Guidance for Human Navigation using a Vibro-Tactile Belt Interface and Robot-like Motion Planning

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***Abstract*— We present a navigation guidance system that guides a human to a goal point with a tactile belt interface and a stationary laser scanner. We make use of ROS local navigation planner to find an obstacle-free path by modeling the human as a non-holonomic robot. Linear and angular velocities to keep the 'robot' on the path are dynamically calculated, which are then converted to vibrations and applied by the tactile belt. We define directional and rotational vibration patterns and evaluate which ones are suitable for guiding humans. Continuous patterns for representing directions had the least average angular error with $8.4°$, whereas rotational patterns were recognized with near-perfect accuracy. All patterns had a reaction time slightly more than 1 seconds. The person is tracked in laser scans by fitting an ellipse to the torso. Average tracking error is found to be 5cm in position and $14°$ in orientation in our experiments with 23 people. Best tracking results was achieved when the person is 2.5m away and is facing the sensor or the opposite way. The human control system as a whole is successfully demonstrated in a navigation guidance scenario.**

I. INTRODUCTION

A severe loss of vision hinders an individual's ability to complete daily activities such as walking safely. Mobility tools such as canes and guide dogs provide invaluable assistance to these people. With advancing technology, assistive mobility devices have been available to the visually impaired. However, these devices are used only as secondarily to traditional tools and a more comprehensive solution is desired. Our proposed solution is a companion robot traveling with the blind person and guiding him to a destination with a haptic interface. There are several research problems that needs to be solved before such a system can be realized, such as reliable human tracking, joint path planning of the robot-human pair and interfaces that can represent spatial information. We start with the simpler problem of guiding a person to a location in the room with a stationary robot or sensor. Our approach is based on controlling the human like a robot using a tactile belt interface.

Guiding a human with a tactile belt is similar to autonomous mobile robot navigation. A mobile robot is controlled by inputs to its motors whereas in our system the human is controlled by vibration motors. In the case of a non-holonomic robot, the inputs to the motor controller is in the form of a linear and angular velocity. Our approach is to model the human as a robot, plan a path to the goal and to convert the input velocities into vibration patterns. In order to do this, we consider two types of vibration patterns: directional and rotational. There are differences between controlling a robot and a human because there is more uncertainty on human's motions given for a given velocity command and there is a time delay between the applied vibration and human's recognition of the signal. One other difference is the sensor placement; as a mobile robot localizes itself with its on-board sensors whereas in our system an external sensor localizes the human. Keeping these differences in mind, we adapt robot path planning and control methods to human guidance.

In this paper we present a tactile belt interface, a laser-based human tracking method and a motion planner for navigation guidance. More specifically, after briefly describing our tactile belt prototype, we evaluate the recognition accuracy and reaction times of 4 directional and 4 rotational vibration patterns. We then introduce our ellipse-fitting approach to estimate the position and orientation of humans. Finally, we describe the navigation guidance system and present a demonstration.

II. RELATED WORKS

Below we review the body of related work in the areas of haptic human-machine interfaces, person tracking and navigation guidance.

A. Haptic Interfaces

Haptic human-machine interfaces have been used in a broad range of applications including waypoint navigation [1], facilitating navigation for blind pedestrians [2] or the elderly [3], helping firefighters to find their paths [4], teleoperation [5], driving support [6], flight support [7], gaming [8] and dancing [9]. The intended application of a tactile display device influences its design and form factor as they can be in forms of handheld devices [10], [1] and wearable devices [11].

Tactile belts are one of the most popular wearable haptic interfaces. Ways of using tactile belts include discrete [12] and continuous [13] direction encoding, distance encoding [14] and rhythm modulation [15]. Different direction encoding methods in tactile belts is discussed in [16].

B. Laser Based Human Tracking

Leg detection is common practice for robots where a laser scanner is placed at ankle height [17], [18], [19], [20]. Leg tracking in cluttered environments was found to be prone to false positives by Topp [19]. Some approaches attempted to reduce the false positives by employing multiple layers of laser scans, usually at the torso height in addition to

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ankle height [21], [22]. In a comparison study, Schenk [23] showed that upper body tracker achieved better results than leg tracker, due to the simpler linear motion model instead of a walking model. Double-layer approach was generalized to multi-level in depth images by Spinello [24].

C. *Navigation Guidance*

Some of the related work on tactile belts demonstrated GPS-based waypoint navigation using a single actuator [25] or continuous range of directions [26]. An alternative to encoding directional information is to convey how much distance is left to a waypoint or an object of interest [14], [7], [27]. It is shown in [28] that recognition accuracy of vibration patterns is reduced when people are walking instead of standing still.

Haptic feedbacks are also used in human-robot interaction. Scheggi [29] used a tactile bracelet in a scenario of a human leader followed by a team of mobile robots. Navigation feedback was achieved through a tactile belt in telepresence context in [5]. In [30], turning instructions through tactile actuators attached to the handlebar of a Segway platform is shown to reduce the cognitive workload. A robotic system that is designed to provide haptic feedback to promote self-initiated mobility in children is presented in [31]. A robot that guides a visually impaired person in structured indoor environments is given in [32].

III. System Overview

Our system consists of a Tactile Belt to apply vibration patterns, a stationary laser scanner to track the user and a Navigation Planner that computes the path of the user. Figure 1 shows the system diagram, illustrating the tactile belt and the Controller PC, which incorporates the Human Tracker and Navigation Planner modules.

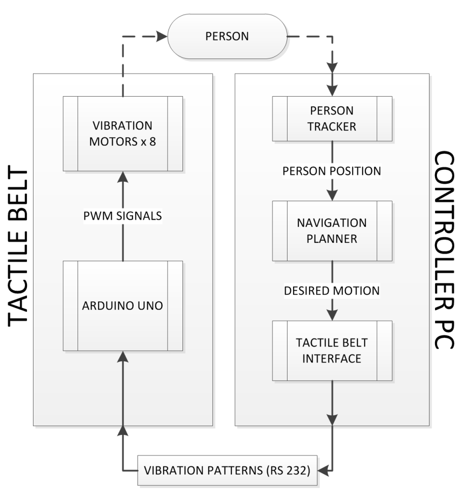

Fig. 1. System overview.

Whenever a goal position is provided to the Navigation Planner by a higher level process, it plans an obstacle-free path from the current position of the human to the goal position. Human Tracker module is responsible for tracking the position and orientation of the user and reporting it to the Navigation Planner. To keep the human on the path, Navigation Planner continiously re-computes the desired motion of the human. The motion command is converted to a corresponding vibration pattern, which is sent as a message to the tactile belt. The processor on the tactile belt reads the message and applies the vibrations with the vibration motors. The path is re-planned periodically because humans usually deviates from the path that is initially calculated and to be able to avoid dynamic obstacles (i.e. bypassers).

IV. Tactile Belt

Our intended application of guiding visually impaired individuals affected our choice of the human-machine interface. Readily available options for assistive interfaces are limited to Braille or devices that presents content with speech synthesis. These ways of presenting information have difficulty dealing with representing spatial information. We also think visually impaired individuals would prefer a non-speech interface because they mostly rely on their sense of hearing in daily life. We therefore use a tactile belt for navigation guidance, because it can represent directions and rotations, be worn discreetly and does not occupy the hearing sense.

In our previous work, we presented the tactile belt and its evaluation in detail [33]. In this section, we summarize the design of the tactile belt and the vibration patterns.

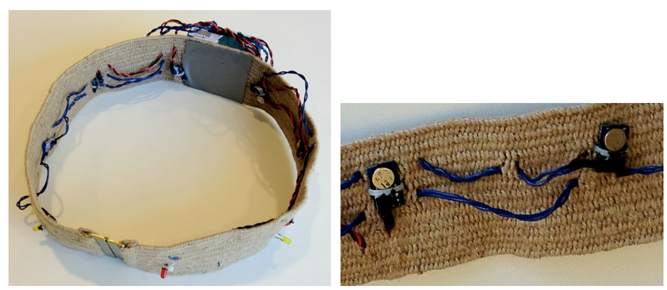

Fig. 2. Tactile belt prototype.

A. *Hardware*

The belt is made of elastic material that provides a 'one fits all' solution. Because the belt is stretched when it is worn, vibration motors makes contact with the human body, increasing the likelihood of a vibration being detected.

There are 8 coin-type vibration motors on the belt, which operates at 9000rpm at 3V rated voltage. Motors are driven with Pulse Width Modulation with a 20 kHz square signal. The processor on the belt is an Arduino Uno, which is powered by its USB port. The communication with the Controller PC is achieved by a serial connection and a serial-to-USB converter.

B. *Software*

We use Robot Operating System (ROS) software architecture for the communication between the Controller PC and the Arduino on the belt. A message from the Controller PC contains 8 bit arrays, an array for each motor. A bit in an array indicates if the motor is going to vibrate or not, during a time interval of 1/16 seconds. When Arduino receives the message, it consequently reads the bit array and synchronously applies the corresponding voltages to motors.

C. Vibration Patterns

We define two classes of vibration patterns depending on the intended human motion: directional and rotational. This is motivated by the motion control of mobile robots, where the velocity inputs are linear and angular. Directional patterns are intended to induce a motion towards a direction and rotational patterns are intended to induce a rotation around self. We evaluated 4 commonly used and intuitive vibration patterns for both directional and rotational motion.

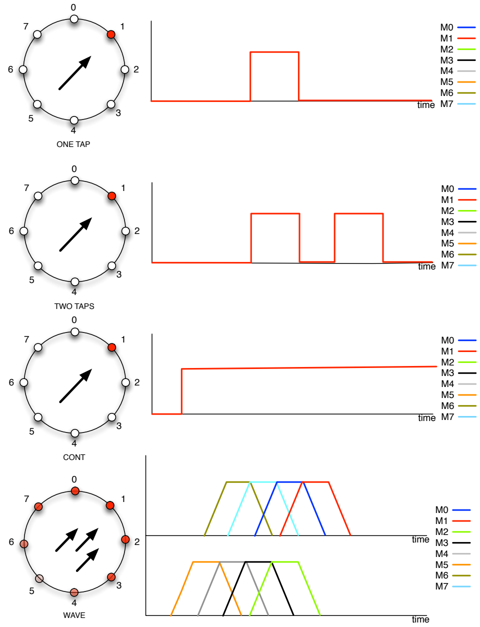

Fig. 3. Vibration Patterns for Directional Motion.

1) Directional Motion:

- **ONE TAP:** a motor is active for 250ms
- **TWO TAPS:** a motor is active 250ms, inactive for 250ms and active for 250ms again
- **CONT:** a motor is active until a new pattern is applied
- **WAVE:** a vibration that starts from the opposite end of desired direction and ends in desired direction

Figure 3 illustrates all 4 directional patterns for towards northeast cardinal direction (Vibration Motor 1).

2) Rotational Motion:

- **SOLO ONCE:** activates all 8 motors consecutively, starting from left motor for clockwise, right for counter-clockwise.
- **SOLO CONT:** repeats **SOLO ONCE** pattern
- **DUAL ONCE:** circle motion is executed for one full circle with two opposing motors instead of one
- **DUAL CONT:** repeats **DUAL ONCE** pattern

Figure 4 illustrates all 4 rotational patterns for a clockwise rotation motion.

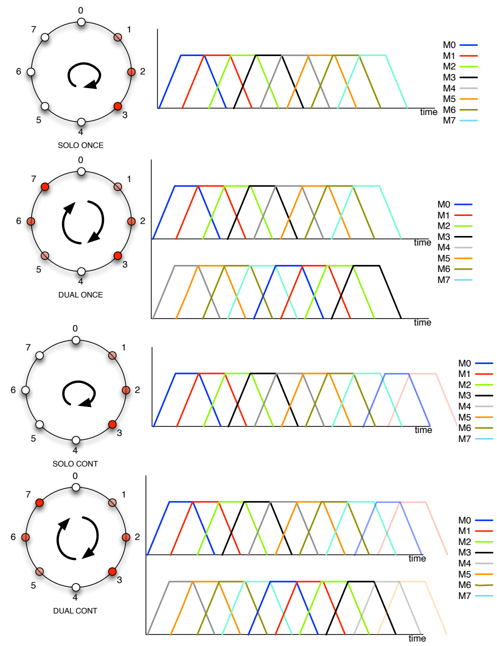

Fig. 4. Vibration patterns for Rotational Motion

V. Navigation Guidance

In this section we describe the components necessary for navigation guidance. First, we introduce our laser-based human tracking system. We then present our robot-inspired path planning approach and explain how the velocity of the commands are mapped to vibrations on the haptic belt.

A. Human Tracking by Ellipse Fitting

The guidance system should be able to track the pose of the human so that it can provide the right navigation commands through the belt. The Human Tracker module tracks the position and orientation of the user by fitting an ellipse to the torso of the user (Figure 5). The Hokuyo UTM-30LX-EW laser scanner, which has 30 Hz refresh rate, is placed placed at torso height (1.27m). Whenever a laser scan is received, it is first segmented into clusters by using a Euclidean distance threshold metric. Tracking is activated when a person-sized cluster gets close enough to the sensor. This cluster is assumed to correspond to the torso of a human. We fit an ellipse to the tracked torso cluster by solving the problem with a generalized eigensystem [34]. This ellipse fitting approach is relatively robust and ellipse specific, meaning that even noisy sensor data always returns an ellipse. Compared to iterative methods, it is computationally more efficient and easy to implement. The speed of the system is limited to the Hokuyo refresh rate.

The centroid of the ellipse is considered as the position and the shorter principal axis of the ellipse is used to estimate the orientation the human. Data association between consecutive frames is achieved by the nearest neighbor approach. By modeling the human torso as an ellipse, there are two orientations that the person can have (facing the sensor or not). The correct angle is determined by choosing the orientation closer to the previous orientation of the human.

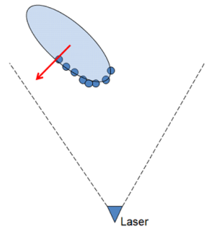

Fig. 5. Human pose is estimated by fitting an ellipse to the torso.

The pose of the human is used in path planning, which is described in next section.

B. Path planning

ROS provides an easy-to-use navigation stack for mobile robots. The input to the navigation stack is a map and a goal point and the output is a path and linear and angular velocities *(v,w)* necessary to keep the robot on the course of the path. We assumed that the human is a non-holonomic robot with a circular footprint. The obstacle information is acquired from the laser scanner and the goal is provided in the sensor frame. Coupled with the Human Tracker, the 'robot' stays localized in the map and with respect to the path. The path is re-planned every second to deal with possible deviations. Next section is concerned with how the linear and angular velocities are converted to the vibration patterns.

C. Velocity to Vibration Pattern Mapping

Given a desired velocity that the 'robot' should execute, we first determine if a directional or rotational vibration pattern should be applied by the belt. If the linear velocity is dominant, then the human should walk towards that direction. If the angular velocity is dominant, the human should rotate around self. If both the linear and angular velocity is close to zero, the human should not move. To calculate which motion is appropriate, the 'robot' is simulated for a fixed amount of time using the motion model in [35]. If the distance the 'robot' took is larger than a threshold, then a directional vibration pattern is used. If it is less than the threshold, a rotational pattern is used. If both of the velocities are small enough, the no vibration is applied.

When the human gets to the vicinity of the goal point, a special stop signal is applied to inform the person that the destination is reached. Stop signal is implemented similar to **TWO TAPS** pattern except all the motors are activated instead of one.

VI. Evaluation

In this section, we report on the recognition accuracies of vibration patterns presented in Section IV and the tracking error of the Human Tracker presented in Section V-A. We then present a demonstration of the human guidance system.

A. Vibration Patterns

To evaluate which vibrations are better suited to guide a human, we conducted experiments on 15 people. We aim to evaluate the vibrations in real scenarios, so the subjects were asked to walk randomly during the experiments. The experiment consisted of 2 parts: first directional patterns and then rotational patterns are tested. Whenever the subject decides on the type of pattern, he/she pressed on a joystick button and uttered the perceived cardinal direction (1-8) or the rotation (clockwise or counter-clockwise). For directional patterns, we measure the angle error between applied and perceived direction. For rotational patterns, we measure the percentage of correct recognition. Reaction time is defined as the time passed between the start of the vibration and the instant the subject presses the button. A total of 344 directional patterns and 256 rotational patterns are randomly applied with the belt. Tables I and II show the results of our experiments.

	ONE TAP	TWO TAPS	CONT	WAVE
Directional Error	12.4°	10.6°	8.4°	23.1°
Reaction Time (s)	1.32	1.13	1.26	1.92

TABLE I
AVERAGE RECOGNITION ERROR AND REACTION TIMES OF DIRECTIONAL PATTERNS

Most accurate directional pattern was **CONT** with a mean angular error of 8.4°, whereas **TWO TAPS** had the least reaction time of 1.13 seconds. **WAVE** performed significantly worse than others.

	SOLO ONCE	DUAL ONCE	SOLO CONT	DUAL CONT
Recog. Accuracy	%100	%92	%100	%98
Reaction Time (s)	1.32	1.84	1.16	1.68

TABLE II
AVERAGE RECOGNITION ACCURACY AND REACTION TIMES OF ROTATIONAL PATTERNS

The second part of our experiment showed that subjects rarely made mistakes in rotation recognition. **SOLO CONT** pattern was recognized by perfect accuracy and it had the least reaction time of 1.16 seconds. **DUAL** patterns did not perform well in our studies.

B. Human Tracking

In order to evaluate the accuracy of the position and orientation estimations of our human tracking method, we conducted experiments of 23 people. Subjects were instructed to stand on 4 targets at different distances with 8 different orientations on each target. For every measurement, positional and angular error is logged. Experimental setup from the sensor's view is shown in Figure 7.

Table III shows the angular error at every target distance and bearing. The average positional error in all experiments was between 0.05-0.06 meters regardless of the distance and the bearing of the human. The average orientation error throughout all the experiments was 14.5°. Error in orientation, however, varied greatly by pose of the person with respect to the laser scanner.

Average error in orientation differed slightly with respect to the distance from the sensor and was the least with 11° when the humans were 2.5m away from the sensor. We

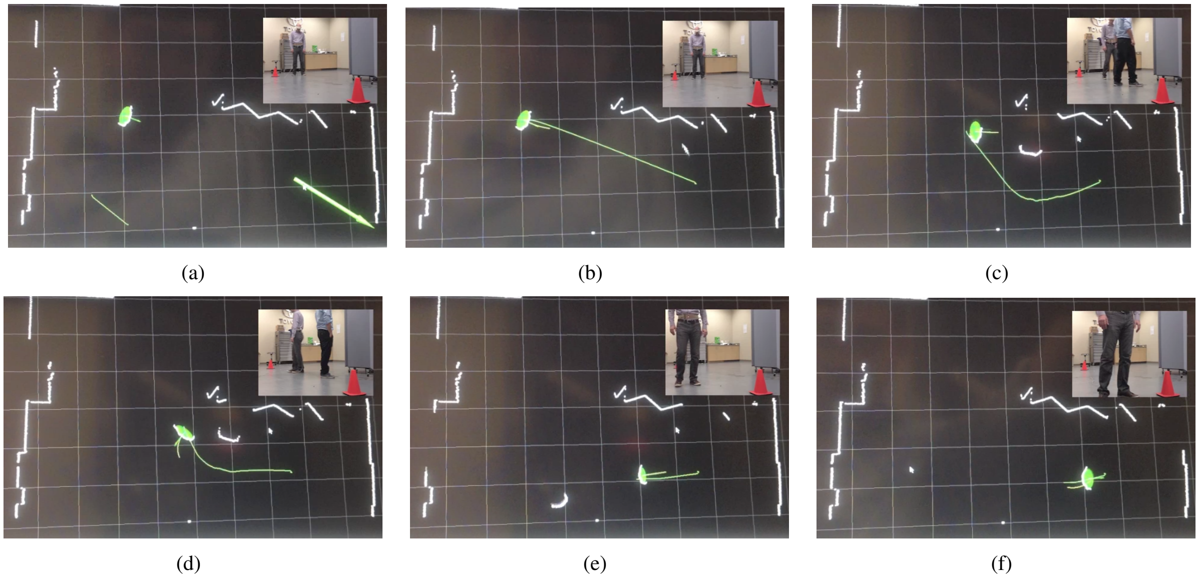

Fig. 6. Autonomous guiding of a blindfolded person using the tactile belt.

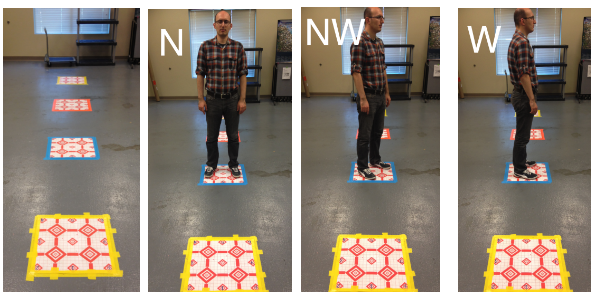

Fig. 7. Experimental setup for the evaluation study of the Human Tracker.

Distance	N	NE	E	SE	S	SW	W	NW	ALL
1.0 m	4°	12°	22°	13°	5°	7°	26°	17°	13°
2.5 m	5°	16°	19°	10°	3°	6°	14°	17°	11°
4.0 m	4°	10°	30°	16°	7°	11°	21°	17°	15°
5.5 m	5°	11°	41°	18°	10°	6°	38°	23°	19°
ALL	4°	12°	27°	14°	6°	7°	24°	18°	14.5°

TABLE III

AVERAGE ORIENTATION ERROR OF HUMAN TRACKER WITH RESPECT TO DISTANCE FROM SENSOR AND BODY POSE IN A STUDY WITH 23 PEOPLE

attribute to the fact that when humans closer than 2.5m to the laser scanner, it captures more of the arms, which makes the fitted ellipse slightly worse.

The bearing of the human with respect to the sensor had a significant effect on orientation error. Least error was achieved when the human faces (4°) the sensor or the opposite way (6°). On the other hand, average orientation error was $24-27°$ when humans are perpendicular to the sensor, because most of the torso can't be seen in that configuration. The ellipse fitting method is efficient and accurate enough to be used for navigation guidance system.

C. Demonstration

We demonstrated that our system can successfully guide a blindfolded person to a goal location in a room. Based on our evaluation results of vibration patterns, we used **CONT** for directional motions and **SOLO CONT** for rotational motions. The experimenter manually provided several goal poses using the GUI. Note that since the system is re-planning frequently, the planner is able to accommodate dynamic obstacles and compensate unpredictable motions of the person. The demonstration is shown in Figure 6 with following steps: a) The guidance starts. The user is blindfolded and is standing at the left of the screen. The human detection system detects him and places an ellipse marker with an arrow depicting his orientation. The operator gives a goal point by clicking on the screen. The goal point is the right traffic cone, and given by the big arrow. b) The system autonomously generates a path for the user. As seen in the picture the path is collision free. At this stage the belt begin to vibrate towards the front of the user. c) An unexpected obstacle (another person) appears and stops in front of the user. The system detects the other person as an obstacle, and reevaluates the path. A new path going around the obstacle is immediately calculated and sent to the user by the belt. d) The user receives a rotation vibration modality, and begins to turn towards the new path. And follows this path from now on. e) The obstacle leaves. The path is then reevaluated and changed. The user receives forward directional belt signal, and advances towards the goal. f) The person reaches to the vicinity of the goal and stop signal is applied.

VII. CONCLUSION AND FUTURE WORK

We successfully demonstrated a system that guides a human to a goal position with external sensing and without physical contact. The system comprises of a tactile belt to apply vibrations that encode spatial data, a human tracker that estimates the position and orientation of the human and a motion planner that assumes the human is a non-holonomic robot with a circular footprint. Output linear and angular velocities of the the motion planner are mapped to corresponding directional and rotational vibration patterns on the belt. We found that continuous patterns for representing directions had the least recognition error and that rotational patterns had near-perfect accuracy. The human tracker serves as the localization service for path planning. Our method fits an ellipse to human torsos, is computationally efficient and has a low positional error. Best person tracking results were achieved when the person is 2.5 away from the laser and is facing the sensor or the opposite way.

The main limitation of our system is the stationary laser scanner because the system loses track if the human navigates to another room. Next step in our research is to place the sensor on a mobile robot that accompanies the human. An interesting research problem is the joint path planning and control of the robot and the human.

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