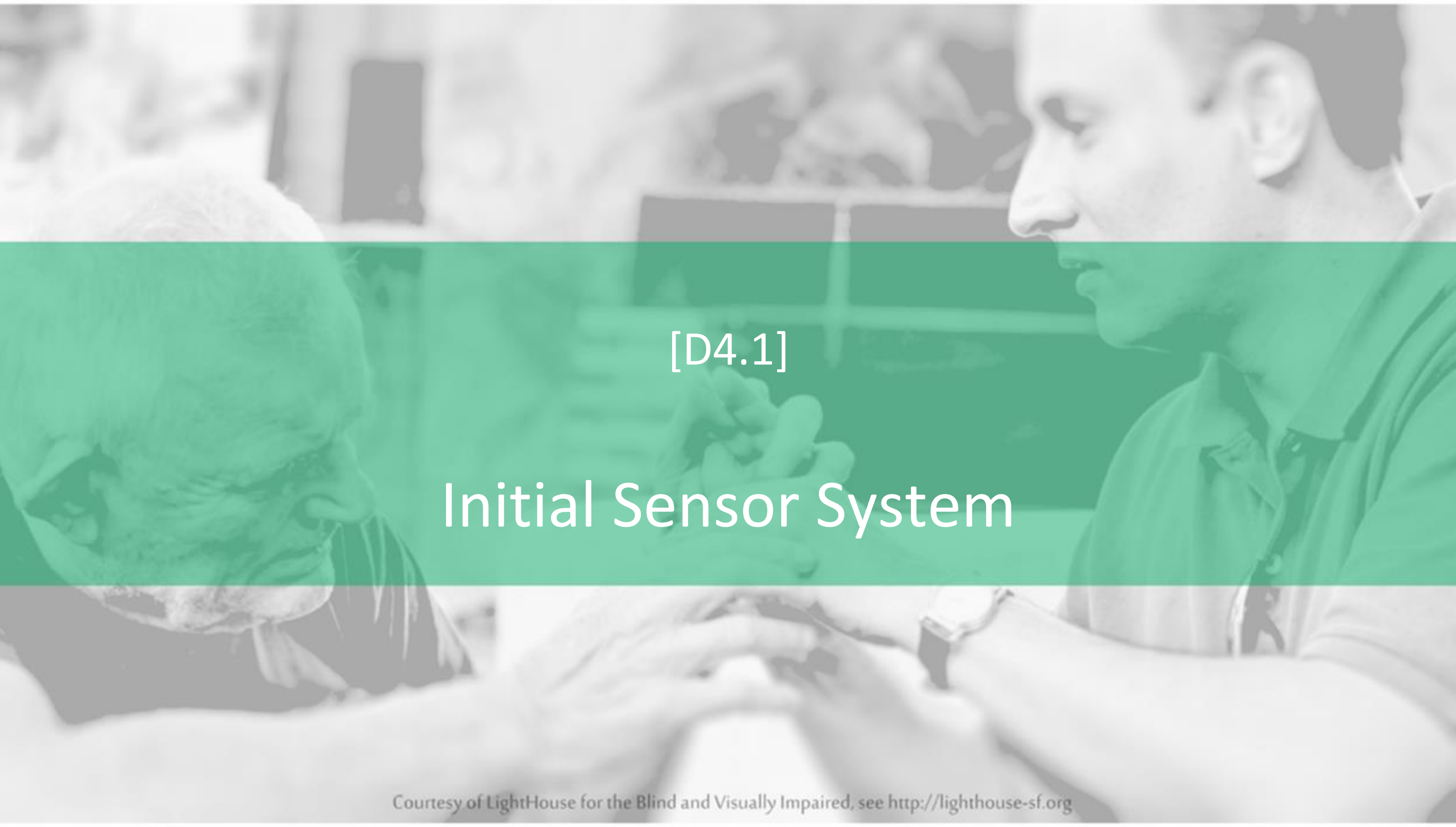
Ref. Ares(2019)7822896 - 19/12/2019

SUITCEYES

1 Jan 2018 - 31 Dec 2020

Smart, User-friendly, Interactive, Tactual, Cognition-Enhancer, that Yields Extended Sensosphere
Appropriating sensor technologies, machine learning, gamification and smart haptic interfaces



[D4.1]

Initial Sensor System

Courtesy of LightHouse for the Blind and Visually Impaired, see http://lighthouse-sf.org

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 780814.

Dissemination level		
PU	PUBLIC, fully open, e.g. web	X
CO	CONFIDENTIAL, restricted under conditions set out in Model Grant Agreement	
CI	CLASSIFIED, information as referred to in Commission Decision 2001/844/EC.	

Deliverable Type		
R	Document, report (excluding the periodic and final reports)	
DEM	Demonstrator, pilot, prototype, plan designs	X
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	

Deliverable Details	
Deliverable number	4.1
Part of WP	4
Lead organisation	UNIVLEEDS
Lead member	Raymond Holt

Revision History			
V#	**Date**	**Description / Reason of change**	**Author / Org.**
v0.1	02/5.2019	Structure proposal	Raymond Holt (UNIVLEEDS)
v0.2	17/5/2019	Draft for Internal Review	Raymond Holt (UNIVLEEDS)
v0.3	10/6/2019	Draft for Internal Review	Raymond Holt (UNIVLEEDS)
v0.4	22/6/2019	Draft for Submission	Raymond Holt (UNIVLEEDS)
v1.0	26/6/2019	Final draft submitted to the EU	Thomas Bebis (HB)
v1.1	16/12/2019	Revised version submitted to HB	Raymond Holt (UNIVLEEDS)
v1.2	19/12/2019	Revised version submitted to the EU	Thomas Bebis (HB)

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Glossary	
Abbr./ Acronym	**Meaning**
AAEON Up Board	A tiny computer intended for use in robotics and Internet of Things projects.
Actuator	An actuator is a component of a machine that is responsible for moving and controlling a mechanism or system.
BLE Beacon	Bluetooth Low Energy Beacon – a beacon that broadcasts information using the Bluetooth Low Energy protocol. Using its identifier and signal strength, the proximity of such beacons to a device can be determined.
HIPI	Haptic intelligent personalized interface – the goal of SUITCEYES and built as a textile structure.
Inertial Measurement Unit (IMU)	A unit measuring acceleration and rotation. Normally comprises an accelerometer to detect linear acceleration, gyroscope to detect rotational velocity, and may include a magnetometer to detect rotation relative to the earth's magnetic field.
RGB-D Camera	A camera capturing both a conventional (RGB) image, and a depth map such that both 3D spatial information is available.
Raspberry Pi	A tiny computer made for teaching computer science. Widely used in development projects.
ROS	Robot Operating System. An operating system that provides methods for capturing and processing sensor information, and delivering instructions to actuators.

TABLE OF CHANGES BETWEEN v1.0 & v1.2

p. [x], Section [y]	previous text	amended text
1, Executive Summary	This report outlines the Initial Sensor System demonstrator developed in this work package which will be integrated into the HIPI in later stages of the project.	This report outlines the Initial Sensor System demonstrator developed in this work package which provides a modular basis for developing the HIPI in later stages of the project.
1, Executive Summary	The system is implemented using the Robot Operating System on an AAEON Up Board, which provides a basis for coordinating multiple sensors and actuators in a manner that can be readily extended and adapted if additional or alternative sensors are required. A mounting for the sensor system has been designed so that it can be worn for testing, and initial steps have been taken to ensure communication with the visual analysis components of Work Package 3 can be undertaken.	The system is implemented using the Robot Operating System on an AAEON Up Board, which provides a basis for coordinating multiple sensors and actuators in a manner that can be readily extended and adapted if additional or alternative sensors are required. The modular nature of this approach means that alternative sensors or algorithms for interpreting their data can readily be used: an important feature, given the varied needs and desires of the population of people with deafblindness. A mounting for the sensor system has been designed so that it can be worn for testing, and initial steps have been taken to ensure communication with the visual analysis components of Work Package 3 can be undertaken.
2, 1. Introduction and Aims	Given the varied needs and capabilities of the population of people with deafblindness, the system has been designed to be reconfigurable so that it can be adapted to the needs of different individuals.	As identified from the User Interviews in conducted in Work Package 2 (see Deliverable 2.1: Requirements for the HIPI), navigating environments was one of the most common needs identified, suggesting that support for navigation and orientation is a valuable part of the project. However, the interviews also identified that the population of people with deafblindness have extremely diverse needs, and the aim of this project is not to develop a single solution that will address all navigation needs of such diverse users, but to develop a platform that can provide a basis for

		future research and development to address the needs of more specific user sets. This is reflected in the approach adopted in developing the initial sensor system: that it is intended to provide the basis for a modular and reconfigurable system that can be adapted to incorporate different sensors in the future, rather than representing a fixed, finished product that will remain static.
		It is worth noting that the platform nature of the proposed makes it difficult to place precise cost and weight limits, as these will depend strongly on the precise scenario and user cases to be addressed. Weight in particular is difficult to be precise about, because it will depend upon how components are arranged around the body – components mounted close to the body can be significantly heavier than those mounted, for example, on the wrist. Nevertheless, for the initial sensor system, the aim is to focus on elements that are as small, compact, light and low cost as possible while still achieving the required functions. It was originally envisaged that the Sensor System would be based around the Raspberry Pi mini-computer, and the initial prototypes of the system were built around the Raspberry Pi platform. However, in order to accommodate the depth camera required for integration with Work Package 3 (which forms the next step in the project), the system has moved instead to the more powerful Up Board. The Up Board is similar in size to the Raspberry Pi, and while more expensive, it remains significantly cheaper than a conventional laptop or

		desktop computer. It is also worth noting that while location data was originally envisaged as coming from a GPS system, it is now expected that most of the SUITCEYES testing will take place indoors where GPS signals are less reliable, and a move has instead been made towards the use of Bluetooth Low Energy Beacons: this is discussed in more detail in Section 2.2.
3, 1. Introduction and Aims	It was originally envisaged that the Sensor System would be based around the Raspberry Pi mini-computer, and the initial prototypes of the system were built around the Raspberry Pi platform. However, in order to accommodate the depth camera required for integration with Work Package 3 (which forms the next step in the project), the system has moved instead to the more powerful Up Board. The Up Board is similar in size to the Raspberry Pi, and while more expensive, it remains significantly cheaper than a conventional laptop or desktop computer. It is also worth noting that while location data was originally envisaged as coming from a GPS system, it is now expected that most of the SUITCEYES testing will take place indoors where GPS signals are less reliable, and a move has instead been made towards the use of Bluetooth Low Energy Beacons. The system has been designed to run using the Robot Operating System (ROS), as this is a well-developed operating system readily available for the Raspberry Pi and Up boards that is designed to co-ordinate the operation of multiple sensors and actuators. The modular approach of ROS makes it easy to use a subset of the sensors selected, or to change the sensors	To support the required modularity, the system has been designed to run using the Robot Operating System (ROS), as this is a well-developed operating system readily available for the Raspberry Pi and Up boards that is designed to co-ordinate the operation of multiple sensors and actuators. The modular approach of ROS makes it easy to use a subset of the sensors selected, or to change the sensors being used, with only minor alterations to the rest of the system. This report provides an overview of the Sensor System developed, presents the outcome of testing its components, and then discusses future steps in its development in the next phase of the project.

	being used, with only minor alterations to the rest of the system. This report provides an overview of the Sensor System developed, presents the outcome of testing its components, and then discusses future steps in its development in the next phase of the project.	
3, 2. System Overview	This section provides an overview of the Sensor System developed, including the rationale behind it and its relationship to the wider SUITCEYES project in upcoming tasks. The Sensor System described in this deliverable will form part of the overall HIPI being developed in the SUITCEYES project. We will use the term Sensor System to refer to the combination of hardware and software developed during Task 4.1, while the term HIPI will be used to refer to the wider system into which the Sensor System will eventually be incorporated over the course of Tasks 4.2 and 4.3.	This section provides an overview of the Sensor System developed, including the rationale behind it and its relationship to the wider SUITCEYES project in upcoming tasks. It is important to understand that the Sensor System described in this deliverable represents part of a modular and reconfigurable platform that can be used to develop the proposed HIPI in later stages of the project: it is not intended as a finalized design. We will use the term Sensor System to refer to the combination of hardware and software developed during Task 4.1, while the term HIPI will be used to refer to the wider system with which Sensor System will need to be adapted to work with over the course of Tasks 4.2 and 4.3.
4, 2.1 System Functions	For SUITCEYES, we have attempted to find a mid-point between these approaches, by scanning the space in front of the user to help them to identify the greatest available space and using proximity detection of landmarks to help provide the user of the HIPI with information to help with higher level navigation. The former requires distance measurement to identify the space in which the user can move without collision, and the latter requires gathering location information through methods such as GPS, Bluetooth, or WiFi positioning systems in order to identify nearby points of interest (streets or buildings	For SUITCEYES, we have explored a mid-point between these approaches, by scanning the space in front of the user to help them to identify the greatest available space and using proximity detection of landmarks to help provide the user of the HIPI with information to help with higher level navigation. The former requires distance measurement to identify the space in which the user can move without collision, and the latter requires gathering location information through methods such as GPS, Bluetooth, or WiFi positioning systems in order to identify nearby points of interest (streets or buildings

	when outdoors, particular rooms or offices when indoors). In addition, collision avoidance raises the question of safety margins: how much space a user must have around obstacles, and when a warning should be provided to the user if they are approaching an obstacle. This margin will depend upon how fast the user is moving, so it is useful to have measures of **self-movement** of the Sensor System. This gives a total of three things that the Sensor System must measure: the space available in front of the system, the proximity of any landmarks useful for navigation; and the self-movement of the system. Consideration must also be given to the future stages of the project, and how the system developed will be capable of integrating with them. The next section describes the sensors and hardware selected to address these issues.	when outdoors, particular rooms or offices when indoors). In addition, collision avoidance raises the question of safety margins: how much space a user must have around obstacles, and when a warning should be provided to the user if they are approaching an obstacle. This margin will depend upon how fast the user is moving, so it is useful to have measures of **self-movement** of the Sensor System. This gives a total of three things that the Sensor System must measure: the space available in front of the system, the proximity of any landmarks useful for navigation; and the self-movement of the system. Consideration must also be given to the future stages of the project, and how the system developed will be capable of integrating with them. The next section describes the sensors and hardware selected to address these issues. It is important to note that the approach presented here represents only one of may possible navigational strategies that could be adopted, and different users may well wish to make different use of distance information (for example, as well as avoiding obstacles, users may wish to shoreline, by following features of the environment, rather than moving into empty space). We make no claim that the approach adopted here is the best, and the modular approach adopted in the system architecture (see Section 2.3) means that alternative algorithms can be readily be implemented to customize the system to the needs of different individuals.
6, 2.2 Sensor Selection	Figure 2 illustrates the way these sensors are combined to cover the area in front of the user. It is worth	Figure 2 illustrates the way these sensors are combined to cover the area in front of the user in the initial

	noting that at present the system does not cover the whole of the 4m long area: to address this, it is proposed that an array of ultrasonic distance sensors be used to cover the furthest points of this array, but this has not yet been implemented.	system design. It is worth noting that the modular nature of the system means that this is not intended as the final layout for the HIPI: t present this layout does not cover the whole of the 4m long area: to address this, it is proposed that an array of ultrasonic distance sensors be used to cover the furthest points of this array, but this has not been implemented in the initial deliverable. It is worth emphasizing that the best arrangement of sensors will be different for different users and scenarios, and the system has the flexibility to accommodate alternative arrangements.
6, 2.2 Sensor Selection	In terms of assessing proximity to landmarks, a variety of methods can be used, such as GPS, Bluetooth Beacons, or WiFi positioning. As most of the experimentation on SUITCEYES will take place indoors, where GPS signals can be unreliable, it was decided to use a Bluetooth-based system, where proximity to Bluetooth Low Energy beacons can be determined from their signal strength, which forms the basis of indoor positioning systems such as Localino[1], and have been used in projects to aid wayfinding for people with visual impairment (Murata et al 2018).	In terms of assessing proximity to landmarks, a variety of methods can be used, such as GPS, Bluetooth Beacons, or WiFi positioning. As most of the experimentation on SUITCEYES will take place indoors, where GPS signals can be unreliable, it was decided to use a Bluetooth-based system, where proximity to Bluetooth Low Energy beacons can be determined from their signal strength, which forms the basis of indoor positioning systems such as Localino[2], and have been used in projects to aid wayfinding for people with visual impairment (Murata et al 2018). This represents a change from the original description of action, which specified that the use of GPS location data would be explored. However, it was felt that it was better to explore location data from alternative sources than merely dismiss it because it could not be reliably achieved indoors through GPS, and the modular nature

[1] https://www.localino.net/
[2] https://www.localino.net/

		of the system means that GPS elements could be readily added for location purposes and outdoors testing in the future. As such, it was felt that this did not represent a significant change from the description of action.
8, 2.3 Sensor Processing	In this way, complex information about the available space can be interpreted without needing to be conveyed entirely to the user. Precise safety margins would need to be determined by user testing, as the system develops. The wider system adopted to capture the information from the sensors and how the information from sensors flows through this is considered in the next section.	In this way, complex information about the available space can be interpreted without needing to be conveyed entirely to the user. Precise safety margins would need to be determined by user testing, as the system develops. The wider system adopted to capture the information from the sensors and how the information from sensors flows through this is considered in the next section. Again, it is to be emphasized that this approach is put forward as an example of what can be done with the system, not necessarily as the optimal navigation strategy, which is likely to vary between users. The modular nature of the system architecture means that alternative strategies could also be implemented in the future.
9, 2.4 System Architecture	However, the system is designed to be modular, such that sensors can be readily added, removed or replaced, to make the system easy to reconfigure.	However, the system is designed to be modular, such that sensors can be readily added, removed or replaced, to make the system easy to reconfigure, depending upon the needs of individual users.

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Executive Summary

Work Package 4 is concerned with the sensing of the environment to support orientation and navigation. This report outlines the Initial Sensor System demonstrator developed in this work package which provides a modular basis for developing the HIPI in later stages of the project. Based upon a review of available distance sensors, the Initial Sensor System utilizes three such sensors (a line laser scanner, an ultrasonic distance sensor, and a depth camera) as well as a proximity detection system based around Bluetooth Low Energy Beacons, and an Inertial Measurement Unit to detect movement of the system. To interpret the complex spatial information gathered from the distance sensors into a form that is easier to convey to the user in a haptic form, a safe ellipse approach is adopted: fitting the largest ellipse to the identified space available, and notifying the user if they are too near the edge of the given space, and of the direction of the center of the available space, so they know in which direction they can safely move. The system is implemented using the Robot Operating System on an AAEON Up Board, which provides a basis for coordinating multiple sensors and actuators in a manner that can be readily extended and adapted if additional or alternative sensors are required. The modular nature of this approach means that alternative sensors or algorithms for interpreting their data can readily be used: an important feature, given the varied needs and desires of the population of people with deafblindness. A mounting for the sensor system has been designed so that it can be worn for testing, and initial steps have been taken to ensure communication with the visual analysis components of Work Package 3 can be undertaken.

1. Introduction and Aims

This deliverable represents the outcome of Task 4.1 of the SUITCEYES project: developing an initial sensor system to map spatial information in front of the proposed HIPI. In line with the Description of Action, the emphasis of this task was to develop an array of distance sensors to measure the space available in front of the user, and then interpret this space and provide information to help the user navigate their environment without collisions. In addition, the use of location information and inertial measurement data have been considered and incorporated into the Sensor System.

As identified from the User Interviews in conducted in Work Package 2 (see Deliverable 2.1: Requirements for the HIPI), navigating environments was one of the most common needs identified, suggesting that support for navigation and orientation is a valuable part of the project. However, the interviews also identified that the population of people with deafblindness have extremely diverse needs, and the aim of this project is not to develop a single solution that will address all navigation needs of such diverse users, but to develop a platform that can provide a basis for future research and development to address the needs of more specific user sets. This is reflected in the approach adopted in developing the initial sensor system: that it is intended to provide the basis for a modular and reconfigurable system that can be adapted to incorporate different sensors in the future, rather than representing a fixed, finished product that will remain static.

Accordingly, the following design goals were set for the initial sensor system:

1. To map the envelope of clear space in front of the HIPI, as a minimum in a cone 4m long and 2m wide at its farthest end from the HIPI;
2. To interpret the envelope of clear space in front of the HIPI and so provide information about safe directions of travel.
3. To be built from low-cost components as far as possible;
4. To be wearable – it should be light enough and small enough to be worn comfortably;
5. To detect the proximity of key landmarks;
6. To detect the motion of the system;
7. To be reconfigurable – it should be possible to adapt the design to the needs of individual users, and add or remove sensors as required;
8. To be capable of combining with visual analysis and ontology modules developed in Work Package 3 and haptic interface units developed in Work Package 5.

It is worth noting that the platform nature of the proposed makes it difficult to place precise cost and weight limits, as these will depend strongly on the precise scenario and user cases to be addressed. Weight in particular is difficult to be precise about, because it will depend upon how components are arranged around the body – components mounted close to the body can be significantly heavier than those mounted, for example, on the wrist. Nevertheless, for the initial sensor system, the aim is to focus on elements that are as small, compact, light and low cost as possible while still achieving the required functions.

It was originally envisaged that the Sensor System would be based around the Raspberry Pi mini-computer, and the initial prototypes of the system were built around the Raspberry Pi platform. However, in order to accommodate the depth camera required for integration with Work Package 3 (which forms the next step in the project), the system has moved instead to the more powerful Up Board. The Up Board is similar in size to the Raspberry Pi, and while more expensive, it remains significantly cheaper than a conventional laptop or desktop computer. It is also worth noting that while location data was originally envisaged as coming from a GPS system, it is now expected that most of the SUITCEYES testing will take place indoors where GPS signals are less reliable, and a move has instead been made towards the use of Bluetooth Low Energy Beacons: this is discussed in more detail in Section 2.2.

To support the required modularity, the system has been designed to run using the Robot Operating System (ROS), as this is a well-developed operating system readily available for the Raspberry Pi and Up boards that is designed to co-ordinate the operation of multiple sensors and actuators. The modular approach of ROS makes it easy to use a subset of the sensors selected, or to change the sensors being used, with only minor alterations to the rest of the system. This report provides an overview of the Sensor System developed, presents the outcome of testing its components, and then discusses future steps in its development in the next phase of the project.

2. System Overview

This section provides an overview of the Sensor System developed, including the rationale behind it and its relationship to the wider SUITCEYES project in upcoming tasks. It is important to understand that the Sensor System described in this deliverable represents part of a modular and reconfigurable platform that can be used to develop the proposed HIPI in later stages of the project: it is not intended as a finalized design. We will use the term Sensor System to refer to the combination of hardware and software developed during Task 4.1, while the term HIPI will be used to refer to the wider system with which Sensor System will need to be adapted to work with over the course of Tasks 4.2 and 4.3. This section first reviews the functions the Sensor System is required to perform in order to meet the design goals set out above; then discusses the main decisions taken in designing the Sensor System; and finally provides an overview of the architecture of hardware and software that make up the Sensor System.

2.1 System Functions

Based on the description of action, the Sensor System is required to provide information to the user that will assist them in navigating their environment without colliding with obstacles, and in orienting themselves within the environment, and we therefore define two corresponding functions that the Sensor System must gather information to support. For **collision avoidance**, it is necessary to map the space in front of the user and to identify in which directions the user should *not* move owing to the presence of obstacles. Except in very crowded environments, this is likely to leave multiple options for directions in which the user *could* move, and it is therefore necessary to provide information to support **wayfinding** and helping the user to orient themselves and identify where they are and whether they are getting closer to their intended destination. Figure 1 illustrates these basic functions in the process of navigating from one room to another.

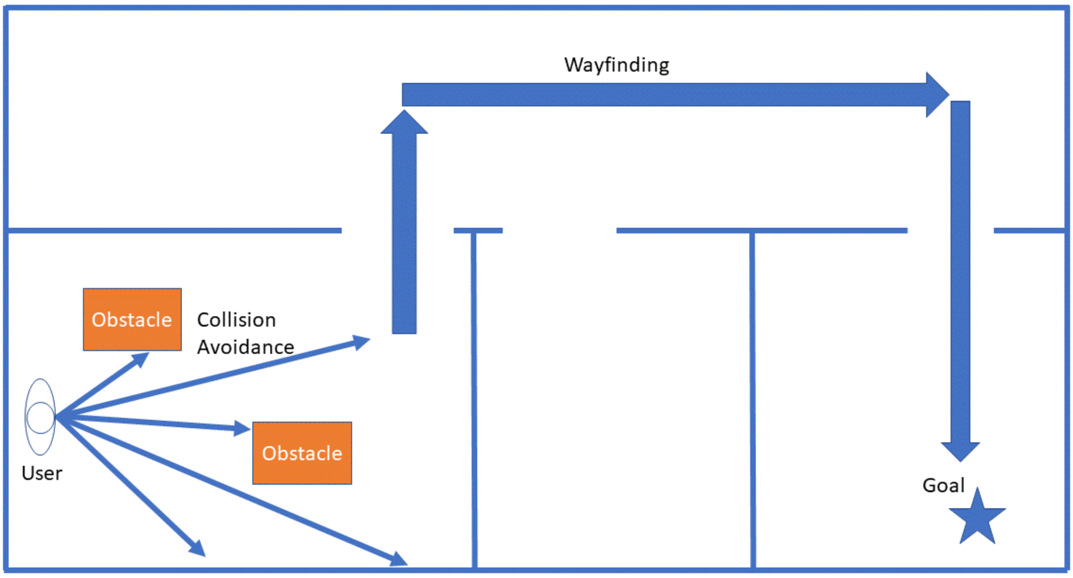

Figure 1: The user needs to move from one room to another – they require collision avoidance support to avoid colliding with walls and other obstacles as they move, but also wayfinding information to orient themselves with respect to the target room – for example, being able to query which room they are in, or identifying which rooms they are passing.

Both functions have received significant attention in the literature on robotics and autonomous systems, providing a range of technologies and methods that can be built upon. However, there are differences in providing information to a robot trying to compute a trajectory and providing information to a human decision-maker. At one extreme, all the information could be passed to the user and they could make the decision about where to go – this is computationally simple but conveying such a volume of information in haptic form is extremely challenging and likely to overwhelm the user. At the other extreme, algorithms could be used to compute a desirable path, and the user simply steered along this path, with no information about why this path is more desirable than others. Such an approach, however, is computationally intensive and difficult to do in a low cost, wearable device, and is likely to be unacceptable to users, since it would require total trust in the system, and provides no contextual information to the user in the event that the system experiences problems.

For SUITCEYES, we have explored a mid-point between these approaches, by scanning the space in front of the user to help them to identify the greatest available space and using proximity detection of landmarks to help provide the user of the HIPI with information to help with higher level navigation. The former requires distance measurement to identify the space in which the user can move without collision, and the latter requires gathering location information through methods such as GPS, Bluetooth, or WiFi positioning systems in order to identify nearby points of interest (streets or buildings when outdoors, particular rooms or offices when indoors). In addition, collision avoidance raises the question of safety margins: how much space a user must have around obstacles, and when a warning should be provided to the user if they are approaching an obstacle. This margin will depend upon how fast the user is moving, so it is useful to have measures of **self-movement** of the Sensor System. This gives a total of three things that the Sensor System must measure: the space available in front of the system, the proximity of any landmarks useful for navigation; and the self-movement of the system. Consideration must also be given to the future stages of the project, and how the system developed will be capable of integrating with them. The next section describes the sensors and hardware selected to address these issues. It is important to note that the approach presented here represents only one of may possible navigational strategies that could be adopted, and different users may well wish to make different use of distance information (for example, as well as avoiding obstacles, users may wish to shoreline, by following features of the environment, rather than moving into empty space). We make no claim that the approach adopted here is the best, and the modular approach adopted in the system architecture (see Section 2.3) means that alternative algorithms can be readily be implemented to customize the system to the needs of different individuals.

2.2 Sensor Selection

In order to develop the system, we reviewed the range of sensors available for each of the three functions, including those that had been used in projects aimed at supporting navigation for people with visual impairment or deafblindness, a summary of which can be found in Appendix 1. Identified commercially available sensors were evaluated against the need for a sufficiently wide field of view, a suitable range and resolution and the need to be lightweight, low cost, and not require large amounts processing power that would be difficult to provide, as well as robustness to ambient light that might confuse light-based systems. An overview of this review process can be found in Appendix 2. It was not possible to find a single sensor that covered all of the identified needs, so a combination of three distance sensors has been considered:

HC-SR04 Ultrasonic Distance Sensor: Detects obstacles in a 4m long, 15° cone. This is light, low cost, and robust to ambient light, but has very low resolution, especially at longer distances. Nevertheless, it provides a fallback in the event of ambient light creating problems for the laser-based systems.

Intel RealSense R200 Depth Camera: Although a depth camera is a relatively high-cost sensor, it is required for the integration of visual analysis algorithms during Task 4.2. The RealSense R200 represents a low-cost depth camera with built-in processing capabilities that make it suitable for use in a wearable device, while providing the synchronized depth-maps and images required for visual analysis. It is most accurate at the 2m-3m range.

Planar Laser Scanner: We were unable to find a sensor that was capable of providing a suitable combination of range and resolution at an acceptable price and processing power. We therefore constructed a bespoke planar laser scanner, which uses a laser emitter to project a line, and a camera to capture to identify the line reflected from obstacles so that a planar depth map could be established using image processing methods (see Appendix 3). Unlike the RealSense R200, this only sweeps a plane rather than a cone, but compensates for this in being significantly cheaper than the RealSense and significantly higher resolution than the ultrasonic distance sensors. A longer range could be achieved with a higher powered laser, but this would require significant development to ensure that such a laser was safe to use.

Figure 2 illustrates the way these sensors are combined to cover the area in front of the user in the initial system design. It is worth noting that the modular nature of the system means that this is not intended as the final layout for the HIPI: t present this layout does not cover the whole of the 4m long area: to address this, it is proposed that an array of ultrasonic distance sensors be used to cover the furthest points of this array, but this has not been implemented in the initial deliverable. It is worth emphasizing that the best arrangement of sensors will be different for different users and scenarios, and the system has the flexibility to accommodate alternative arrangements.

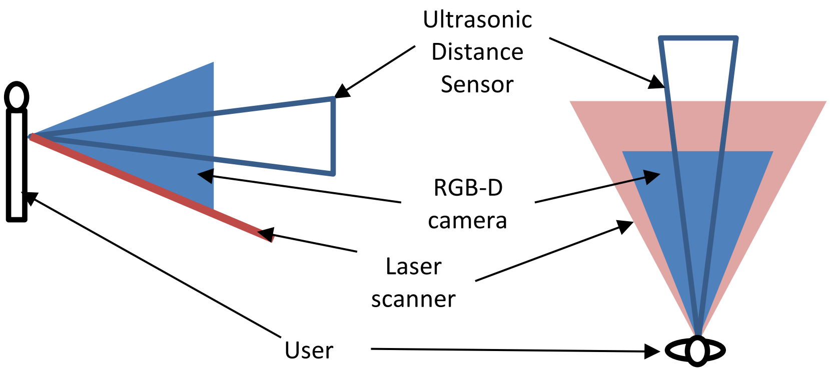

Figure 2: Overlap of collision avoidance sensors relative to user position

In terms of assessing proximity to landmarks, a variety of methods can be used, such as GPS, Bluetooth Beacons, or WiFi positioning. As most of the experimentation on SUITCEYES will take place indoors, where GPS signals can be unreliable, it was decided to use a Bluetooth-based system, where proximity to Bluetooth Low Energy beacons can be determined from their signal strength, which forms the basis of indoor positioning systems such as Localino[3], and have been used in projects to aid wayfinding for people with visual impairment (Murata et al 2018). This represents a change from the original description of action, which specified that the use of GPS location data would be explored. However, it was felt that it was better to explore location data from alternative sources than merely dismiss it because it could not be reliably achieved indoors through GPS, and the modular nature of the system means that GPS elements could be readily added for location purposes and outdoors testing in the future. As such, it was felt that this did not represent a significant change from the description of action.

As information gathered from the beacons is relatively noisy, distance measures from them are necessarily imprecise, and often only accurate to within a few metres: accordingly, it is common practice to categorize the proximity of beacons into immediate/near/far rather than precise distances. Bluetooth Low Energy beacons can be attached to many things – they could be fixed anchor points within a building to identify particular areas of interest (“Reception”, “The Lift”, “Meeting Room A”, “Main Stairwell”) or might be attached to objects of interest or carried by a person of interest, whose proximity could then be identified (for example: “Is my assistant nearby?”).

[3] https://www.localino.net/

For assessing the self-movement of the system, an MPU9050 Inertial Measurement Unit was used to capture linear acceleration and rotational velocity of the system. This is useful to set appropriate safety margins based on whether the HIPI is thought to be moving, and to help determine when new scans were required and to combine multiple scans from the distance measurement systems to improve the performance of the collision avoidance.

In addition to the sensors themselves, there is the question of the hardware and software used to capture and interpret the information they provide. The next section describes the process used to analyze the data from the distance sensors and analyze it to determine usable information that can be conveyed to the user of the HIPI.

2.3 Sensor Processing

As well as capturing raw measurements, it is necessary for the system to also interpret the information captured from the sensors and pass this on to other parts of the system for analysis or to provide appropriate haptic signals. Interpreting the information from the distance sensors is particularly challenging, because it provides quite complex data.

Two basic approaches to interpreting the information from distance sensors can be considered. The first is the "*reactive*" approach in which no attempt is made to interpret information from the sensors – information is fed directly to the user, who must then decide how to react accordingly. An example of this would be using a vibration motor to represent each segment of space scanned and vary the intensity of vibration according to the distance to the nearest obstacle. This is computationally simple but makes the haptic signals very difficult to interpret. At the opposite extreme is the "*planned path*" approach, in which the problem is treated as being the same as guiding a robot – a feasible path is identified by the sensors, and the signals to the user tell them to turn left, right, go ahead or stop. This is simple to convey to the user, but is computationally intensive, and relies on having detailed prior information about the area being navigated (such as having pre-existing maps of the area being navigated), and gives the user no contextual information to help orient themselves – they are entirely dependent upon the performance of the system.

To this end, an alternative approach is proposed – instead of trying to identify obstacles and notify the user about them, it is proposed that the system identify available space, and the user be notified about the direction and potentially the size of this space. To this end, we use the process developed by Deits and Tedrake (2015) to characterise convex regions of obstacle-free space as an ellipse, based on the distance measurement data provided by the distance sensors. This approach is compatible with any of the three selected distance sensors described in Section 2.2, though the higher the resolution of the data, the more precise the ellipse will be. Figure 3 illustrates this concept. The distance measurements pick up the available space, this is characterized as an ellipse, and a safety margin is applied. The user is given two signals – a direction towards the center of the "safe range", indicating the direction in which space is to be found. If the user is outside the defined safety margin, then an alert is given, warning them that an obstacle is near The process for calculating this can be found in Appendix 4.

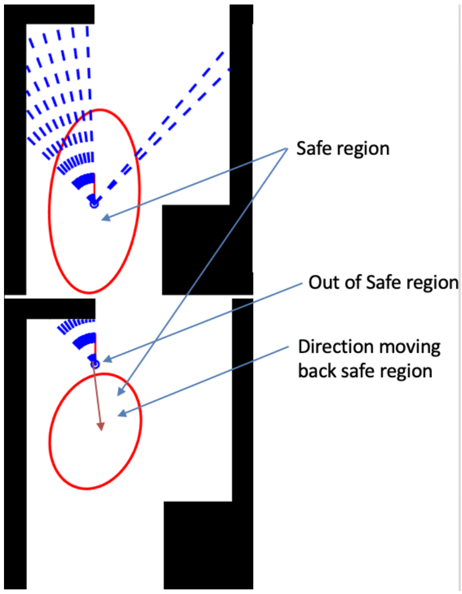

Figure 3: Examples of safe ellipse calculated from scanned data **Top:** The user is within the safe ellipse, so they receive no message. **Bottom:** the user is outside the safe ellipse, so they receive a warning and are directed back towards the centre of the ellipse.

In this way, complex information about the available space can be interpreted without needing to be conveyed entirely to the user. Precise safety margins would need to be determined by user testing, as the system develops. The wider system adopted to capture the information from the sensors and how the information from sensors flows through this is considered in the next section. Again, it is to be emphasized that this approach is put forward as an example of what can be done with the system, not necessarily as the optimal navigation strategy, which is likely to vary between users. The modular nature of the system architecture means that alternative strategies could also be implemented in the future.

2.4 System Architecture

The core of the Sensor System is a mini-computer termed the HIPI Processing Unit, which interfaces with the array of sensors, interprets their information and will correspond with the other elements of the HIPI to deliver information for visual analysis, semantic reasoning and to request appropriate signals from the actuators used to deliver the haptic signals. We selected a mini-computer (an AAEON Up Board) running the Robot Operating System (ROS) as the core of the system. The Up Board provides a similar form factor to mini-computers such as the Raspberry Pi, but has greater processing capabilities and has the USB 3.0 ports required to in interface with the Intel RealSense R200 camera. ROS provides an operating system specifically designed for the co-ordination of multiple sensors and actuators, and includes many functions that are valuable to collision avoidance and wayfinding. In addition, the use of ROS makes it easy to add and remove sensors in line with the modular approach we are adopting. To co-ordinate the operation of the sensors selected in Section 2.2, a separate microcontroller (an Adafruit Feather) is used. This captures information from the IMU and Bluetooth beacons in the environment, which it passes to the HIPI Processing Unit. In agreement with colleagues at CERTH working on Work Package 3, connections to the Realtime[4] framework have been included so that messages can be delivered to the Realtime Message bus being implemented in Work Package 3, in readiness for integrating visual analysis and semantic reasoning in Task 4.2. Figure 4 illustrates how the elements of the Sensor System fit together, and how they relate to the elements from other work packages that the Sensor System will need to integrate with in the next stages of the project.

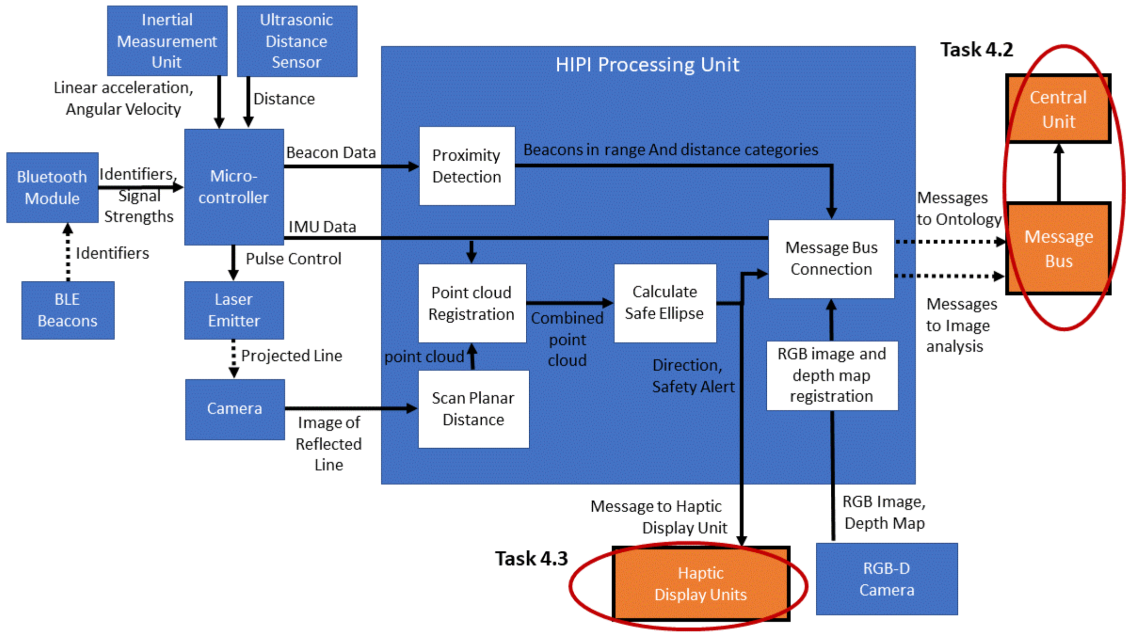

Figure 4: Overview of the Sensor System (dashed lines denote elements to be integrated from Work Packages 3 and 5 in Tasks 4.2 and 4.3 respectively)

Appendix 5 provides a full list of the components selected, their costs, weights and power consumption, while Section 3 provides a more detailed description of the hardware and software modules being used. Figure 5 illustrates the prototype system itself, as intended to be worn. The current system weighs approximately 200g for the sensor elements, with a further 300g for a battery capable of powering for an estimated 7 hours at full power consumption. Components cost approximately 350 Euros, though the cost of mounting and attachment to the HIPI will need to be considered over and above this. However, the system is designed to be modular, such that sensors can be readily added, removed or replaced, to make the system easy to reconfigure, depending upon the needs of individual users.

[4] https://framework.realtime.co/messaging/

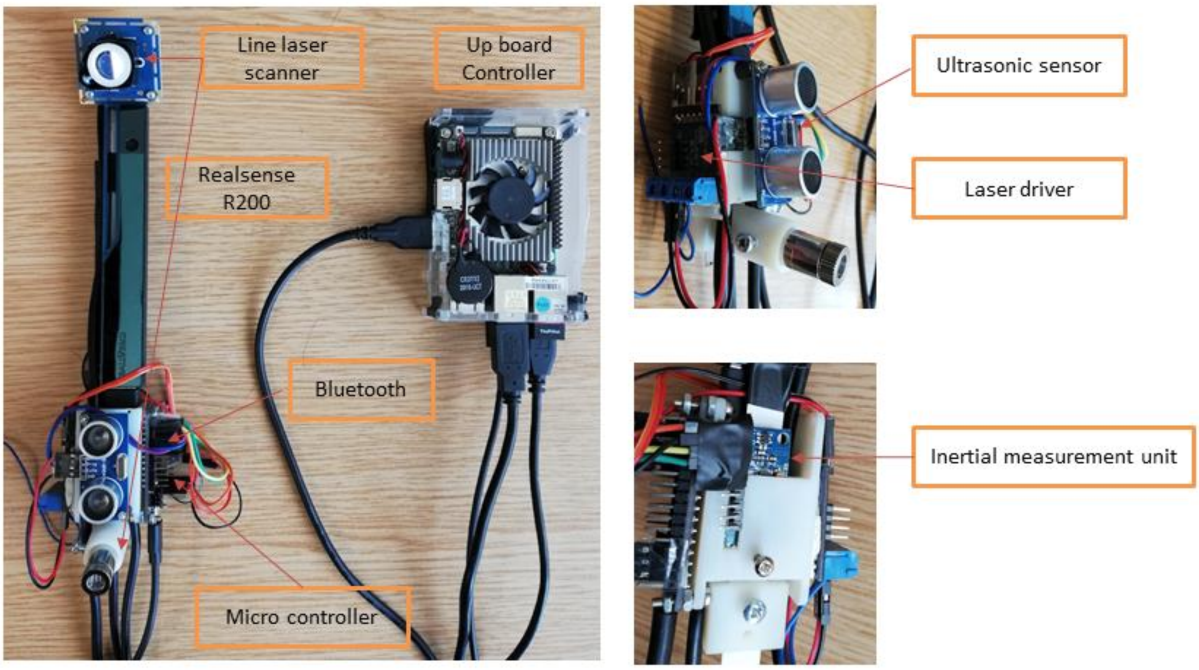

Figure 5: The Initial Sensor System

3. Testing

This section outlines some of the tests used to assess the viability of the sensors adopted in this system, particularly the Intel RealSense R200, and the BLE Beacon proximity sensors.

3.1 Intel RealSense R200 Depth Camera

The RealSense R200 Depth Camera can obtain synchronized RGB and depth images, as illustrated in Figure 6. RGB images (such as Figure 6(a)) are conventional colour images, while the depth image (Figure 6 (b)) indicates how far away different parts of the image are. Point cloud data also can be generated from the Intel RealSense R200.

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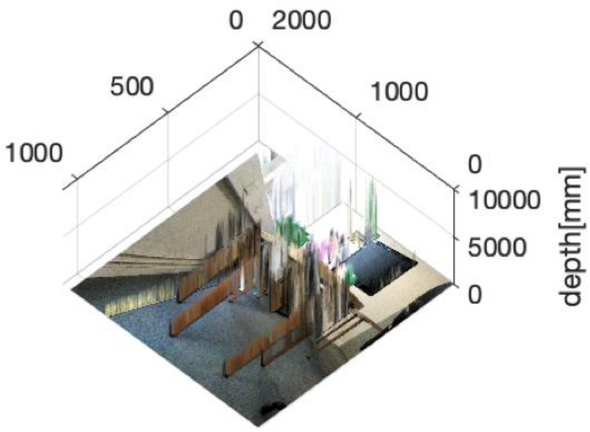
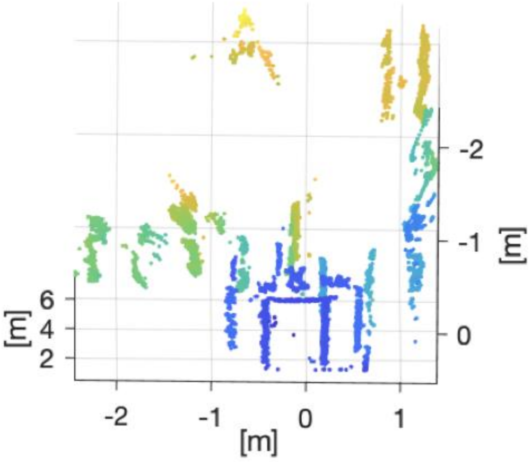
(a) RGB image (1920X1080)

(b) Depth image (480X360)



(c) Register a depth image to RGB image



(d) Point cloud data

Figure 6: Example of (a) RGB image (b) depth image, (c) a depth image registered to an RGB image, and (d) the point cloud returned by RealSense R200.

The RealSense R200 was tested by placing a planar target in front of it, and images were then captured at different distances, with the results shown in Figure 7. The RealSense is capable of measuring targets from 0.5-4 meters, however, the valid point ratio (the proportion of points identified) drops significantly in the short distance (<1m) due to over-saturation of the image by the active IR illumination, and in the far distance (>2.5m) due to being outside the IR illumination range. Therefore, only the range between 1.0–2.5 m could be measured reliably. This is the range in which object recognition is most likely to be needed, so this fits well for Task 4.2 and the ability to provide depth maps to augment visual analysis is positive. However, the sparseness of the point cloud at ranges longer than 2.5m indicate that it is not suitable for collision avoidance at this distance, emphasising the need for other sensors such as the ultrasonic to cover a further distance.

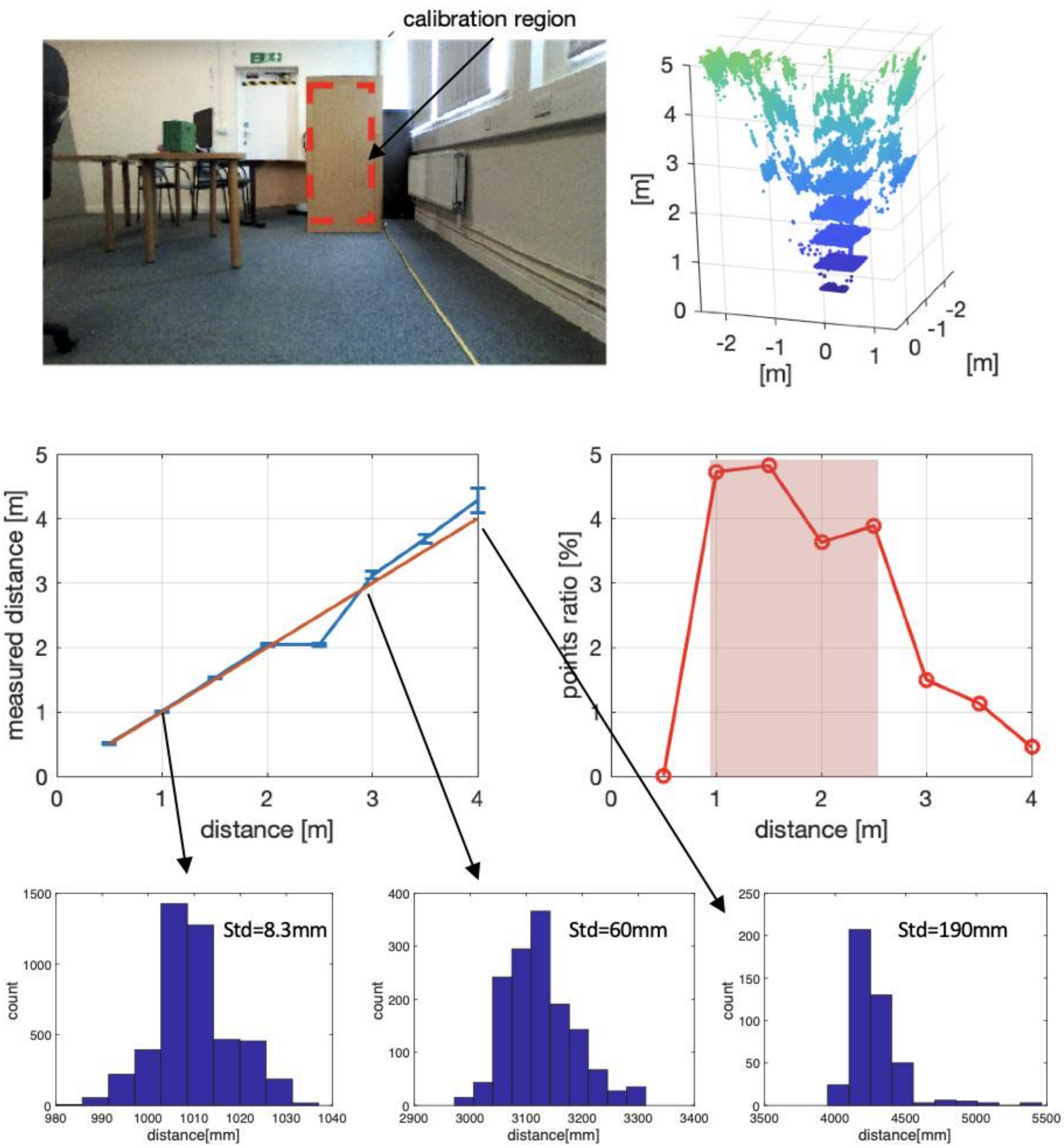


Figure 7: Testing of RealSense R200 Camera.

If an object is identified by visual analysis, and an appropriate bounding box established, it is possible to identify the distance of the object from the user by projecting its bounding box in the RGB image to the depth image, to estimate the distance and orientation of the object. Figure 8 illustrates the results of this process: a bounding box on the RGB image has been specified to simulate the results of visual analysis, and the distance for that bounding box is identified from the corresponding points on the registered depth map.

Figure 8: an example of target object distance measurement: once a bounding box for a recognised has been established in the RGB image, it can be projected to the depth image to estimate the distance.

The Intel RealSense was also tested with the safe ellipse generation process described in Section 2.3, with a graphical representation of the ellipse displayed on a computer monitor so that the change in the ellipse could be viewed in real time, and verify that the distance measurement and ellipse calculation could be performed when moving. Figure 9 below provides an illustration of how the ellipse changes as an obstacle is approached, and in the bottom image, an alert being generated (denoted by the red dot to the left of the ellipse) when the user is no long within the safe ellipse. The left hand column shows the RGB images gathered from the RealSense, the central column the point cloud returned by the RealSense and the right hand column a visual representation of the safe ellipse boundary and the safe ellipse. The dot to the left hand side of the ellipse boundary turns red when the use is outside the safe ellipse, as shown in the bottom image, when the obstacle is near.

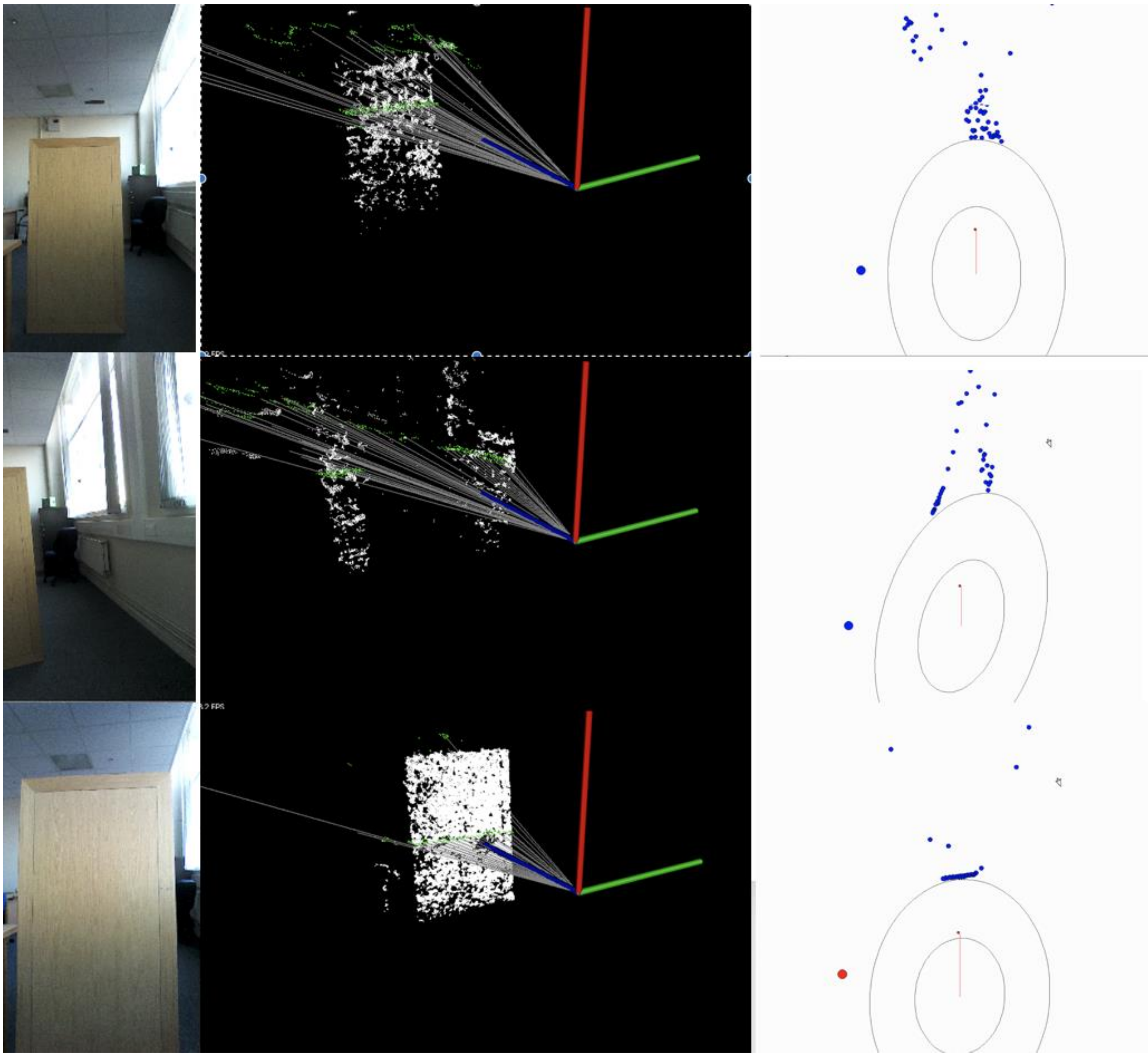


Figure 9: Results of using Intel RealSense and Safe Ellipse generation to assess ability of system to identify safe ellipse as an obstacle is approached.

3.2 BLE Beacon Proximity Detection

To investigate the suitability of the BLE Beacon approach, we calibrated six DSD-TECH HM10 BLE beacons, which use the iBeacon protocol, in one dimension using the Log Normal Shadowing Model (LNSM – Hashemi (1993)) as shown in Figure 10. This allows the estimation of distance from the BLE beacon's Received Signal Strength Index (RSSI) as measured by the Bluetooth Module of the Sensor System. Note that the data is noisy, so a 20-point median filter was applied in order to reduce the noise in the signal and improve consistency of responses.

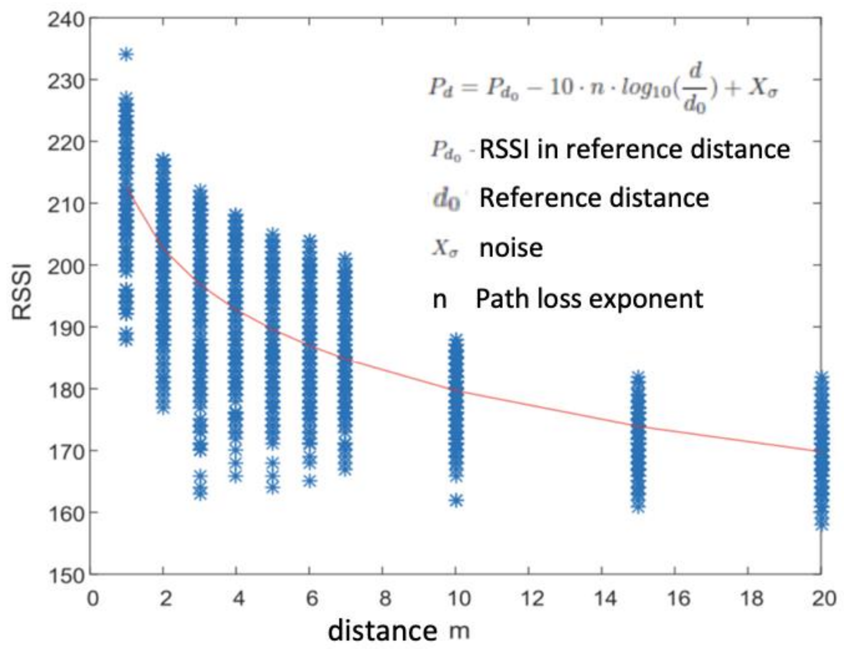


Figure 10: Curve fitting with Log Normal Shadowing Model (LNSM) for six BLE beacons RSSI in 1 dimension

BLE beacons can also be affected by multi-path losses or shadowing due to reflected signals or noise sources, which can interfere with measurements. To characterize the error of proximity detection in a 2 dimensional space, six BLE Beacons were set up win a rectangular grid 7m x 9m. Measurements of the RSSI and estimated distance for each beacon were then taken at each of the measurement points shown in Figure 11.

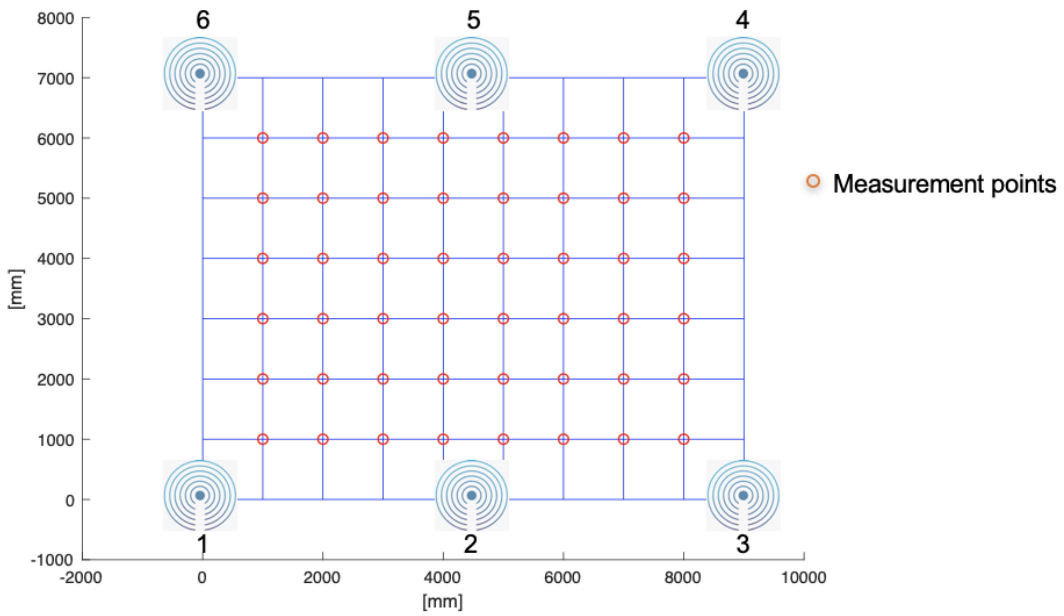


Figure 11: Experimental set up of proximity detection for BLE Beacons

Figure 12 shows the RSSI signals from the six beacons at different distances. It can be seen there exists significant interference in beacons 1 and 6 between 4 and 10 meters, which makes their results unreliable, while the other four beacons follow the Log Normal Shadowing Model described above, and the RSSI drops down with distance increasing relative to the beacon. This highlights the importance of testing for noise and path loss.

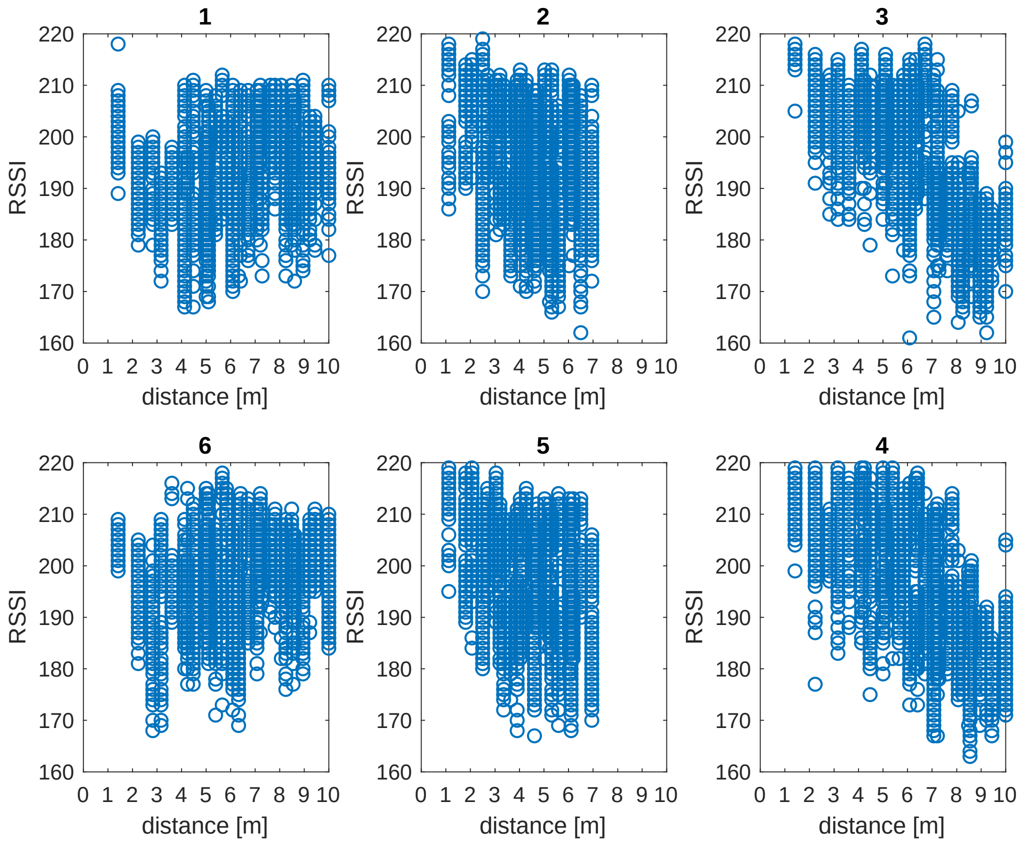


Figure 12: Changes in RSSI signal over distance for the six BLE Beacons. Note the noise in the signals, and the interference in Beacons 1 and 6 above 4m, which leads to RSSI increasing rather than decreasing.

Proximity detection was achieved by classifying the estimated distance into the following four groups: Immediate (less than 2 metres from the Beacon); Near (2m-5m from the Beacon); and Far (5m-10m from the Beacon). Figure 13 illustrates the proportion of classifications into each category at different distances from each beacon. With the exception of beacons 1 and 6, which were affected by interference, the BLE beacons are able to differentiate between a beacon within 2m and a beacon within 7m, so can provide some value in identifying proximity to waymarks.

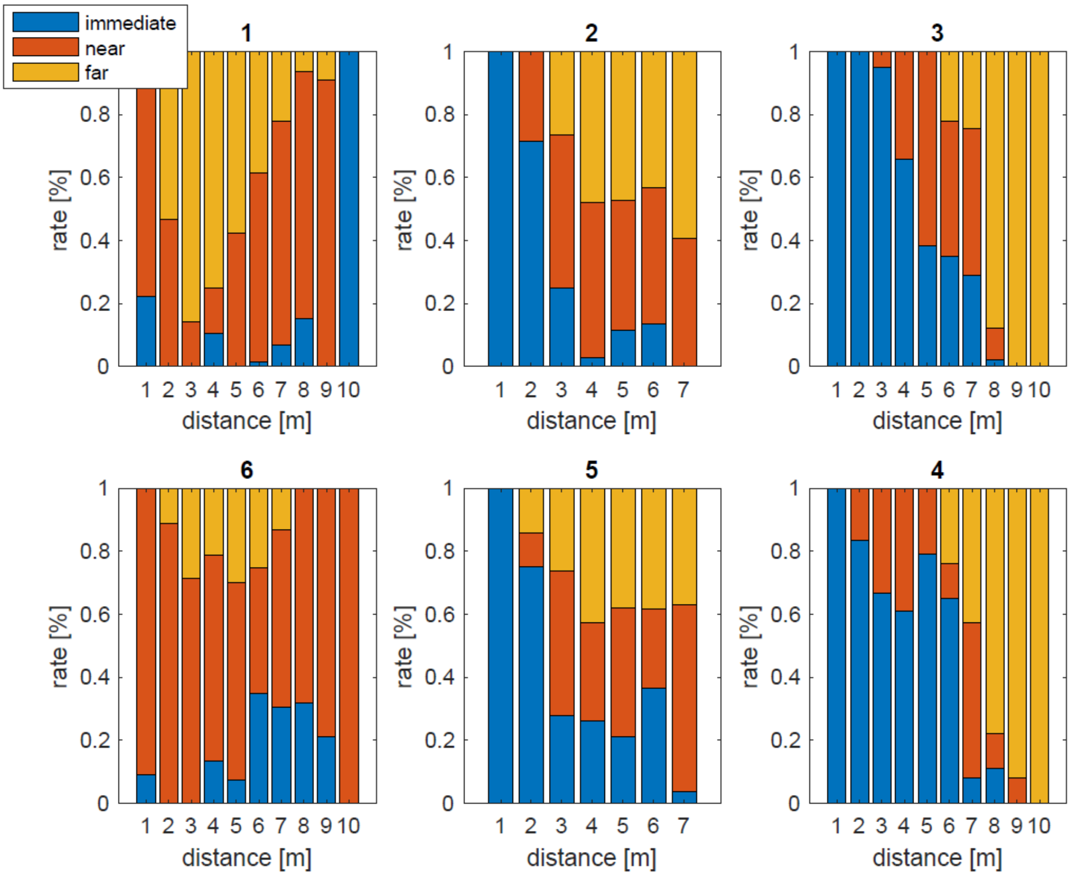


Figure 13: Classifications of proximity and different distances from each sensor. The noisy RSSI signals mean that the boundary of each category is necessarily fuzzy.

Conclusions

This report has outlined the main components of the Initial Sensor System for Work Package 4. A suite of sensors has been selected, and a system architecture designed based on ROS that enables their integration and processing, with links to the Realtime Message Bus in readiness for Task 4.2. The approach adopted is modular, such that different combinations can be used. If no depth camera is required, then the system could be implemented at lower cost on a Raspberry Pi using the planar laser scanner, for example; alternatively, if depth camera images are required for visual analysis, then the more powerful combination of an Up Board and Intel RealSense camera would be more appropriate, and it is this design that we will be taking forward into Task 4.2.

In line with the description of action for the SUITCEYES project, during the course of this task we have undertaken a review and identified a set of appropriate sensors for inclusion in the HIPI; implemented an algorithm for interpreting spatial information from these sensors into a more appropriate form for haptic communication; devised a housing that permits these sensors to be worn on the body; and verified the performance of these sensors. This work only represents the first step in developing the sensors. Many of the parameters need to be fine-tuned based on user testing, and the use of semantic reasoning and visual analysis from Work Package 3 to enhance the raw sensors information will also be valuable.

Appendix 1: Review of Collision and Navigation Systems for People with Visual Impairments

Work on portable obstacle avoidance systems prior to 2010 has already been reviewed by Dakopoulos and Bourbakis (2010). The authors classified navigation systems into three main categories: Electronic travel aids (ETAs), Electronic orientation aid (EOAs) and Position locator devices (PLD). These three kinds of device can be further related to three concepts widely used in navigation systems: collision avoidance, wayfinding and navigation, as shown in Figure 14.

Collision avoidance is the process of moving in a known forward direction without colliding with any obstacle, and it is this that Dakopoulos and Bourbakis' class of Electronic travel aids address: sensing the local environment and feeding back to the user to avoid collisions by allowing the user to change their course (for example, by stepping to one side).

Wayfinding represents the process of finding a route between locations direction moving to the destination without a map: this is similar to the idea of Electronic orientation aid (EOAs), providing orientation information to the user so that they can select an appropriate route.

Navigation: represents the process of self-location on a known route or map, using Position locator devices (PLD) such as GPS and a known map.

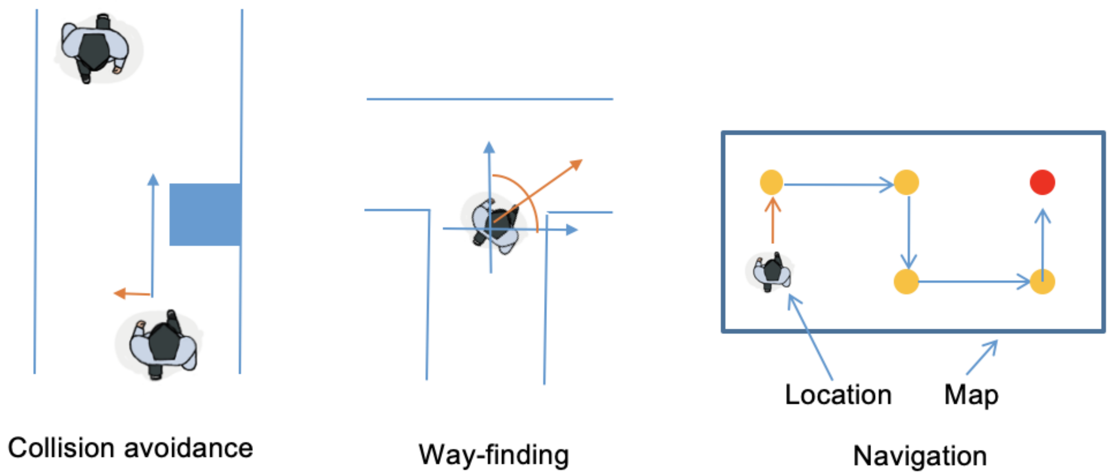


Figure 14: Collision avoidance, Wayfinding and Navigation.

A1.1 Collision Avoidance

As we are interested in the haptic collision avoidance systems, we have restricted select those systems that have both sensors and haptic feedback elements and focus on the control (information interpretation) method that maps the sensor input to the haptic interface. 10 cases were selected, the first 5 of which had been reviewed in Dakopoulos and Bourbakis (2010), a summary of which can be found in Table 1. We examined the type of sensors used, the haptic interfaces used, and how information was mapped between the two to avoid collisions.

Table 1: Haptic collision avoidance systems

Author	Project	Sensor	Sensor Mount	Haptic Interface Type	Mapping of Spatial Information to Haptic Information	Control type
Zelek et al. (2001)	University of Guelph	Stereo camera	Worn on front of chest	A tactile glove	glove with five piezoelectric buzzers on each finger tip, finger corresponds to a spatial direction	Reactive
Meers and Ward (2005)	Electron-Neural Vision System	Two stereo cameras digital compass	Head	An electrodes glove	The amount of stimulation is directly proportional to the distance of the objects in the direction pointed by each finger.	Reactive
Ito et al (2005)	CyARM	Ultrasonic sensors	Handheld	Tension of a wire that is attached on user	tension of a wire represents obstacles distance	Reactive
Johnson and Higgins (2006)	Tactile Vision System	Stereo camera	Head	a tactor belt with 14 vibration motors	sliced in 14 vertical regions. Each vibrator motor is one region and vibration intensity corresponds to distance	Reactive
Cardin et al. (2007)	EPFL Project	Sonars		8 Vibration motors from one shoulder and ending to the other	Vibration intensity is proportional to the obstacle distance	Reactive
Bourbakis at al (2013)	Wright State University	Stereo-camera	glass-mounted	a 2-D vibration array vest	maps a high to low image resolution to a low-resolution 2-D array of vibrators.	Reactive
Cosgun et al (2014)	Georgia Institute of Technology	a stationary laser scanner	Not wearable	Vibration motors	Plans an obstacle-free path by modeling the human as a robot using local navigation planner and keep the ’robot’ on the path.	Path plan
Lee and Medioni (2015)	University of Southern California	RGB-D camera	glass-mounted	Vibration motors vest	Performs real-time 6-DOF visual odometry to generate a 3D voxel map and keep user on the planned path	Path plan
Wang et al (2017).	Fifth sense	RGB-D camera	Wear in front of chest	Vibration motors belt	The system plans step-by-step a safe motion trajectory in an identify walkable space	Path plan
Katzschmann et al. (2018)	ALVU MIT	7 time-of-flight distance sensors	Waist	haptic strap vibration motors	Projects distance sensor information on the body using haptic strap	Reactive

Sensors: Most of the earlier studies used stereo cameras to get the depth of an image, and were mounted on the head to obtain a good field of view. Ultrasonic sensors were also used, being more robust than stereo cameras but having a lower resolution of detection. In the past ten years, with the development of RGB-D camera, Time of Flight camera, they have been applied in these collision avoidance systems (Lee and Medioni, 2015; Wang et al (2017); Katzschmann et al 2018). LiDAR or laser scanner is rarely used, it is probably because they are not portable and expensive, Cosgun used a stationary laser scanner to measure the user's position. A more detailed comparison of different commercial distance sensors could be found in Appendix 2.

Haptic Interfaces: In the ten surveyed cases, three types of haptic actuator were used: vibration (8 times), electrode (once) and tensioned wire (once). Vibration motors were therefore the most popular haptic feedback device, having been mounted in gloves, belt, shoulder and vest: in most cases, each vibration motor represents one direction and maps a 2d planar space, such as each direction corresponding to a finger (Zelek at al.2001) or a different positon on a belt Katzschmann et al (2018). Bourbakis et al (2013) developed a two dimensional array to map the information from 2d images extending the 2d plane to a 3d space. The distance is indicated by the intensity of vibration, however, the resolution is low, largely being able to distinguish "near" or "far". Ito et al (2005) used a wire to generate different tension forces, which potentially increase the resolution of distance representation.

Collision avoidance Methods: Two collision avoidance methods were identified. "Reactive" methods represent the direction of different obstacle by the location of haptic feedback, with differences in intensity representing different distances. Training is generally necessary to use such devices effectively. A recent study using reactive methods is ALVU (Katzschmann et al 2018) composed of an array of time-of-flight distance sensors worn around the front of a user's waist, and an array of vibratory motors worn around the user's upper abdomen. It was assumed that user will move their body to cover a large space using 7-point distance measurement sensors. "Planned Path" methods follow from more recent work introduced from robotics into the assistance system using perception data from a LiDAR, camera, or RGB-D camera to build a local map in the form of occupancy grid maps, so that a collision-free path can be planned using graph-based search algorithms. Cosgun et al (2014) developed a navigation guidance system by modeling the user as a non-holonomic robot with a tactile belt interface and a stationary laser scanner. A local navigation planner was used to generate an obstacle-free path dynamically, then the system keeps the user on the path by converting direction and rotation information to vibration patterns. This method includes: pose estimation, local map building and path plan steps, there are various ways to achieve these functions. Lee and Medioni (2015) and Wang et al (2017) applied RGB-D sensors to make portable systems under the planned path approach.

A1.2 Wayfinding

Wayfinding requires more than avoiding collisions with other objects: it also requires guidance information to help the user make decisions about which way to turn, particularly in unfamiliar environments. Wayfinding is a decision-making task based on the interplay of traversability estimation (determining which areas are valid to move across – differentiating doorways, hallways and stairs, for example) and information about position within the environment (such as might be gathered from signage or landmarks).

Ideally, the output of a wayfinding process should be a safe route that includes the functions of collision avoidance but also includes estimation of whether free space is suitable to cross. Aladrén et al (2016) and Yang et al (2016) have demonstrated the use of RGB-D cameras to generate an obstacle free path or traversable area to allow user to move and avoid collisions. The key function is to segment the environment and detect feasible ground combing information from RGB image and depth image.

However, wayfinding needs to process a large amount of data (such as 2d depth images) and recognize features of the data to get semantic information, which leads to a low scan rate for the sensor system, making it unsuitable for use in a dynamic environment which may be subject to change (such as having people moving around). Furthermore it is difficult for a single sensor to cover the wide range of distance, resolution and intense light environments required for both collision avoidance and wayfinding. Some researchers separated these two functions and used RGB-D sensors or Time of Flight cameras to detect key elements of the environment (hallway, doorway, stair) for wayfinding and a white cane for collision avoidance (Zhang and Ye, 2017; Ye and Qian, 2018). Audio interfaces are the most popular feedback in these studies: it remains to be seen whether the same information can be conveyed effectively in a haptic form. Table 2 provides a summary of wayfinding methods intended for individuals with visual impairment.

Table 2: Wayfinding methods for individuals with visual impairments.

Author	Project	Sensor	Sensor mount	Interface	Method
Yuan and Manduchi (2004)	University of California Santa Cruz	Point laser triangulation	Handheld	No	Environment features detection (steps, drops-off)
Aladrén et al (2016)	Universidad de Zaragoza	RGB-D camera	hanging from the user's neck	audio interface	combination of depth information with image intensities, providing the user with obstacle-free paths
Zhang and Ye (2017); Ye and Qian (2018)	Virginia Commonwealth University	3D time-of-flight camera	Mounted on white cane	audio interface	The system uses visual SLAM to estimate pose and location of user in a building
Wang and Tian (2012)	The City College of New York	RGB-D camera	Not clear	No	extract parallel lines on RGB channels and projects on Depth channel to recognize pedestrian crosswalks, upstairs, and downstairs
Yang et al (2016)	Zhengjiang university	RGB-D camera	Glass	audio interface	Preliminary traversable area is processed using RANdom SAmple Consensus (RANSAC) segmentation, then a seeded growing region algorithm, using the depth image and RGB image, enlarges the preliminary traversable area.

A1.3 Navigation

Navigation requires map building, route generation and real time location to monitor progress through the route. Real time location can be achieved by using internal sensors such as an IMU pedometer (Hesch and Roumeliotis, 2010; Flores, 2017), or external sensors such as wireless positioning systems. The IMU pedometer suffers from accumulate errors over long periods of movement. Wireless position systems include GPS, Wi-Fi, and Bluetooth Low Energy Beacons. GPS (Global Positioning System) has been widely used in outdoor environments, but it cannot provide accurate temporal and spatial estimates indoors. Early work on alternatives to GPS for indoor environments have explored using specialized beacons: for example, ActiveBadge (Want et al (1992)) uses infra-red beacons; Cricket (Nissanka, 2000) uses a combination of radio frequency and ultrasound signals. Nowadays, Indoor positioning has focused more on methods that rely on existing short-to-mid range communication techniques between mobile devices (Bluetooth), wireless local area network (WLAN) and wireless sensor network (Zigbee – Hu et al. 2011).

Murata et al (2017) have methods using Bluetooth Low Energy Beacons to deliver turning information after locating the user in a map using a “fingerprinting” method by measuring signal strengths at different locations on the map. This successfully demonstrated the system in a large scale space in the campus, however it was found that missed turns were a common issue where the user turns too early or too late, and they conclude that it may require a wayfinding module to define a more accurate turning angle and turning position. Bai (2015) developed a coarse-to-fine multi-resolution system using GPS, Wi-Fi and camera to navigate user in a different scale region to leverage this issue. Another interesting approach is to deliver landmark information allowing users to be aware of the environment they are in, for example, at street crossing or bus stops (Bai, 2015; Flores, 2017): proximity detection using Bluetooth Low Energy Beacons could be one way to achieve this. It is not clear that if it could be further developed to apply landmarks with a topological map for navigation (a map that captures relationships between places, rather than a metric map which captures distances) with a real time location system. A summary of location-based methods for navigation are summarized in Table 3, on the next page.

Table 3: Location-based methods for supporting navigation of persons with visual impairments

Author	Project	Sensor	System
Hesch and Roumeliotis (2010)	University of Minnesota	three-axis gyroscope a 2D-laser scanner foot-mounted pedometer	Extended Kalman filter based visual –IMU odometry and foot-mounted pedometer to trace and locate the user in a know map
Bai (2015)	University of Pittsburgh	GPS Wi-Fi Digital camera	A coarse-to-fine multi-resolution system: a global positioning system (GPS) layer for building identification; a Wi-Fi - barometer layer for rough position localization; and a digital camera - motion sensor layer for precise localization.
Liao (2013)	University of Minnesota	iBeacon	A mobile accessible information system , receive transportation information at key locations when to cross streets, incorporates a geospatial database
Sato et al 2017; Guerreiro et al 2017 Murata et al 2018;	NavCog	iBeacons	A smartphone-based real-time localization system provides turn-by-turn navigation over large spaces, depends on pre-built map and Fingerprint Collection
Flores (2017)	UC Santa Cruz (2017)	Wi-Fi access points	The system conveys travel-related information to blind passengers when using public transportation.
Flores (2017)	UC Santa Cruz (2017)	inertial measurement unit	The system helps blind people retrace the path taken inside a building

Appendix 2: Review of Commercial Distance Measurement Sensor

In various navigation and collision avoidance systems for blind and visually impaired people reviewed in Appendix 1, a wide range of distance measurement sensors have been used: ultrasonic distance sensors, Time of Flight distance sensor, depth cameras, Time of Flight cameras, laser scanners and LiDAR. To assess which should be included in the SUITCEYEs project, we conducted a survey of the distance measurement sensors available on the market and evaluated their possible application in the project. We classified sensors based on the type of emitter (ultrasonic, Infrared LED, laser, Radio Frequency or Stereo Camera) and the method of assessing distance from sensor readings (by time of flight, triangulation or received signal strength), as shown in Figure 15. In addition, we considered whether sensors provided a single point measurement of distance (which we termed 1D), or returned a set of distances along a line or across a grid (which we termed 2D).

Figure 15: Different sensor types and associated methods of distance measurement

Sensor Type	Time of Flight	Triangulation	Received signal strength
Ultrasonic	O		
Infrared LED	O	O	
Laser	O	O	
RF			O
Stereo camera		O	

Both time of flight and triangulation methods for distance estimation operate by emitting signal pulses into the environment and detecting the signal reflected off objects in the environment. In time of flight methods, it is the time between the signal being emitted and the reflected signal being received that is used to calculate distance, based on the speed of the signal's propagation (the speed of sound for ultrasonic sensors; the speed of light for light-based (infrared LED or laser) sensors. In triangulation, the sensor and emitter are set a small distance apart, and the angle of the reflected signal is used to estimate distance.

The type of sensor being used has an impact on the range and precision of distance measurement. Ultrasonic Sensors typically generate soundwaves at above 40 kHz so that they do not conflict with human hearing. However, due to attenuation caused by air, the range of the sensor decreases as the frequency increases with 40 kHz providing a range of around 4m. The sound signal spreads out in a cone of typically 15-20 degrees. By contrast, laser sensors can produce a very tight point, and their range can be varied depending on the wavelength of the light used and the power of the emitter. However, lasers have significant safety considerations that must be addressed: the light source needs to emit a safe wavelength of light at a non-damaging power level to avoid causing damage to the eyes of anyone in the vicinity. Infrared LEDs have fewer safety issue than lasers, with an angle of 2-3^{o}, and a measurement range of around 10 m for time of flight methods, but a shorter range of about 1m for triangulation. Infrared LEDs and lower powered lasers can work in varying light conditions but can be affected by large amounts of IR interference such as sunlight.

Received signal strength takes a different approach – by measuring the strength of a radio signal in a wireless environment, and using this to infer distance from the receiver to the emitter. This is different in that it requires beacons to be setup in the environment that can emit the required radio signals. Radio signals spread in all directions, and are capable of passing through walls, though they are also subject to interference and signal loss caused by the environment.

The following pages provide a summary of the outcomes of the review of candidate sensors. This was undertaken by identifying a range of available sensors across the types shown in Figure 14, and reviewing their datasheets. Attention was restricted to those that were potential candidates for being low-cost, portable and low-power.

A2.1 1D Distance Sensors

We first reviewed the use of 1D distance sensors (those that return a single point distance estimate). These have the benefit of being generally lower cost than 2D sensors however, as they provide only a single point measurement, multiple 1D sensors would be required to cover an area and this could easily eliminate their cost advantage. However, the benefit of using multiple 1D sensors is greater control over their arrangement, and the potential ease of integrating them into a garment. Table 4 provides a summary of the properties of potential candidate 1D sensors that were considered in the SUITCEYES project, while Figure 16 provides a visual comparison of their range as against their field of view.

Within 1D Ultrasonic and IR Led triangulation-based sensors can cover a certain range of measurement but cannot measure a single point accurately due to their large field of view; they also have a relatively short range (below 5 meters). However, their low cost and small size allow them to be installed around the human body, and detect the proximity obstacles from different directions. Laser-based time of flight sensors have the smallest field of view and provide high measurement accuracy on a point target, but they are expensive for a long distance measurement (> £100), or at lower costs tend to have very short range (<2m) for obstacle detection. LED-time of flight sensors (Benewake), could potentially be used for a long-range obstacle measurement. Bluetooth Low Energy beacons (iBeacon) could provide distance information using the received signal strength method with low resolution but long distance, and could be developed for proximity detection and indoor position system.

Table 4: Properties of Candidate 1D distance sensors

Name	Ultrasonic	Laser-ToF1	Laser-ToF2	LED-TOF1	LED-TOF2	LED-Triangulation	iBeacon
Type	HC-SR04	VL6180X	LIDAR-Lite 3	Benewake	TeraRanger	GP2Y0A710K0F	HM-10
Principle	Ultrasonic Time of Flight	Laser Time of Flight	Laser Time of Flight	Infrared LED Time of flight	Infrared LED Time of flight	Infrared LED distance Sensor	RSSI Bluetooth
Range	0.02 - 4m	0.05-2m	0 - 40m	0.3 -12m	0.5-14m	0.1 - 5m	100m
Accuracy			+/-2.5cm	1%(<6m), 2%(6-12m)	±4cm <14m, 1.5% > 14m		low
Update rate	40kHZ		500Hz max	100Hz	600Hz		
Field of View	30° Cone	point	point	2.3°	3°	Cone	
Voltage	5V	5V	5V	5V	10V	5V	5V
Weight		1.4g	22g	6g	8g		
Size	45*20*15mm	20.5*18*3mm	20*48*40mm			58*17.6*22.5	
Price	£4.00	£15.00	£118.18	£35.46	£132.00	£18.00	£7

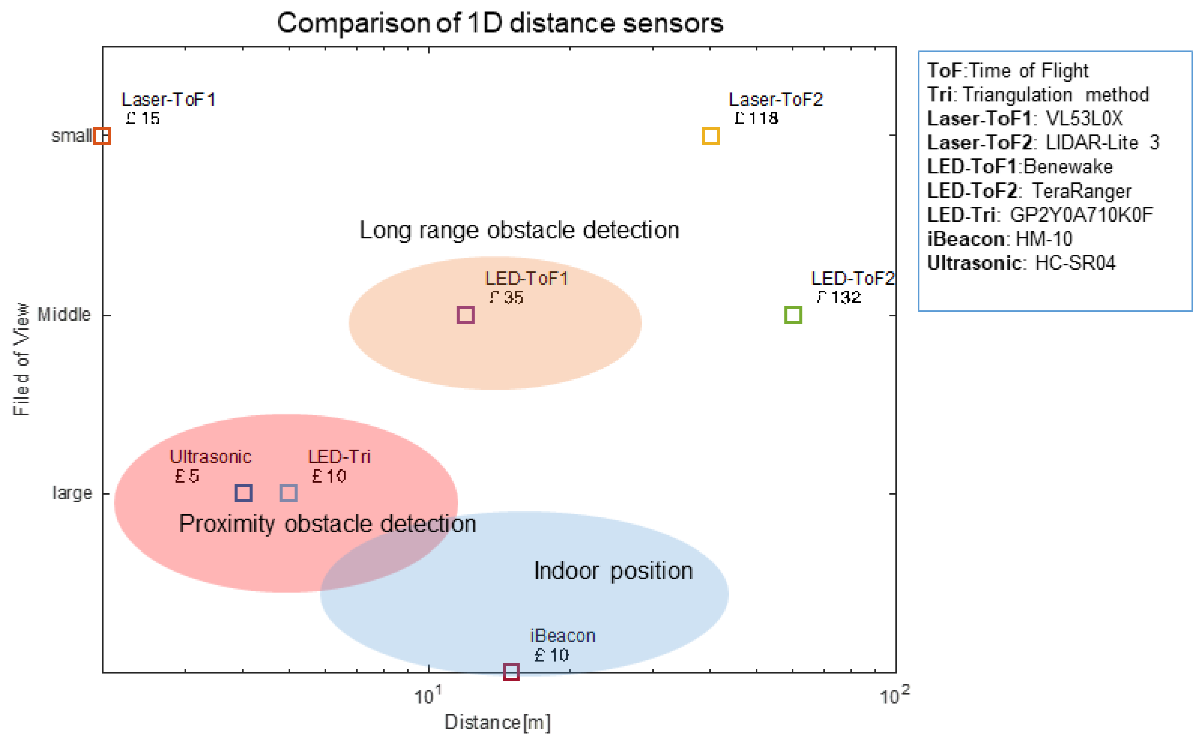


Figure 16: Comparison of 1D Distance Sensors

A2.2 2D Distance Sensors

2D distance sensors return information as a set of distances measured across a grid. They have the advantage that they cover an area rather than a single point, providing more useful information for obstacle detection, but are generally more expensive, larger and heavier than the 1D distance sensors reviewed above. A range of different 2D distance sensors are available.

LiDAR can be seen as a point distance sensor (laser rangefinder) with a mechanical rotation device, that extends the field of view to be a line or two dimensional image. LiDAR are popular in robotics and autonomous vehicles, but need to be mounted so that there are no obstructions in any direction, and can also be rather expensive and heavy, making them less suitable for wearable devices. Time of flight cameras use LEDs or laser light to illuminate the entire frame and the sensitive camera can record the time that the light arrives at each pixel of the frame individually. This generates a very accurate depth image from which a dense point cloud can be generated. These cameras can be made quite compact due to the need for only one lens and the technology being rather simple. However, these cameras can be susceptible to background light from external sources and low resolution.

Triangulation based laser scanners are commonly used for stationary scanning: two kinds of laser scanner are on the market, one uses a line laser to extend the point distance measurement into a line, while the other use a motor to rotate one triangulation based point distance sensor to seep an area.

Structured light cameras provide a 2D version of the triangulation approach, extracting depth information by calculating the disparity between an emitted light pattern and the received image from a camera lens. The light pattern, usually infrared, is projected as a 2D pattern over the entirety of the frame. The camera then captures the pattern from a different angle and calculates depth based on the deformities caused by 3D objects. This technology is cheap, but the sensors have limited range as the pattern can get lost within background light. The depth data is accurate within this range and most cameras, such as the Kinect V1 from Microsoft, also have an RGB camera to allow computer vision techniques such as face detection or motion capture to be applied.

Stereo cameras mimic stereo vision by using two identical cameras separated by a fixed distance. The depth information is calculated from variations of key points or features present in both images. This is a very computationally expensive process, but the data acquired is resilient to background light. They also have a much larger range than the other types of depth camera as they do not rely on projecting light of their own.

Generally, the accuracy of 2D depth sensors is: LiDAR > Time of Flight camera> Structured light camera. Longer measurement distances require stronger illumination power, and increases the sensor weight. The cost of sensor increases with the accuracy and longer measurement distance. LiDAR are widely used for many outdoor robots, but their high cost and complexity precludes their use in low-cost applications, while other low-cost depth sensing technologies are not suitable for outdoor use. Monocular and stereo cameras are not considered here due to a significant amount of computation. The RealSense R200 does the stereo registration on its own chip (active stereo), easing the computational load on the controller; but the RealSense R200 may fail to recognize low-texture objects (walls). The application of time of flight cameras are limited by their cost and the power consumption: laser scanners are more robust in detecting obstacles than both time of flight cameras and structured light cameras. Table 5 and Figure 17 on the following page provide a comparison of the different 2D sensors considered for the project.

Table 5: Properties of Candidate 2D distance sensors

	Kinect V2	CamBoard pico flexx	DepthEye OPT8320	OPT8241	Kinect V1	RealSense R200	ZED	RB-Lsl-07	RPLidar	Hokuyo URG	Velodyne VLP-16
Principle	ToF Camera	ToF Camera	ToF Camera	ToF Camera	Structured light	Structured light	Stereo camera	Line laser distance sensor	Line laser distance sensor +servo	Lidar 1 channels +servo	Lidar 16 channels
Range	0.5-4.5m	0.1-4m	0.2-2m	4m	0.8-3.5m	0.5-3.5m	0.5-15	0.1- 4m	0.15-12m	0.2-6m	100m
Accuracy								<3% of distance	0.5-1.0%	±3%	
Resolution	512X424	224X171	80X60	320X240	320X240	480X360	640X480				
Frame rate	30Hz	45Hz	1000Hz	60Hz	30Hz	30Hz	100Hz	10Hz	10Hz	10Hz	5-20Hz
Field of View	70.6X60	62X45	74.4X59.3	74.4X59.3	57.5X45		110 max	Line	360°	360°	360°
Voltage	12V(15W)	300mW	5V	15W	5V(2.25W)	1.7W	5V	5V	5V		9-18V8W
Weight	970g	8g	20g		160g	65g	159g	50g	190g	160g	830g
Dimensions	249X66X67 mm	62X66X29 mm		88X60X24.3 mm	180X35X25 mm	9.5X102X3.8 mm	175X30X33 mm				
Price	£100.00	£180.00	£180.00	£551.00	£100.00	£80	£364	£118.03	£90.00	£1,058	£7,000

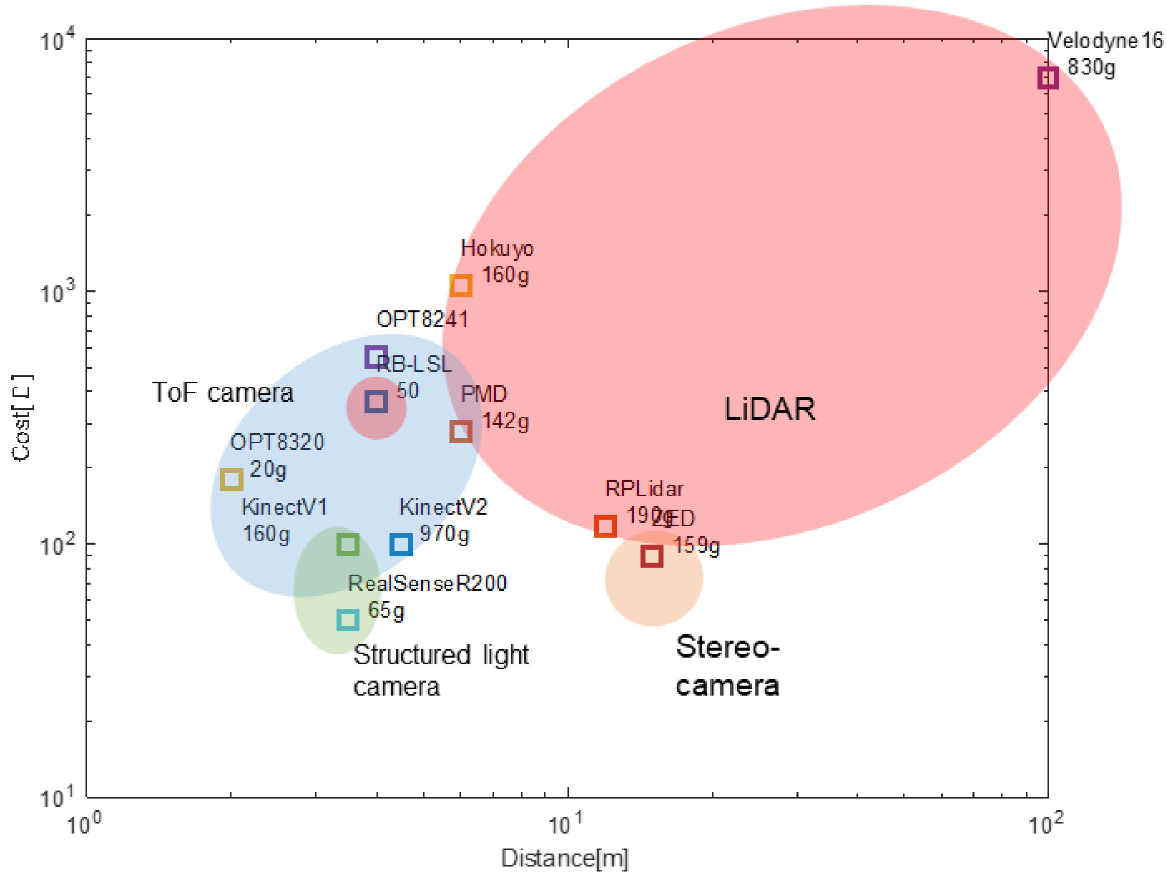


Figure 17: Comparison of 2D Distance sensors based on cost and range

A2.3 Evaluation of Distance Sensors

Each distance measurement sensor has its own set of pros and cons, and the "best" one to use will depend upon the situation. The best method maybe to decide which types of tasks users will need to perform, and to evaluate the relative importance of performance on each of sensors. For deafblindness navigation tasks, it requires the sensor to be low cost, lightweight, compact and wearable without fatigue. It has to work with limited resources of computation and memory in an embedded controller. Furthermore. It should be robust and provide fast response to a dynamic environment, and be adaptable to different lighting conditions.

In reviewing potential sensors for inclusion in the Sensor System, we considered eight criteria: weight, cost, range, resolution, field of view, number of dimensions (1D or 2D), accuracy, and light resistance. Figure 18 provides a visual summary of how we rated each class of sensors against these criteria.

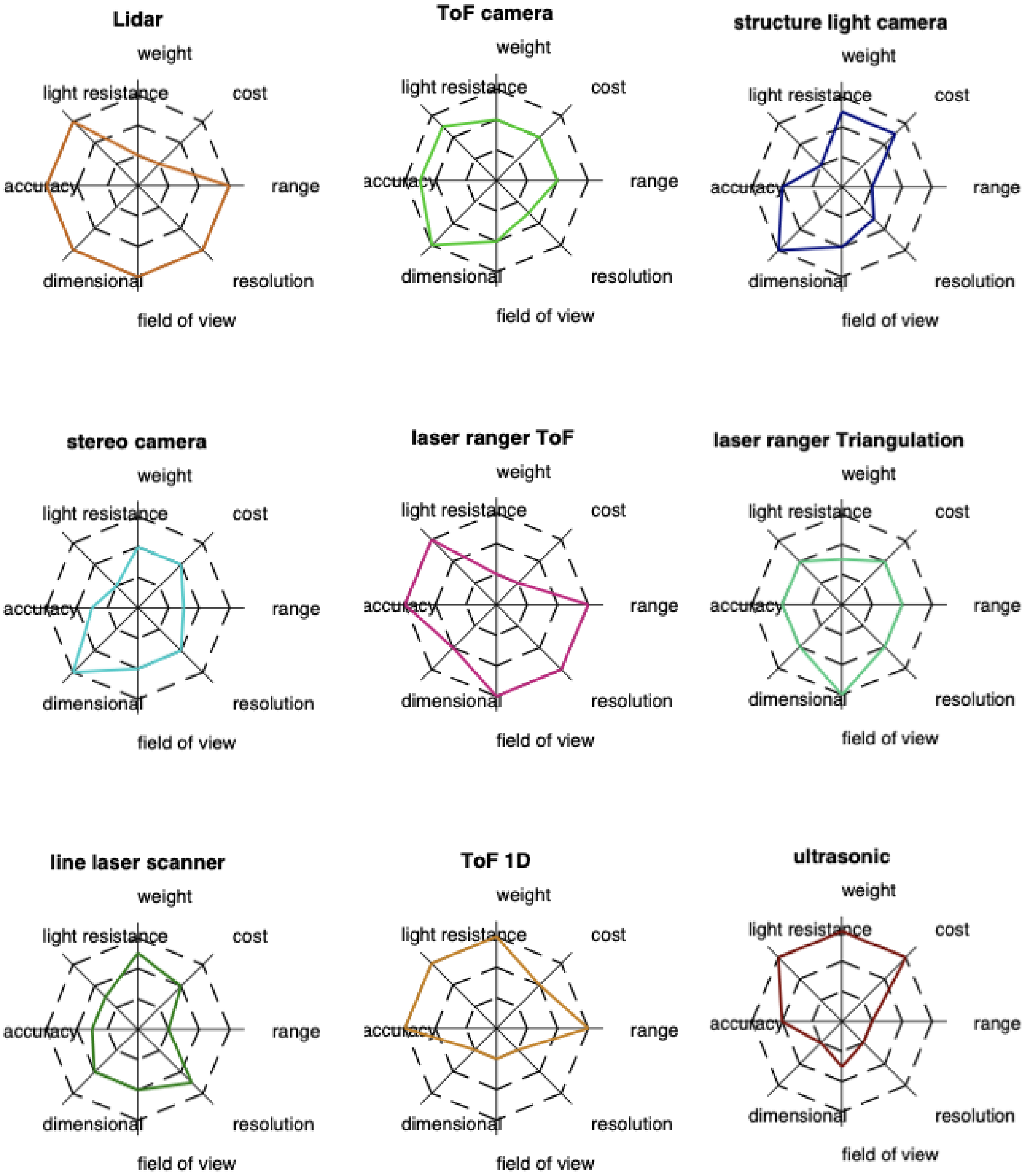


Figure 18: Qualitative comparison of different sensor types based on evaluation criteria: entries nearer the edge of the plot indicate better performance

The Intel RealSense R200 provides an acceptably low-cost depth camera that could be used at a medium range (2-3m) with acceptable processing power and as an RGB-D camera it provides the means for capturing data for visual analysis in Task 4.2. At longer ranges, sensors tended to be either extremely expensive and power intensive, or one-dimensional, measuring a single point. No one-dimensional sensor is able to efficiently map the space on front of the user, since it either has diminishing resolution with distance (such as an ultrasonic distance sensor), making it difficult to locate precisely where an obstacle is in relation to the cone that is covered, or a very narrow field of view, making it difficult to assess the space efficiently without using multiple sensors, or requiring the user to turn to sweep the sensor across the area in front of them. Ultimately, no single sensor meets all the requirements set out for it, and it is therefore recommended that a combination of sensors be used: the RealSense R200 providing a structured light scanner that can provide 2D depth data in the area 2m-4m in front of the user; with ultrasonic sensors providing a low-resolution addition that is robust to ambient lighting conditions. Given the relatively narrow field of view of the RealSense and ultrasonic distance sensors, the potential for developing a laser line scanner that could be integrated into the system will also be explored, to offer a wider field of view and high resolution. The intended performance of this combination of sensors and how they are intended to offset each other's weaknesses is shown in Figure 19.

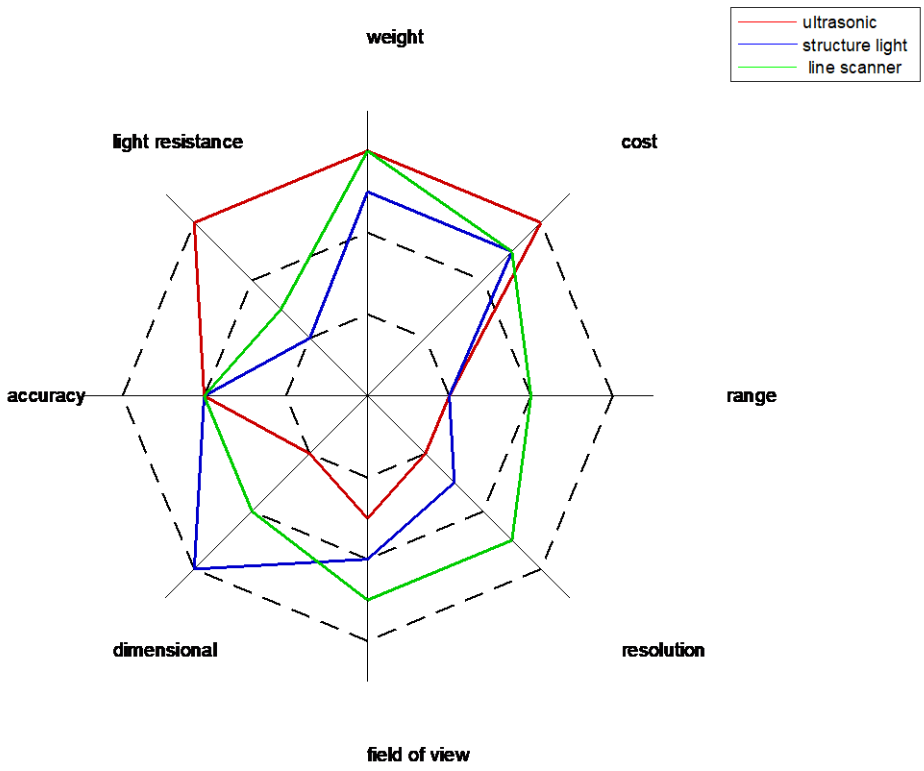


Figure 19: Intended Performance of selected sensors against performance criteria.

Appendix 3: Development of a Planar Laser Scanner

The review of distance sensors presented in Appendix 2 illustrated the challenges of identifying suitable sensors for use in a wearable system such as the HIPI, with challenges related to a limited field of view and limited resolution if cost and weight are to be kept. An array of multiple 1D sensors provides one solution to widening the field of view, but this inevitably increases costs and makes for more bulky products. Line laser scanners are a promising technique to achieve a wide field of view with a high resolution at a relatively low cost and energy consumption. This approach utilizes a line laser instead of a single point laser so that it does not need any rotational part. A common USB camera can then be used as a receiver to calculate the distance based on the triangulation method, as illustrated in Figure 20.

Figure 20: Prototype line laser scanner.

A key benefit of developing a bespoke laser scanner is that its elements can be integrated into the fabric of the HIPI, and matters such as measurement range, resolution, accuracy and field of view can be varied to meet the needs of different individuals by adjusting the design, making it more adaptable to our needs than the fixed laser scanners currently available. To facilitate this customization, design software was developed in order to how design parameters affected performance, such that different variations can be rapidly produced using off-the-shelf components and 3D printed parts. This is important in enabling both experimentation and iteration of the HIPI, as well as in providing personalisation, such that the precise location and focus of the scanner can be adjusted to the needs of the individual.

There are three distinguishing characteristics of our design from prior work on low-cost laser distance sensors such as the Revo LDS (Konolige et al, 2008) or the Smartphone LIDAR (Gao and Peh, 2016) or commercial laser scanners:

(1) a detailed 3d laser scanner model has been developed instead of the 2d model used in the previous studies;

(2) a compact design for personal wearable navigation, that can easily be integrated with other RGB-D sensors in a small space;

(3) the ability to combine with other sensors (ultrasonic distance sensor and IMU) to provide safety control of the laser.

A3.1 Three dimensional triangulation measurement model

A triangulation-based laser scanner consists of a laser illuminator module and a camera detector separated by a baseline distance. As illustrated in Figure 21, a thin laser plane is projected to the object point, and the camera captures the laser illuminated object. Given the known location of the laser and properties of the camera, the object points in 3D space can be estimated by computing the intersection of the camera ray and the laser plane from the image pixels captured by the camera.

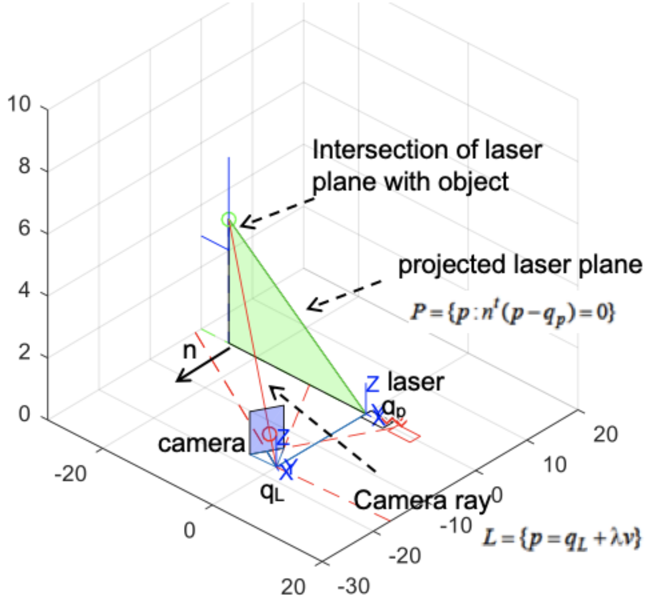


Figure 21: Triangulation by line-plane intersection

The Open Computer Vision library[5] was used to extract the laser line from the images taken by the camera and thereby return the pixels of interest. Converting the pixels recorded in the camera's 2d image to 3D world coordinates requires knowledge of the camera's intrinsic and extrinsic parameters. The intrinsic parameters are characteristics of the camera sensor (pixel width and height, pixel co-ordinates of camera center) which are functions of the chosen camera, and the extrinsic parameters describe the camera's position and orientation, which are functions of how it is mounted in the wider design. The outlined under Lanman and Taubin (2009) were then used to convert from the raw image to a 3D point cloud.

A3.2 Design Parameters

In this section, we discuss the main design parameters which affect the extrinsic properties in the triangulation process. The laser scanner should be wearable and measure a wide region of area in front of user for navigation. We model the laser scanner as shown in Figure 22 in two dimensions and set the origin of the world coordinates in the center of the laser beam output. The main design values include:

α : the rotation angle between the laser and the y axis around the laser point p_l;

[5] http://opencv.org

β : the rotation angle between the camera and the y axis around the camera's focal length position p_f;

d: the distance between the laser and the camera.

In our design, both camera and laser angles and the length of the baseline can be adjusted: this is different to the approaches taken by Konolige et al (2008) and Gao and Peh (2016) where the camera is fixed to be perpendicular to the baseline. In our design, the camera and laser are oriented towards the floor rather than horizontally, so that they can capture low lying obstacles and to reduce the risk of direct exposure to the eyes of other people. If the camera is set perpendicular to the baseline, then the baseline itself would need to be at angle to the user, thereby sticking out from the user's chest as illustrated in Figure 22, in a way that is not desirable in a wearable device.

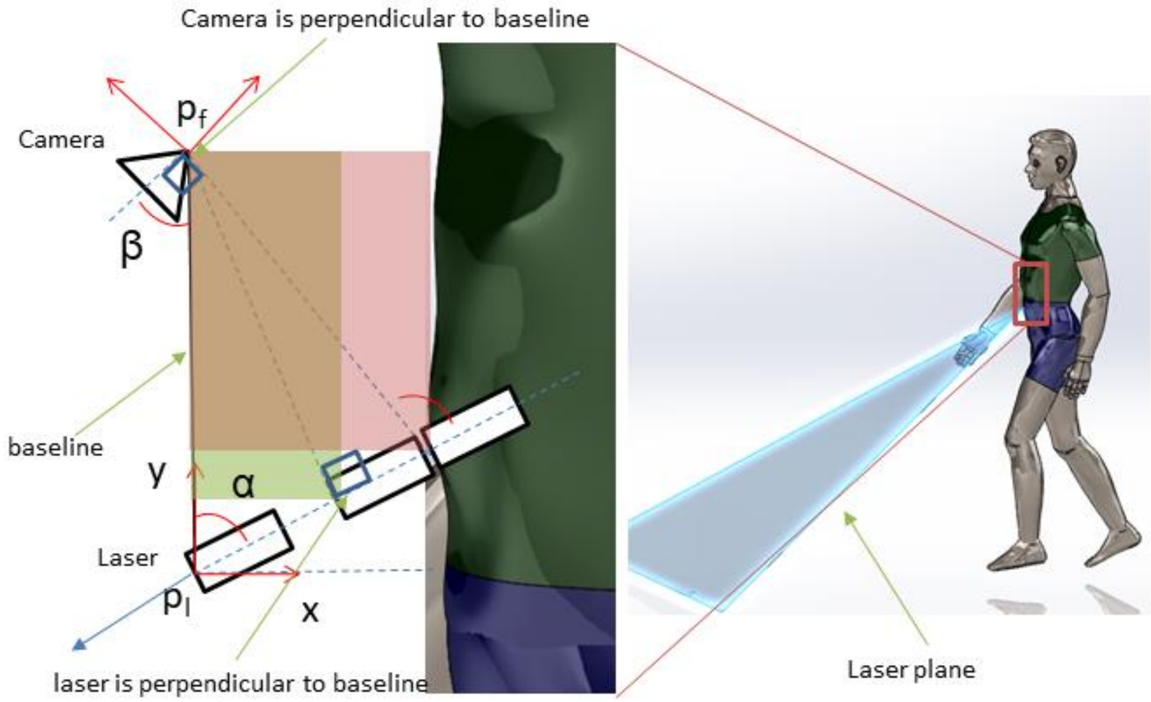


Figure 22: Main design parameters and laser scanner mount place

The design parameters that can be controlled for this system are camera focal length, baseline, camera angle and laser angle. These can be adjusted to influence measurement distance, resolution (defined as $\Delta d/\Delta pixels$) and the overall size of the system.

To assist in selecting appropriate design parameters, a MATLAB program was written that will estimate the resolution at short distance, resolution at long distance, minimum measurement distance and maximum measurement distance using numerical methods based on a set of design parameters provided by the user (intrinsic camera properties, baseline length, camera angle, and laser angle). These values assist designer in choosing values to meet design targets, as shown in Figure 23, enabling alternative designs to be considered if the design needs to be adjusted to different needs. The mounts for both the camera and laser are 3D-printed, so that they can easily be adapted to different angles based on these calculations.

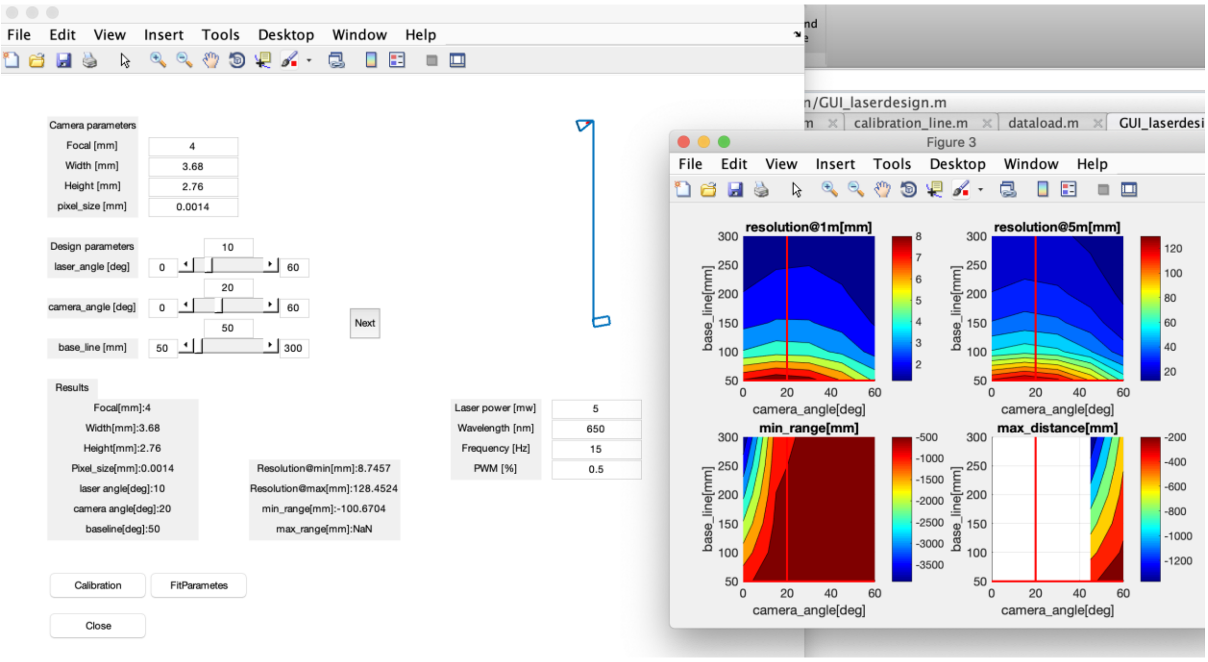


Figure 23: Line laser design software interface

Once the scanner has been constructed, it can be calibrated by collecting a set of calibration images at known distances and using a non-linear least squares method starting from the design parameters to find a set of calibrated values that best describe the behavior of the scanner and which can be used for the practical calculation of distance.

A3.3 System integration

The system hardware has a micro-controller to trigger the laser emitter by using a laser driver. The microcontroller also reads data from the ultrasonic distance sensor, and Inertial Measurement Unit as part of the wider sensor system, and these can be used to provide interlock safety functions in real time as described below in Section A3.4. The camera detects the illumination line generated by the laser and passes images to the software modules for processing continuously.

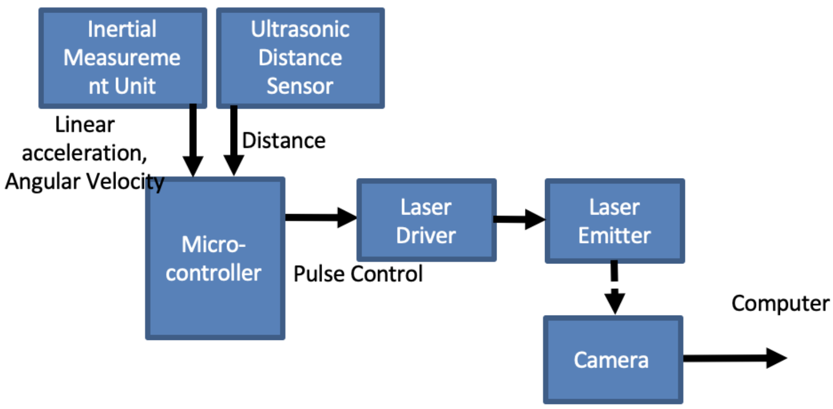


Figure 24: Block diagram of hardware components.

A3.4 Laser eye-safety Considerations

The maximum range of any laser scanner relies on the illumination output power of the laser which is limited by eye safety considerations, as lasers are a coherent light that can cause permanent harm to the eye if shone directly into them for a length of time. There is a tradeoff between laser power and eye safety, however, well-designed controls and laser interlocks to reduce the risk of exposure can be included to reduce the risk of injury by ensuring that no one the laser is not used when someone is within the Nominal Ocular Hazard Zone (NOHZ - the distance in which the radiance can cause damage to the eye), as illustrated in Figure 25.

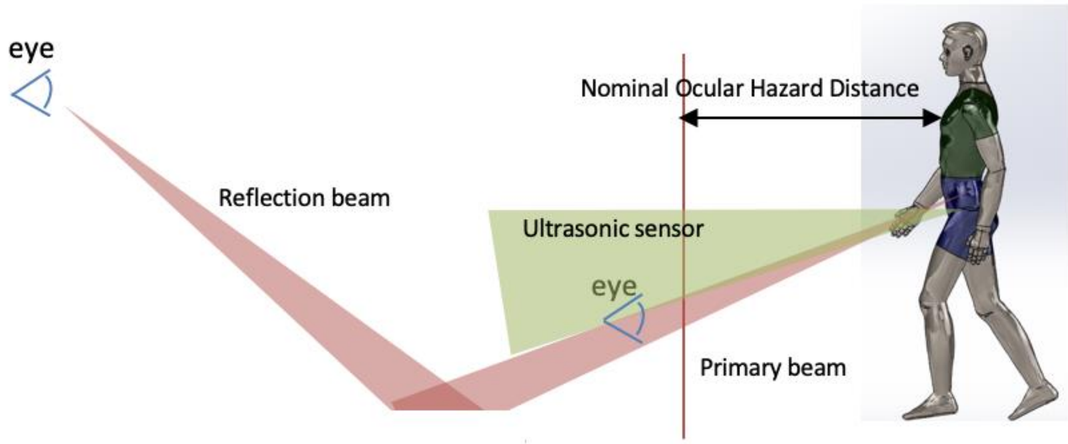


Figure 25: laser safety and inter lock illustration

To estimate the Nominal Ocular Hazard Zone (NOHZ) we used the method presented in Thomas et al (2001), which calculates the size of the NOHZ as:

$$r_{NOHZ} = \frac{P * t * w}{A * MPE * \phi}$$

Where MPE – the maximum permissible exposure limit – is calculated from ANSI Z136.1-2000 and Z136.6-2000 as:

$$MPE = 1.8C_a t^{0.75} \times 10^{-3} \times n^{-0.25}$$

Where C_a is aa correction factor taken from ANSI Z136.1-2000 based on wavelength of the laser; t is exposure duration: for a pulsed laser, t= 1/(f*duty cycle), for a continuous laser, t=0.25s (the time required for an aversion response to protect the eye); and *n* is the number of pulses in 10s; ϕ is the divergence of the primary beam; A=0.385cm^2 (the area of the pupil); P is the pulse power; and w=0.7cm (the pupil width).

Orienting the laser towards the ground does reduce the risk of it striking an eye, but this is not sufficient, as there would still be risks to children, animals, or someone bending or lying down, for example, as well as risks of reflected beams. Given the capabilities of the system described under A3.3, three methods are available that can be used to minimize hazards:

(1) Using a microcontroller to pulsed the laser and reduce the lowest Maximum Permissible Exposure and therefore the Nominal Ocular Hazard Zone;

(2) Using an ultrasonic sensor to shut down the laser if there is any object in the Nominal Ocular Hazard Distance (NOHD) in the front of the laser scanner as illustrated in Figure 25; in which case the system will have to depend on Ultrasonic sensors or the Intel RealSense at close ranges.

(3) Using the Inertial measurement unit to estimate when the use is moving and shutting down the laser when the user stops moving (to avoid continuous focus on any object).

A3.5 Case Study

Camera selection: The camera ELP- USB130W01MT-B/W has a focal length of 3.04 mm (larger focal lengths demand longer lenses, a greater Focal Length leads to a smaller Field of View as the angle becomes smaller) and physical sensor dimensions of 3.63mm by 2.72mm.

Table 6: Specifications of ELP- USB130W01MT-B/W camera

Specifications	Values
Sensor resolution	2592X1944 pixels
Sensor image area	3629X2722µm
Pixel size	1.4umX1.4µm
Horizontal field of view	100 degrees
Shutter	Rolling
Module size	38X38 mm

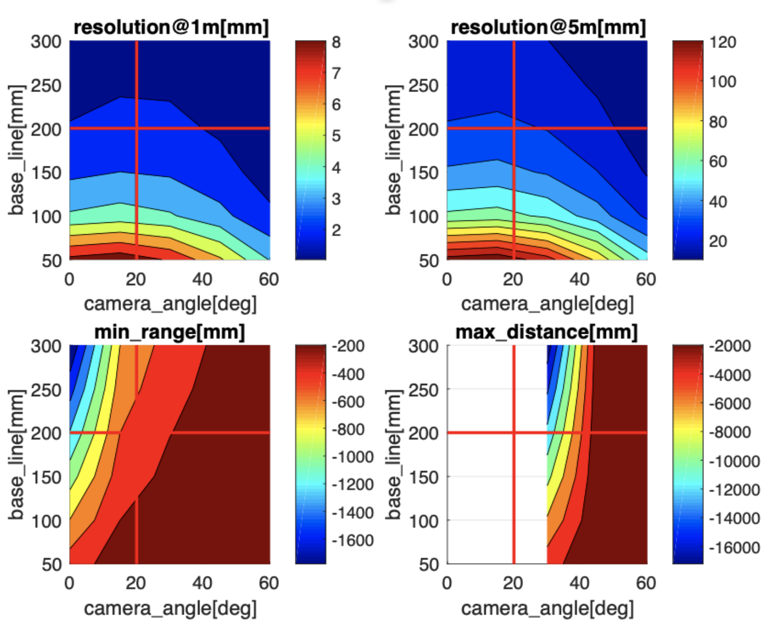


Figure 26: Calculation results: resolution at short distance, resolution at long distance, minimum and maximum measurement ranges

Laser selection: we selected an off-the-shelf visible wavelength 5mW Class 3R line laser as illuminator and added an optical bandpass filter to reduce the ambient light. According to ANSI Z136.1-2000 standard for eye-safe lasers, the lowest Maximum Permissible Exposure (MPE). The 5mW line laser is effectively pulsed at 15Hz with a 50% duty cycle, with the specifications given in Table 7.

Table 7: Specifications of laser line emitter

Specifications	Values
Peak Power	5mW
PWM frequency	15Hz
PWM Duty	50%
Wave length λ	650nm
NOHZ	0.13m
ϕ	π/3 radians

As the laser is pulsed at 15Hz, with a duty cycle of 50%, each pulse lasts t = 1/30th of a second, and there are n = 150 pulses in 10s. Following Thomas et al's (2001) method, a nominal ocular hazard zone of 0.1m is calculated as follows:

$$MPE = 1.8C_a t^{0.75} \times 10^{-3} \times n^{-0.25} = 4.0124 \times 10^{-5}\, J/cm^2$$

$$r_{NOHZ} = \frac{P * t * w}{A * MPE * \phi} = 0.1m$$

System integration: A Pmod Hb3 H-bridge is used as the PWM driver interface between the controller and the laser source, with a microcontroller was used to control the pulse (an Adafruit Feather). An Ultrasonic distance sensor HCR and Inertial measurement unit (IMU) MPU9250 are used to provide the interlock features. A challenge is synchronizing USB cameras. Since there is no way of doing this via hardware, synchronization would not be used. We used ROS to implement the algorithms on both a Raspberry Pi 3B+ and AAEON Up board.

Calibration: The maximum calibration error is 130mm at 2meter. The error comes from physical model (sensor pixel size), estimation of laser line position in the image, the calibration process and mechanical mounting. The error could be reduced by careful adjustment of these values. Figure 27 provides an illustration of the point cloud returned by the laser scanner.

Figure 27: Example of point cloud returned by planar laser scanner.

A3.6 Discussion

The potential for designing a bespoke laser line scanner that can be adjusted to the particular needs of the project has been demonstrated, and the components for this system have the potential to be readily integrated into the rest of the sensors system and the wider HIPI. However, the precise power of laser will depend upon the range required for distance measurement, and likewise the precise field of view (whether two scanners should be included, or using a wide angle camera and laser line projector) will need to be determined, and these depend upon user testing as the project develops.

Appendix 4: Calculation of Safe Ellipse

This appendix presents the process for calculating an ellipse representing the safe range for the user, which can be used as a way of interpreting complex distance 2D distance sensor information into a form that is easier to convey in a haptic form. The ellipse represents a safe region for the user which is free from obstacles, so that the user can be alerted if they are outside this region, and directed back towards the centre of this region. This allows the system to identify a bundle of safe routes for the user to make decisions about moving, rather than trying to notify the user of every obstacle or planning a path to follow. If the user is out of the safe boundary, then they will receive a warning that an obstacle is close to them and also will obtain a direction that allows user to move back the safe region. We define the safe region using a semi-ellipse (we will use the term “safe ellipse” in the following sections), which can map a large area of obstacles free region with less variables, actually it also could be modelled using other shapes such as a circle.

A4.1 Safe ellipse calculation

The first step in generating the safe ellipse is to calculate the **safe ellipse boundary** which is represented by $\varepsilon(C_b, \mathrm{d}) = \{\mathrm{x} = C_d\mathrm{x} + \mathrm{d}\ |||\mathrm{x}|| \leq 1\}$, $\mathrm{v_k}$ are detected **obstacle points** from sensors. Due to the limitation of the field of view of the sensor system it cannot cover 360 degrees around the user, we also add a sensor **measurement limit** which is a rectangle:

$$\mathrm{P} = \{x|A_b x = b_b \quad A_b = [0,1; 1,0; -1,0; 0,-1], b_b = [l_b, l_u]\}$$

Where: $l_b = [back, left\ side]$, $l_u = [front, right\ side]$. The algorithm is to search for a largest area ellipse which has all **obstacle points** outside it and locates in the **measurement limit** rectangle, which is formulated as follows:

$$\max_{A,b,C,d} \operatorname{logdet} C_b$$

$$\text{subject to } a_j^{\mathrm{T}} v_k = b_j \ j = 1, \dots, N$$

$$\sup_{\|x\| \leq 1} a_i^{\mathrm{T}}(Cx + d) \leq b_i \ i = 1, \dots, N$$

$$A_b x = b_b, \quad A_b = [0,1; 1,0; -1,0; 0,-1], b_b = [l_b, l_u]$$

a_j are the rows of A , b_j are the elements of b.

This is illustrated in Figure 28.

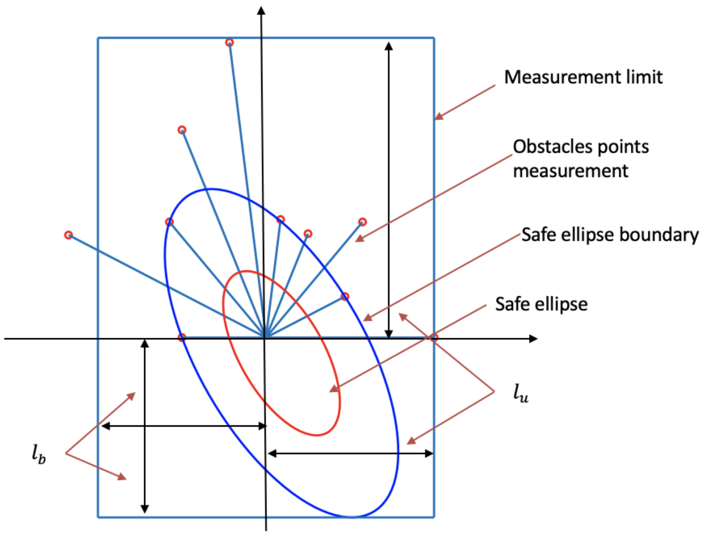


Figure 28: Illustration of the safe ellipse calculation.

We adopted Deits and Tedrake's (2015) method to solve this convex optimization problem, which computes the largest ellipse area by using the iris (Iterative Regional Inflation by Semi-definite programming) approach. This algorithm was originally developed for the problem of planning footsteps for a bipedal robot on rough terrain.

This provides the safe ellipse boundary – a measure of the amount of available space. To determine whether the user has sufficient space or is too close to the safe ellipse boundary, a **safe ellipse region** is further defined using a specified safety margin. Here, we define this as half semi-axis of the safe ellipse boundary $f = 0.5$. This needs to be refined during experimentation We will add velocity factor V in the future experiments using feedback information of Inertial measurement unit. Another factor is the uncertainty of sensor measurement, which could be represented as a covariance ellipse matrix.

Ideally, the sensor should measure a wide Field of View (FoV) of about 180 degrees, so that the front and side measurement limits can be set as the maximum range of sensor, and a large reliable safe region can be estimated. With a small FoV sensor, we are more heavily dependent upon the side and back measurement limits. Appropriate values for the measurement limit must be determined during experimentation: currently a short distance value of 2m to each side and behind are used to make the safe region reliable but the size of ellipse reduced.

A4.2 Safe ellipse implementation

We have implemented the safe ellipse method both in MATLAB simulation and on the AAEON UP board controller using IRIS[6] and the optimization solver Mosek[7]. The simulation allows user to control the movement through a simulated 2D environment and demonstrated ellipse calculated in each case, to validate the algorithm.

[6] https://github.com/rdeits/iris-distro
[7] https://www.mosek.com/

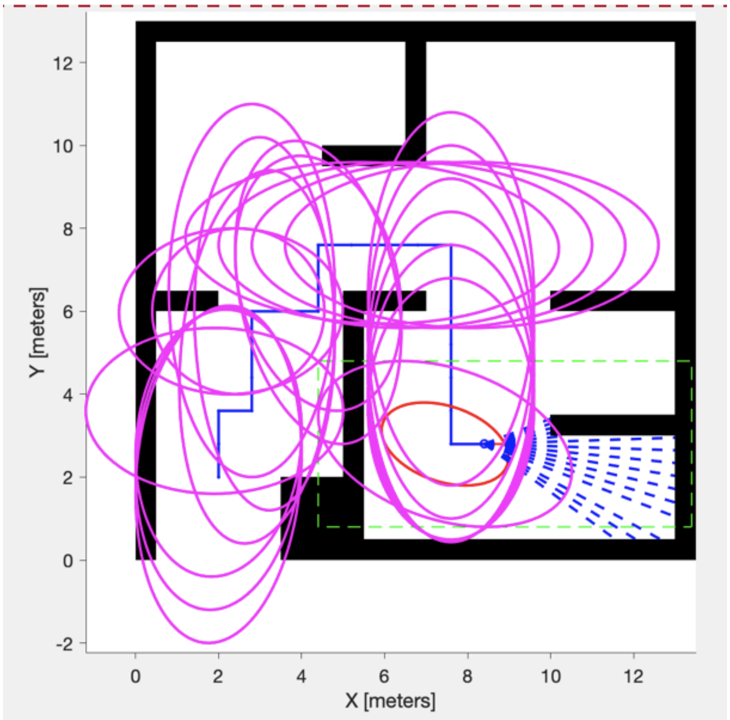


Figure 29: Boundary Ellipses generated in the MATLAB simulation over the course of moving through an environment.

In the controller, obstacles are detected using the distance sensor (depth camera or laser scanner). The 2D point cloud is processed and sampled, these data from several scan frames can be registered by using the inertial measurement unit, then optimized (using IRIS, and Mosek installed on the AAEON UP board) to estimate a safe boundary and safe region.

Appendix 5: Components of the Sensor System

Module		**Type**	**Size**	**Weight**	**Output**	**Data interface**	**Supply Voltage**	**Current**	**Max.power cons**	**Cost (EURO)**
RGBD-sensor		Real sense R200	20 x 130 x 7 mm	65 g	RGB image Depth image (0.4-2.8m) PointCloud data	USB 3.0	5V	0.32A	1.6 w	90
Line laser scanner	camera	ELP-USBFHD03AF-A100	40*40mm	~30 g	PointCloud data FoV:62º (1-5m)	USB2.0	5V	0.22A 0.01A	1.1w 0.005w	56 23
	laser		Phi20*30mm	~20 g						
Ultrasonic sensor		HC-SR04	45X20X15mm	9g	Distance (2cm-4m)	I/O	3.3V	0.015A	0.075w	11
Inertial Measurement Unit		MPU9250	25.5mm x 15.4mm	9g	Angle velocity, Acceleration Magnetic field	I^2C	3.3V			6
Bluetooth		nRF52 Bluefruit LE	51x 23 x 8mm	6g	ID, received signal strength index	I^2C	5V	0.33A	1.65w	28
Microcontroller		Adafruit Feather				USB2.0				
HIPI Processing Unit		Up board	85.60 x 56 x 21mm	49g		USB3.0X1 USB2.0X4	5V	3A	Max=15W	90
WiFi Module				Negligible						7
Battery				350g			21000mAh	~7h		45
			Total	538g						356

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