GUIDO: Guiding User-friendly Independent Driving Object, a robot for visually impaired patients in Japan

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CONTENTS

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***Abstract*—Due to the growth in overall and increasingly aging population in Japan, the number of blind people is expected to increase in the next years. Promising new innovations from assistive technologies can help Japanese patients with visual impairment to (re)gain their independence. With this study we ought to contribute to future field of haptic guidance, and answer the question: how can the remaining exterior receptive senses of the blind individual be used to design a guide dog robot to guide the user. This paper describes 3 different designs to guide a blind person using either a dog or cane model with haptic feedback, sensor data and path planning algorithms to walk independently. Using the cost analysis and a risk analysis, the paper concludes that, the robotic guidance dog with connected haptic handle, is the best solution for blind and visually impaired people to design a guide dog robot to help the user gain independence.**

I. Introduction

A. The global picture

Visual impairment and blindness is a common pathology. Over 284 billion people suffer from visual impairment and 39 million across the globe are blind. In the future, the WHO expects this number to rise due to the aging population and because the global population is still growing [24]. Countries as Japan also have an increasingly aging population [8]. Since there are a lot of people who need assistance with this pathology, technological innovations are needed to help with their mobility in Japan.

B. Robotic development assisting blind patients

Recent years has shown promising innovative developments in the field of assistive technologies for the visually impaired and blind people [5]. Vision is an important and vital sensory modality in the functioning of daily live. Therefore the loss of vision has impact on multiple aspects that can be implemented in everyday life. These aspects entail for example technologies, services, equipment, processes, and environmental modifications [12]. Several causes of blindness can be: blindness by birth or diseases such as cataract, glaucoma, trachoma, vitamin A deficiency, refractive errors, old age and onchocerciasis [10]. In order to address these aspects, a range of assistive technologies have been produced ranging from optical devices such as smart glasses and AI lenses [13] to mobility-related devices such as canes and the BrainPort V100 that aids visually impaired and blind patients in seeing with their tongues [23].

Other treatment methods of (partial) blindness are more invasive such as cataract surgery. These methods are more focused on the restoring of sight and are proven to be cost effective in developing countries and higher developing countries. However, this cost-effectiveness is mostly only available for patients close to urban areas. In higher developed countries such as Japan cataract surgery may not be as available in the rural areas and the extra costs next to direct costs of the surgery add up to a higher cost index [1]. Moreover, cataract surgery is an invasive treatment option which recurrently leaves patient partially blind, worsens the complications or make patients irreversibly blind [6]. Especially in a country such as Japan with a rapidly growing aging population, cataract-induced visual dysfunction and blindness is increasingly common, due to the fact that blindness and cataract prevalence increases with age [6]. Furthermore, other conventional technologies have been proven to work efficiently and accordingly, however they are known to be quite high-end and frequently focused on one dimension of the pathology's effects (for example: accessibility, improved quality of life an safety). Popular traditional solutions are the guidance dog that are only accessible for blind or visually impaired patients in the possession of certain wealth, and they don't really work for unfamiliar environments because the dog needs excessive training to learn the environment before it can serve as a guide. The user needs assistance from a sighted person to overcome this limitation which may not always be available [14], especially with the growing elderly population in Japan. Another solutions could be the use of a cane however that does not provide the necessary safety to the user as the guidance dog. [21]. In order to solve these problems and limitations, a robot guidance dog may present a good solution[15], as they can work in unfamiliar environments. With today's path planning algorithms and due to the decreasing costs of hardware, the prices of these robots are expected to drop so that the product can also be used in developing countries.

C. Country of choice

For implementing a robotic solution to the said problem, Japan would be a fitting country as they are familiar with many robotic devices. Even though Japan is known to be a highly developed country, Japan has a higher cost index for these cataract surgeries. Japan has also an increasing aging population which indicates they have an increase of age related blindness diseases. The reason to choose this country to introduce such a robotic technology is because it is one of the most robotic dense countries in the world. This signifies that its elderly population is familiar with robotics in their daily lives. Therefore this country would give the best result in integrating a robotic guidance dog in its medical treatment options [19].

D. Identification of the Gap

The problem currently in Japan is that the increasingly aging population may induce cataract visual dysfunction and may results in an increasing blind population. Current technologies available do not focus on the pathology's multiple effects and do not focus on gaining independence in unfamiliar environments. Also, there is a need for more guide dogs that need little training, because training dogs is time consuming and expensive. This paper proposes to find a solution so that bind people in Japan can walk in unknown environments without the help of a guide. By looking at earlier inventions, there is a gap in the current state of the art guide robots for blind individuals. See also the related work in chapter 2. It was found that the implementation of haptic feedback and vibrotactile feedback into the design of a guide robot to let blind people walk around independently was not yet designed. This has let to the following research question:

"How can the remaining exterior receptive senses of the blind individual be used to design a guide dog robot to guide the user in an unknown environment in Japan?"

II. Definitions

Before we delve into design and experiments, the report needs to focus on certain aspects of robotics. We fixed some of the constraints of the robots in this chapter for later designs, this made sure that the project is feasible in the set time. Research has been done to find related work, and to see the current state of the art technologies for current robots. With that knowledge in mind, new solutions for blind and visually impaired can be designed. In this section, the terms used for the robotic designs are also further explained. First, the current robotic applications for blind and visually impaired are researched. Thereafter, three main subjects of robotics are briefly discussed: haptic feedback, path planning and robot dynamics and control.

A. Related work

A research group have made a substitution of a robot guidance dog which can enhance mobility, aid for the blind by providing patients with the functions of guidance dogs without the excessive training that is needed for real guide dogs. The robot, called Meldog, still had a remaining problem: the choice of sensory display of the navigation information acquired by the robot was not appropriate for presentation to the remaining exterior receptive senses of the blind individual [29]. There are research papers that try to find solutions for this with the use of for example haptic feedback [33] or ultrasonic and infrared sensors [21] [28]. Yet so far no research team have made the effort towards implementation of successfully automating guidance devices for the blind. This means that there is still a gap between the available technology and the correct implementation for the focus group of blind and visually impaired patients.

B. Haptic feedback

Robots can assist humans through physical human-robot interaction, to solve complex tasks together. When a human interacts with machines, it is called haptics. This technology can ensure that robots can now guide users from a start towards the goal position with the help of the sense of touch [31]. This is why haptic feedback could be helpful for the patients suffering from blindness, especially because blind people are able to detect tactile information even better than sighted people [4]. A type of feedback for the patient from a robot guidance dog can be auditory, however this can cause a bigger error signal due to overlapping auditory signals in the environment. These overlapping signals can result in a higher cognitive load for the user [18]. This is why, after looking at related work, the decision has been made to work with haptic feedback as a tool to guide users to their destination. Force feedback is a type of haptic feedback where a force from a handheld device is used to communicate from the robot to the user. For this, impedance control is the best way to communicate forces, as impedance control describes the relationship between force and motion [26]. A handle with vibrotactile feedback can mimic the robots movement, which is the way to the optimal path from start to goal, by producing force pulses that are translated to skin displacement at the patient's fingertips. These pulses are generated with voicecoils actuators in the handle to create accelerations. The skin displacement is in turn perceived as a directional pulling force. Desired actuator control can be produced by finding the optimal frequency and pulse width of the actuator inputs. The handle can transmit the optimal path by maximizing the speed and amplitude of these signals in the desired direction per timestep and minimizing them in the opposite direction [17].

C. Path Planning

Path planning is the theory behind converting high level specifications of tasks from humans into low-level descriptions of how to move for a robot [16]. This is done by specific path planning algorithms that calculate the optimal path for a robot with certain inputs. Motion planning algorithms are dealing with problems in an *implicit* representation of the *state space*: a list of all possible situations that could arise. For a robot guidance dog, the state space must at least hold the position and orientation of the robot, but this list could be expanded in later designs. The larger the state space, the more time it could cost to come up with an optimal solution. Roboticists can choose to make implicit representations of the state space, so that the algorithm can solve for the infinite possible ways to move. After defining the state space and geometric representations of the world the robot is working in (for example 2D and 3D), a path planning algorithm must be selected. In this project the path planning algorithm that is most suitable to use in the experiments and tests are the *incremental sampling, single-query models.* The reason behind choosing this model is because it can overcome getting trapped in a local minimum which than can lead to a robot getting stuck just before the goal, while choosing for a weaker notion of completeness called *probabilistically completeness*. This indicates that with enough points, the probability that the algorithm finds a solution converges to one. In this case the robot will work with a model called *Rapidly exploring Random Tree (RRT)*.For this specific application RRT* is chosen since it can perform in complex higher dimensional environments to safely guide the blind patient. Moreover, this algorithm can be extended to versions that can perform in dynamic environments for real-time path-planning, reduce energy costs and reduce computing time [20] [22] Which is then altered to be *Optimal*. This implies that the path found by RRT* is the shortest possible path towards the goal.

D. Robot dynamics

In this section, the focus is lied on the dynamics of the vehicle that is driving next to the patient. To constrain ourselves towards an optimal solution for blind people, it was decided to look for a car model before designing the concepts. The model we choose can be described through inverse kinematics of a 6 wheeled robot, designed to move around in uneven terrain. These kinematics are robust to obstacles that the car might encounter on the streets. The model consists of 4 steerable wheels and 2 unsteerable wheels between them. By adjusting the joints between the set of wheels, the rover becomes capable of steering over rough terrains [7].

E. General specifications and report structure

Generally the design of the robot guide dog needs to be able to walk over small obstacles such as steps and sidewalks, therefore the chosen design is based on the following robot: Figure 1 shows how this robot is able to climb over small obstacles with the help of the 6 wheels. For the conceptual designs, this model is used for the simulation environment to show the working principle. The general specifications that the robot guidance designs should meet are based on

Figure 1: The design aspects and specifications for a climbing robot

a visually impaired elderly subject group in Japan. Here it is focused on guidance instead of prevention since in this subject pool guidance and mitigation in the pathology is more important and efficient [9]. The following specifications should be met in the designs:

1. The design should be easy to use, maneuver and serve as mainly a guidance to a visually impaired user.
2. The user should receive directional haptic feedback from the design in order to correctly follow a desired path.
3. The design has to be able to correctly avoid obstacles.

Therefore this paper provides an extended conceptual design review of an assistant guidance robot which is aimed on mainly elderly visually impaired or blind patients in Japan. For the designs we strive for high quality and low cost with all the necessary information to provide the patient. This information includes: object recognition, mobility and navigation but also accessibility, independence, participation and inclusion into society by creating a guidance dog and/or cane design with haptic feedback. The following proposed designs focus on further enhancing this transmitted information for the patient. The designs and their specifications are displayed in the following structure: (1) design concept and specification, (2) hardware and software design, (3) experimental setup. After each design is described they are discussed in the analysis and evaluation which consists of a cost analysis, risk analysis and a house of quality. At last the conclusion discusses the optimal chosen design.

III. Designs and Experimentation

A. ***Design 1: Robotic guidance dog with connected haptic handle***

1) design concept and specifications: The initial design is a guidance robot with an attached handle for visually

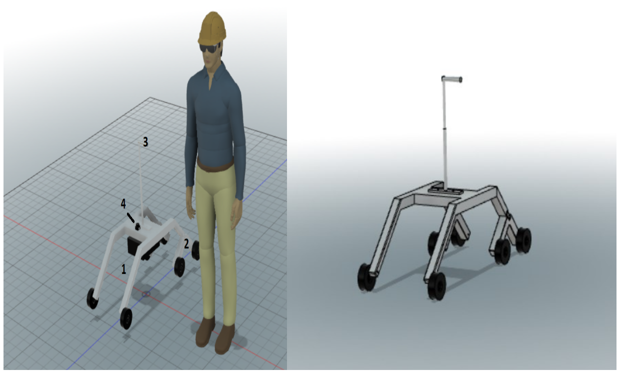

Figure 2: Model made in CAD with following main components: 1. Battery storage, 2. climbing wheels, 3 haptic handle bar and 4 the Large range sensors

impaired or blind patients using mainly global path planning and kinematic control. It is a non-holonomic system, with 4 degrees of freedom.

In order for the guidance robot to maneuver a patient through a certain environment a path needs to be created from the robot's software embedded in the microcontroller. The software will consist of (1) a path planning algorithm with an obstacle avoidance module, (2) the kinematics of a 6 wheeled mobile robot [7], (3) and desired actuator controls for the haptic handle.

The path is created using an RRT* algorithm. It is a sampling-based path planning method, is low costly, optimal, anytime, asymptotically optimal, probabilistically complete, and it is considered as a useful and efficient path planning algorithm especially in complex environments [16]. Furthermore, it can guarantee the generation of a collision-free path while it handles non-holonomic and dynamic constraints. The map input for the RRT* algorithm embedded in the controller module is constructed by the large range sensors in combination with camera tracking. The obstacles from the environment are generated from the sensor data points into convex figures. Kinematic control for the 6 wheeled robot is designed according to Chang et al [7]. This model is able to perform on an uneven terrain for several configurations.

The directional feedback will be given to the patient via a haptic handle which is attached to the robot guidance dog. The patient is holding the guidance robot as a lawnmower or suitcase. This haptic controller handle gives in return vibrotactile and tactile feedback which mimics the movement of the robot. A human can perceive a pulling sensation when subjected to asymmetric accelerations at the fingers.

A 3D model of design 1 as a rough outline is presented in *Figure 2*.

2) hardware and software design: The Robotic feedback controller design would consist of a handheld device providing tactile feedback. The transparency and latency (response delay) are tested by simulation with haply in pygame. More about the python simulation is written in the experimental setup. The navigation of the robot with use of the handle relies on the interaction of the patient with the haptic device. Haply mimics the hardware handle in order to simulate the response of the patient maneuvering through the simulation. The hardware components in the handle are 4 voicecoil actuators providing tactile feedback, 4 series elastic actuators providing vibrotactile feedback, microcontrollers communicating connecting the software to the hardware and a handle remote. These components are displayed in the right column of *Table I*

The Robotic guidance dog design consists of sensors, 3D camera, motor controller and micro-controller which combines the information from the sensors and camera in order to avoid obstacles to thereafter convey it to the user via the handle. The structure of the robot consists of two 90 degrees axles in the front on which the motors and the wheels are mounted. These axles can move independently. To ensure a stable balance of the robot, the rear axle is joined with the base of the rover with a 45-degree bend. The robot's dimensions are: 1 meter in length, and 0.48 in width and 1 meter in height. To ensure that the robot can maneuver over challenging terrains and driving situations, the independently moving joints help in combination with multipurpose all terrain high-grip wheels. The 12 V geared DC motors produce high torque figures which helps for the robot to gain and sustain the grip to move forward and climb up on obstacles by forcing the front transaxles. The robot is powered by a 12 V DC battery. The robotic guidance dog is made from PVC material because PVC has been proven to be strong, lightweight, durable and is highly cost-effective [3]. A SD card module is added for systems memory in order to provide the robotic guidance dog to safe multiple paths to the system. The measurements of most mechanical components from PVC have diameter of 25 mm with wheels of around 125 mm and a PVC pipe with length of around 2 m. All of these components are displayed in the left column of *Table I*.

Table I: Hardware for the haptic controller handle and the robotic guidance dog.

Hardware requirements	
Robotic guidance dog	Haptic handle
Sonar sensors Laser range sensors Stereo RealSense camera ODrive Motor Controller PVC pipe 6 90-degree PVC elbow 6 45-degree PVC elbow 2 PVC caps Hard plastic plate 6 Robot wheels 12V DC battery 12V DC metal gear motor SD card module	4 Voice Coil Motors (VCMs) Touch sensor (barometric) Haply (simulation) microcontroller Handle bar
Total costs hardware: € 430	

3) Experimental setup: An experimental setup for design 1 must prove the feasibility of a guide dog connected to the user with the help of haptic feedback force. The first step in testing the haptic feedback for the patient is by making a simulation in Pygame. A 2D simulated environment is created in Python where a test person needs to be able to walk to a goal position without looking at the screen. In this design the user represents the walking robot since the user walks with the robot dog while holding the handle. The black lines growing through the environment while the software iterates represent the RRT* tree. The optimal path is thereafter deducted and the robot dog guides the user through the environment while following this optimal path. The person starts walking at slow speed (less than 2km/h) as they receive tactile feedback from the haptic handle which is represented in the test simulation as the haply device [11]. The test person has to hold the handle/haply and follow the directional feedback without looking at the simulation. The simulation displays how the patient is walking through the environment with the design and how it's following it's path, this can be seen in Figure 3.

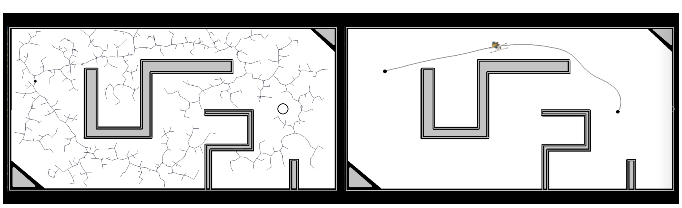

Figure 3: Simulation of how the patient maneuvers through the environment with the first design. (1) On the left the RRT* algorithm is shown creating the most optimal path, (2) on the right the patient is shown walking with the robotic guidance dog while following the optimal path.

Figure 4: Image taken from the Haply website [11]

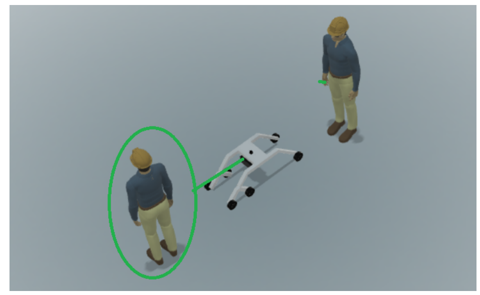

Figure 5: Concept 2 with object detection and a haptic teleoperating device in the hand of the user

B. *Design 2: Robotic guidance dog with separate haptic handle*

1) design concept and specifications: The follow-up design is a guidance robot with a separate handle module for visually impaired or blind patients to hold like a remote. This design uses mainly kinematic control and local path planning where the path is generated by taking data from the sensors and 3D camera during the movement of the robot. It is a non-holonomic system with 4 degrees of freedom.

In order for the guidance robot to maneuver a patient through a certain environment certain feedback needs to be created from the robot's and handle's software embedded in the microcontroller. The software will consist of (1) local obstacle avoidance module in the robot which communicates the feedback to the remote handle, (2) the kinematics of a 6 wheeled mobile robot [7], (3) and desired actuator controls for the haptic handle remote.

The feedback in the remote handle is created using a local obstacle avoidance module in the robot. The robot dog consists of a 3D camera and large range/sonar sensors that takes data per time step of it's surroundings. From this data obstacles are identified in real time as the robot guidance dog maneuvers through the environment while staying in close proximity to the user [16]. It can guarantee the generation of a collision-free path for the robot guidance dog module while it handles non-holonomic and dynamic constraints since the identification of these obstacles influence the robot's next move. For this specific application local obstacle avoidance is chosen because it allows the guidance robot to adapt their movements to dynamic environments and it gives the user more autonomy while walking [16]. Thus, the input for the controller module is constructed by the large range sensors in combination with camera tracking which is done in real time. The obstacles from the environment are generated from the sensor data points into convex figures. Kinematic control for the 6 wheeled robot is designed according to Chang et al [7]. This model is able to perform on an uneven terrain for several configurations.

Vibro-tactile feedback will be given to the patient via the separate haptic handle remote. The patient is holding the handle as a small remote in it's hand while the robot guidance dog maneuvers separately in front of the patient. This haptic controller remote gives in return vibrotactile feedback. The vibrotactile feedback transfers warning signs to the user as they are approaching the obstacle too closely. The vibro-tactile feedback of the remote produces the directional pulling forces the same way as described in the first design [17]. The feedback is often perceived by the user as a directional feedback, this could convey accurate signals to the user about its path to the goal [30].

A 3D model of design 2 as a rough outline is presented in *Figure 5*.

2) hardware and software design: The Robotic feedback controller design would consist of a handheld device providing vibrotactile feedback. The transparency and latency (response delay) are tested by simulation with haply in pygame. This setup also tests how the combination of the feedback cues are being perceived. The navigation of the robot relies on the obstacles sensed and the direction the patient is moving. The robot guidance dog and the remote handle module therefore communicate separately and wirelessly. Haply mimics the hardware handle in order to simulate the response of the patient maneuvering through the simulation. The hardware components in the handle are 4 voicecoil actuators providing tactile feedback, a touch sensor sensing when the handle is being pushed by a user, a microcontroller communicating connecting the software to the hardware and a handle bar. Therefore, the navigation of the user relies on the interaction of the mobile robot with the haptic device remote which in turn interacts with the user. These components are displayed in the right column of *Table II*.

The Robotic guidance dog design consists of sensors, 3D camera, motor controller and micro-controller which combines the information from the sensors and camera in order to avoid obstacles to thereafter convey it to the user via the handle. The hardware specifications for the robotic guidance dog module are the same as the first design, only the dimensions are different. The robot's dimensions are: 1 meter in length, and 0.48 in width and 0.465 meter in height. All of these components are displayed in the left column of *Table II*.

Table II: Hardware for the wireless haptic controller handle and the robotic guidance dog.

Hardware requirements	
Robotic guidance dog	Haptic handle
Sonar sensors	Voice Coil Motors (VCMs)
Laser range sensors	Series Elastic Actuators (SEA)
Sonar sensors	Touch sensor (barometric)
Stereo RealSense camera	Haply (simulation)
AVR microcontoller	Radio packet controller
PVC pipe	
6 90-degree PVC elbow	
6 45-degree PVC elbow	
2 PVC caps	
Hard plastic plate	
6 Robot wheels	
12V DC battery	
12V DC metal gear motor	
SD card module	
Total costs hardware: € 600	

3) Experimental setup: An experimental setup for this design must prove the feasibility of a separate guidance robot for visually impaired or blind person using haptic force feedback. The first step in testing the haptic feedback for the patient is by making a simulation in Pygame. A 2D simulated environment is created in Python where a test person needs to be able to walk to a goal position without looking at the screen. In this design the walking robot is represented with a large sensor data cone that detects the obstacles in the environment. First, the guide robot will start with detecting obstacles. The person in this environment starts walking at slow speed (less than 2km/h) and it will receive tactile and vibrotactile feedback from the data gathered from the guidance dog to the haptic handle remote. Since in this design the robot guidance dog is not attached to the handle, the dog stays close to the user within a radius of around 2 meters. The user has to walk around the obstacles, and it receives vibrotactile feedback from the remote handle which is represented in the test simulation as the haply device. The test person has to hold the handle/haply and follow the directional feedback without looking at the simulation. As the user follows the directional feedback, the vibrotactile feedback will transmit gradually as the person approaches an object in closer proximity. The simulation displays how the patient is walking through the environment with the design and how it's following it's path, this can be seen in Figure 6.

C. Design 3: Robotic cane with haptic handle

1) design concept and specifications: The last design is a guidance robotic cane with a haptic handle for visually impaired or blind patients using local path planning where the path and position is generated by taking data from the sensors and 3D camera on the cane. The cane system has 6

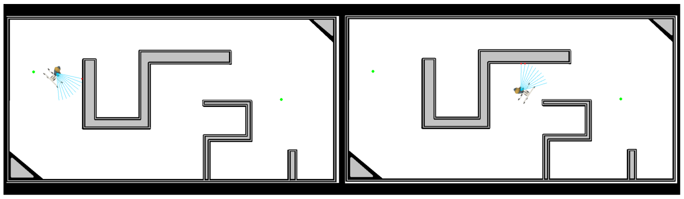

Figure 6: Simulation of how the patient maneuvers through the environment with the second design. (1) On the left you can see the sensor data cone detecting an obstacle (represented as the red dots), (2) on the right the robot guidance dog is shown walking through the environment while it adapts its movements to the obstacles detected.

degrees of freedom.

In order for the user to maneuver with the haptic guidance cane through a certain environment a path needs to be created from the robot's software embedded in the micro controller. The software will consist of (1) a path planning algorithm with an obstacle avoidance module, (2) position estimation control [32], (3) and desired actuator controls for the haptic handle.

The path is created using the interaction of the human steering the cane through the environment. The cane module consists of a 3D camera and large range/sonar sensors that takes data per time step of it's surroundings. From this data obstacles are identified in real time as patient maneuvers through the environment while holding the cane. The cane can guarantee the generation of a collision-free path for the user because the cane can detects an obstacle and steer around it. The user immediately feels this steering action and can follow the cane's new path easily without any conscious effort [27]. For this specific application local obstacle avoidance is chosen in combination with human interaction because it allows the guidance robot to adapt their movements to dynamic environments and it gives the user more autonomy while walking while still being guided by choice [16]. Thus, the input for the controller module is constructed by the large range sensors in combination with camera tracking which is done in real time. The obstacles from the environment are generated from the sensor data points into convex figures. The end of the cane model is rolled forward by the kinematics of a roller bearing.

Vibrotactile feedback will be given to the patient via the haptic handle attached to the end where the patient holds the cane. The patient is holding the handle to receive directional feedback in order to guide themselves through the environment. This haptic handle gives in return vibrotactile feedback. The vibrotactile feedback transfers warning signs to the user as they are approaching the obstacle too closely whereas the tactile feedback transfers directional feedback to the user. The tactile feedback of the remote produces the directional pulling forces the same way as described in the first design [17]. The vibrotactile feedback is often perceived by the user as a warning, therefore in combination with directional feedback this could convey accurate signals to the user about its path to the goal [30].

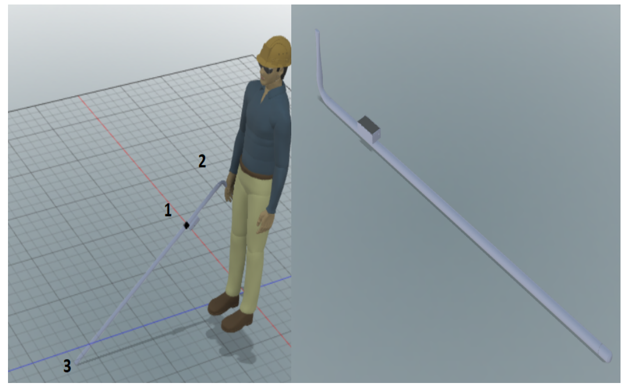

Figure 7: Model made in CAD with following main components: 1: lidar camera, 2: vibrotactile handle and 3: sensor for feedback

A 3D model of design 3 as a rough outline is presented in *Figure 7*.

2) hardware and software design: With this design the user will receive similar feedback as with a conventional cane since its design is almost identical. However, in the electrical guidance cane the end consists of a ball transfer unit and the cane consists of several sensors for mobile communication with the handle, global positioning (GPS) and for object detection (ultrasonic sensor). Other sensors (IR and water sensor) next to the ball transfer unit are for water and pit (for example staircases) detection.

The Robotic feedback controller design would consist of a handheld device providing tactile feedback. The transparency and latency (response delay) are tested by simulation with haply in pygame. The navigation of the robot with use of the handle relies on the interaction of the patient with the haptic device. Haply mimics the hardware handle in order to simulate the response of the patient maneuvering through the simulation. The cane can be switched in an active (with feedback) and passive (normal cane) mode with the switch on the handle. The hardware components in the handle are 4 voicecoil actuators providing tactile feedback, 4 series elastic actuators providing vibrotactile feedback, microcontrollers communicating connecting the software to the hardware and a handle remote. These components are displayed in the right column of *Table III*.

Table III: Hardware for the haptic controller handle and the robotic guidance dog.

Hardware requirements	
Robotic cane	Haptic handle
Ultrasonic sensors	4 voicecoil actuators
GPS module	Touch sensor (barometric)
IR sensor	Microcontroller
Water sensor	
Ball transfer unit	
SD card module	
Cane	
Switches	
Total costs hardware: € 300	

3) Experimental setup: An experimental setup for this design must prove the feasibility of a haptic feedback guidance cane for a visually impaired or blind person using haptic force feedback. The first step in testing the haptic feedback for the patient is by making a simulation in Pygame. A 2D simulated environment is created in Python where a test person needs to be able to walk to a goal position without looking at the screen. In this design the patient using the haptic guidance cane is represented as the cane with a large sensor data cone that detects the obstacles in the environment. First, the cane will start with detecting obstacles. The person in this environment starts walking at slow speed (less than 2km/h) and it will receive tactile and vibrotactile feedback from the data gathered from the haptic handle on the cane. The user has to walk around the obstacles, as they receive vibrotactile and tactile feedback from the haptic handle which is represented in the test simulation as the haply device. The test person has to hold the handle/haply and follow the directional feedback without looking at the simulation. As the user follows the directional feedback, the vibrotactile feedback will transmit gradually as the person approaches an object in closer proximity. The simulation displays how the patient is walking through the environment with the design and how it's following it's path, this can be seen in Figure 8.

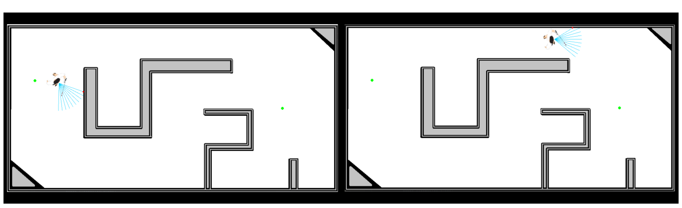

Figure 8: Simulation of how the patient maneuvers through the environment with the third design. (1) On the left you can see the sensor data cone detecting an obstacle (represented as the red dots) on the end of the cane, (2) on the right the patient is shown walking through the environment while they receive directional feedback and they adapt their movements to the obstacles detected.

IV. Analysis and evaluation

In this chapter, the cost analyses is shown together with a risk analysis and a house of quality. This chapter is divided in the following sub paragraphs: First, the cost analysis is performed on all 3 concepts. Secondly, The risk analysis is performed to determine which design is the most suitable for

A. Cost analysis

The following *Figure 9* further explains the cost of developing and maintaining the robot guide dog in Japan.

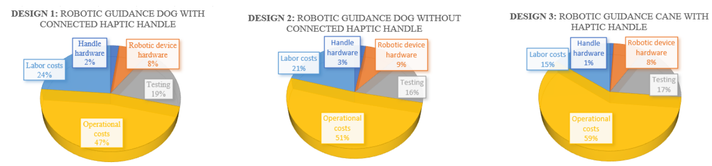

Figure 9: The cost analysis of all designs

The costs for the robotic guidance solutions are divided in the following segments: (1) labor costs, (2) testing, (3) operational costs, and (4) hardware costs. Labor costs represent the costs to produce the robot guidance designs. Testing costs represent the testing phase costs for the product. Before the product is given to the user, excessive tests must be done to determine if all the software and hardware is working accordingly. Operational costs represent the maintenance, software procurement, storage and security of the product [2]. The hardware costs represent the cost of each component in the robotic solution (cane/dog and handle). A calculation of the component costs per design is also displayed on the bottom of *Table I, II, III*. These costs only contain the cost of the production of the product itself. When the product is introduced in the market the prize increases according to the sellers,governmental and medical policies.

Existing cane solutions for guidance for the visually impaired have market costs ranging from around 20 to 500 euros depending on its robotic application. Moreover, a fully trained guidance dog costs around 30.000 euros with additional costs for taking care of it. Analysing our design solutions to the existing solutions show that the costs for robotic application are mainly available for people with middle-income since production costs per design range from 300 to 600 euros. From this analysis can be deducted that design 1 is in the middle prize range and it provides promising design specifications such as a robotic companion, optimal path guidance, mobility and autonomy. Design 3 is in the lower prize range and it provides similar design specifications as in design 1, however the design is lacking the aspect of a robotic companion and it does not provide the amount of mobility as design 1 has. Design 2 is in the higher prize range and is cost-effective wise not a better option than design 1 since this design provides the user with more autonomy, but then for a much higher prize than the other designs.

B. Risk analysis

This subsection will analyse how to choose the best concept by translating the users wishes towards design criteria. Next, the concepts are tested to find which design meets the design criteria of the patients the most.

C. House of quality

The house of quality shows how to translate the wishes of the user into functional design criteria and if needed is complemented with extra criteria [25]. To do this, the design team had to use translate the most important client wishes (independence would be most prominent one) into a subjective criteria list. The team came up with the following criteria:

- amount of haptic feedback
- Usability in new environments
- Easy to use
- number of parts

These criteria are believed to best translate the wishes of the end user into usable criteria to determine which design fits the criteria the most. See also figure 10 to see the translation of the wishes in green, towards the criteria in purple. Their degree of improvement is shown in blue.

Blind people wishes	Degree of improvement	Amount of Haptic feedback	Usability in new environment	Easy to use	Number of parts
Independence	3	+	++		
Unpredictable environments	2	++	++		
User friendly	3	+	+	++	-
Qualitative feedback	2	+	+	-	
Inexpensive	1	-	-		++
technical relevance		35	41	17	8

Figure 10: House of quality

With the criteria out of the previous analysis, the next step is to determine which design is the best for our user group. Each criteria is given a certain weight factor, according to the importance to the user, and than each of the 3 concepts is put into the matrix to determine how well the concepts take the given criteria into account.

	Usability in new environment	Easy to use	Number of parts	Amount of Haptic feedback	Total points	
Weight	3	2	1	2		
Concept 1	+	++	-	++	30	
Concept 2	++	+	-	+	28	- = 1
Concept 3	-	++	++	-	20	+ = 3
						++ = 5

Figure 11: Risk analysis

Out of the risk analysis the scores of the concepts are as followed: concept 1 has a score of 30, concept 2 scores 28 and finally concept 3 scores 20 points.

D. Future work

To look at the code used for this paper, a Gitlab repository is created. In here, the code for the Path planner and the Pygame is explained. The design of the software will be elaborated with a more robust software such as the dynamic RRT* in the future, this is an extra local path planner to optimize the current RRT*. The Haply software and experimental setup will also be elaborated in future work.

The cost analysis displays that robot solutions are cost effective against currently available technologies, and are to be considered when choosing the final design. As mentioned in the introduction, this solution should be able to help all blind and visually impaired people in the future. Therefore, the cost for the prototype is important to help people in developing countries as well.

V. Conclusion (and Outlook)

In this paper, the main question was to find out how the remaining exterior receptive senses of the blind individual can be used to design a guide robot to help a user in an unknown environment. To answer the main question, a large literature research has been done and this paper has shown 3 designs based on the research that the designers think represent the needs of the blind and visually impaired the most.

With the help of the cost analysis and the risk analysis it was decided to continue design 1. The choice was made based on the lower cost to develop, because it is important to look also into solutions for the developing world, where lower costs are important to take into account. Also, design 1 scores the most points in the risk analysis, concluding that this design is most suitable for the patient.

After the final design has been chosen, a name for the Guide dog Robot has been made. In the future, this robot will be revered to as GUIDO: Guiding User-friendly Independent Driving Object, a robot for visually impaired patients.

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