Evaluation of Rotational and Directional Vibration Patterns on a Tactile Belt for Guiding Visually Impaired People

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ABSTRACT

We present the design of a vibro tactile belt and an evaluation study of intuitive vibration patterns for providing navigation assistance to blind people. Encoding directions with haptic interfaces is a common practice for outdoor navigation assistance but it is insufficient in cluttered indoor environments where fine maneuvers are needed. We consider rotational motions in addition to directional in our application. In a usability study with 15 subjects, we evaluate the recognition accuracy and reaction times of vibration patterns that include 1) directional and 2) rotational motion. Our results show that the directional pattern of two intermittent pulses was preferred by most subjects, even though it had slightly more recognition error than patterns with continuous vibrations. Rotational patterns were recognized by subjects with almost perfect accuracy. Average reaction time to all vibration patterns varied between 1 and 2 seconds. Our tactile belt design was found comfortable, but it was also found slightly noisy.

Index Terms: H.5.2 [User Interfaces]: Haptic I/O—Benchmarking; K.4.2 [Social Issues]: Assistive technologies for persons with disabilities—Navigation guidance

1 INTRODUCTION

According to 2010 data of the World Health Organization, there are 285 million blinds or people with low vision in the world. For the visually impaired, daily life events such as basic navigation become a challenge. Although they rely mostly on traditional mobility assistance tools such as mobility cane and guide dogs, handheld and wearable devices are quickly entering market. We believe that a mobile robot can help the blind people to move through difficult environments. A companion robot can monitor the environment for the human and guide him to his desired destination. This requires scene understanding, a human-machine interface and joint navigation of human and robot. We break apart the problem and first focus on the interface between the human and the robot in this work. Haptic interfaces are a common option for the visually impaired because it can be worn discreetly and it does not use the hearing sense. Tactile belts have been shown to successfully provide navigation assistance in indoors and outdoors. Our initial application domain is indoor navigation, where a robot can localize itself in a map and navigate to a goal point. Navigation guidance indoors is a challenge because the path is likely to have more curves than straight lines, in contrast to outdoor navigation. The ability to control the orientation of the human will be necessary for correctly executing the calculated paths. In order to address this problem, we consider two types of vibrations: Directional patterns that induce a motion towards a direction and rotational patterns that induce a rotation around self. To our knowledge, rotation motions haven't been studied in depth in the context of blind aid devices. Moreover, there is an inherent time delay between application of the vibrations and the reaction of the human. We aim to measure this delay and then incorporate it in planning and control of the human motions.

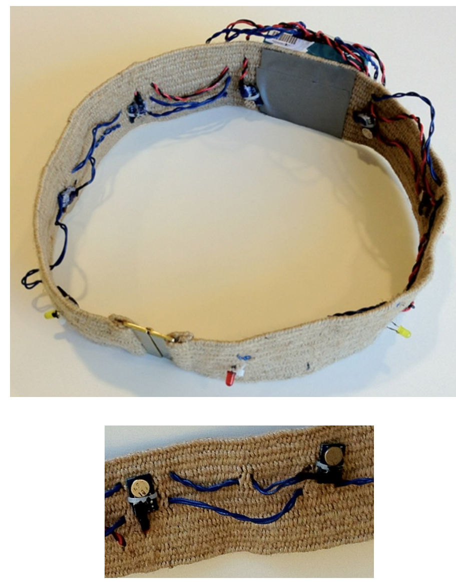

Figure 1: Tactile belt prototype and two of its coin vibration motors.

In this work, we describe our tactile belt and then evaluate 4 directional and 4 rotational vibration patterns applied by it. Effectiveness of a vibration pattern is measured by the recognition accuracy/error and reaction time. We conduct a post-study survey to evaluate the usability of the belt prototype and to find out which patterns are preferable to users. Human subjects were instructed to walk during the experiments so that the results reflect a real navigation assistance scenario.

The organization of the paper is as follows. After a brief overview of the tactile belt literature, we first describe the hardware and software design of our tactile belt prototype in Section 3. Then, we specify several vibration patterns that might be suitable for indoor navigation guidance in Section 4. Finally, we describe our evaluation setup in Section 5 and present its results in Section 6.

2 RELATED WORKS

Tactile belts are commonly used for providing tactile feedback. A study [11] found that tactile belts provided faster and more accurate directional information than tactile grid arrays. See [10] for a discussion on form factors and design considerations of tactile belts. One of the earliest works on tactile belts is the *ActiveBelt* [13], which has 8 vibration motors around the waist for encoding directions. It is shown in [8] that continious direction encoding using interpolation of the vibration intensities yielded better accuracy than discrete encoding. A 6-motor tactile belt that can exhibit rhythmic patterns with different intensities is described in [2]. Directions were identified with 81% accuracy and average reaction time was 4.8 seconds. Different representation of vibration patterns for direction encoding in tactile belts is subject to ongoing work [12]. Experiments on signal duration as cue for distance to a person are conducted in [7].

Some of the related work on tactile belts demonstrated outdoor waypoint navigation using GPS localization. Marston [6] presents a GPS-enabled route guidance tactile belt with only a single motor that helps the user to find the right orientation towards the path. Heuten [4] demonstrates outdoor pedestrian navigation experiments using a tactile belt that encodes a continuous range of directions. In this work, route completion and deviation from the path are measured for quantitative evaluation. An alternative to encoding directional information is to convey how much distance is left to a waypoint or an object of interest [7, 3, 9]. Van Erp [3] showed the usefulness of the tactile display for pedestrians, a helicopter pilot and a boat driver. In this work, a combination of GPS and compass for localization and distance to the next waypoint is encoded. It is shown in [5] that typical movement context such as walking reduced the recognition accuracy of vibration patterns.

3 Tactile Belt

The belt is made of elastic material so that the vibration motors make contact with the human body and the angle between motors is fixed. This property allows us to represent the 8 cardinal directions consistently for every user.

Upon receiving a vibration pattern, the controller on the belt applies corresponding sequences of voltages to the vibration motors. A vibration pattern incorporate the activation frequency, duration and rhythm of vibrations for all motors.

3.1 Hardware

8 coin type vibration motors are placed uniformly placed around the belt. Although coin motors provide less strength than cylindrical motors, their size and shape make them ideal for the belt application. The motors have 3V rated voltage, 9000 rpm rotation, 90 mA rated current and a maximum 50db mechanical noise and they are driven by a single ULN2803A chip with Pulse Width Modulation (PWM) at 20 kHz.

For controlling the belt, we chose an Arduino, which is a relatively cheap open source electronics prototyping platform. The communication between the Controller PC and the belt is achieved by a RS-232 serial port. Arduino Uno has a built-in USB-to-serial converter and the electronics are powered by this USB port.

3.2 Software

Our system makes use of the Robot Operating System (ROS) software infrastructure for interprocess communication and message passing [1]. Controller PC sends messages to Arduino on belt, which consists of a bit array for each of the 8 motors. A bit in the array indicates if the motor is going to vibrate or not, during the corresponding time slot of 1/16 seconds. Upon receiving the bit arrays command, Arduino starts executing the bits one by one. Since all the motors are actuated in the main controller loop, the vibrations are synchronous.

4 Vibration Patterns

We define two main classes of vibration patterns depending on the type of intended human motion: directional and rotational. Directional patterns induce a motion towards a direction. Rotational patterns induce a rotation around self, which is intended to control the orientation of the human.

4.1 Directional Motion Vibration Patterns

- **ONE TAP:** a motor is active for 250ms

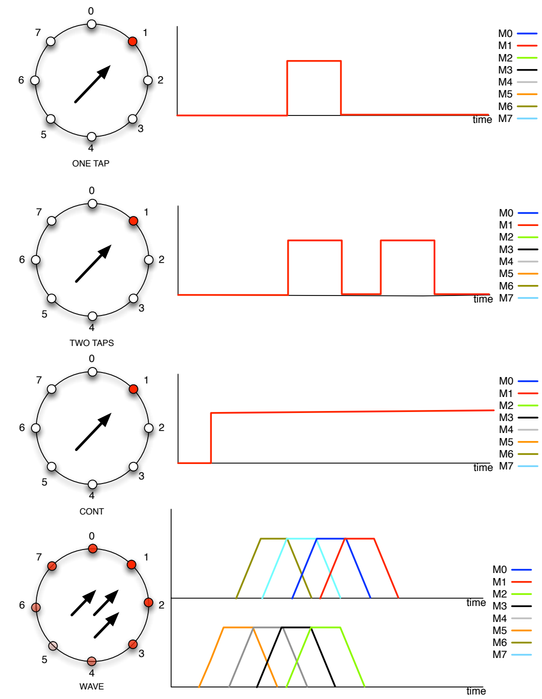

Figure 2: Vibration Patterns for Directional Motion.

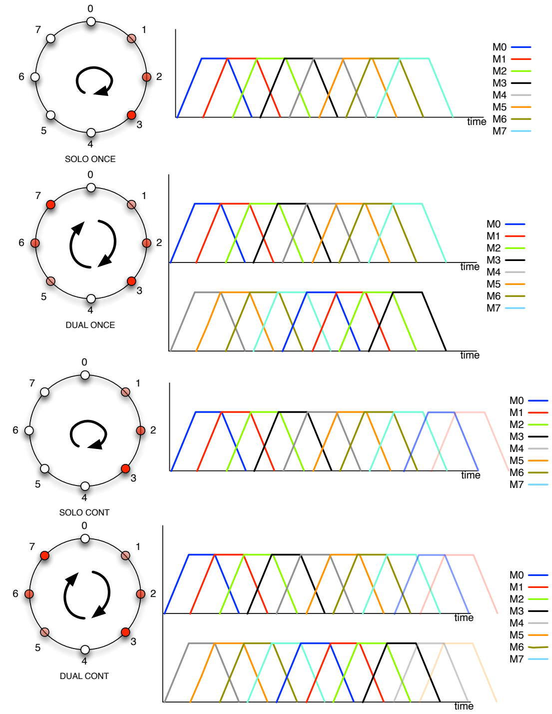

Figure 3: Vibration patterns for Rotational Motion

- **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 feeling that starts from the opposite end of desired direction and ends in desired direction

Figure 2 illustrates all 4 directional patterns for towards northeast cardinal direction (Vibration Motor 1).

4.2 Rotational Motion Vibration Patterns

- **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 3 illustrates all 4 rotational patterns for a clockwise rotation motion.

5 EVALUATION

We evaluated the vibration patterns to find out which ones are better suited for indoor guidance. 15 participants (13 male, 2 female) volunteered in the study and none had experience with tactile belts.

5.1 Procedure

The subject first went through a training for 5 minutes where experimenter applied directional and rotational patterns and told the correct direction/rotation. The subject is instructed to walk randomly in a confined area so that the patterns are tested while the human is in motion. The subject was asked to press a button on a Xbox controller whenever he/she decides on the direction/rotation and then tell the direction (coded 1-8) or rotation (left or right). The experiments consisted of 4 studies:

I) 5 samples from each of the **ONE TAP, TWO TAPS, WAVE** directional patterns are applied in random order.

II) 8 samples from **CONT** directional pattern are applied.

III) 2 samples from each of the 4 rotational patterns are applied.

IV) 2 samples from each of the 4 rotational patterns while a random directional motion pattern is applied in between samples.

Upon the completion of the experiment, the experimenter applied all vibration patterns one by one and asked which directional and rotational pattern the he/she would prefer. Then, a post-study survey is conducted.

We hypothesize that subjects will prefer a one-time signal pattern in I to continuous pattern in II because a long lasting vibration may be annoying to the users. Our second hypothesis is that applying intermediate directional patterns will reduce the recognition rate of rotational patterns. This would be tested by comparing Study III and IV results.

5.2 Measures

3 metrics were used for evaluation:

- **Recognition error (RE):** Angle difference between applied and perceived direction
- **Recognition accuracy (RA):** Percentage of correct recognition
- **Reaction time (RT):** Time between the start of the pattern to the instant the subject decides on an answer. A timeout occurs if subject can not give an answer in 5 seconds.

The post-survey consisted of 4 usability questions on a 10-point Likert scale. Participants were also asked for their preferred directional and rotational patterns.

6 RESULTS

6.1 Directional Patterns

6.1.1 Recognition error and RT w.r.t. pattern type

A total of 344 directional pattern samples were sampled in Studies I and II. Since the directions are discretized, RE from any single test ranges from 0 to 180° with 45° increments. Results with respect to pattern type is in Figure 4.

With a mean RE of 8.4°, **CONT** pattern was the most accurate directional pattern, followed by **TWO TAPS** pattern with 10.6°. Subjects recognized **TWO TAPS** the fastest by an average of 1.13 seconds. **WAVE** pattern performed significantly worse than others on both measures.

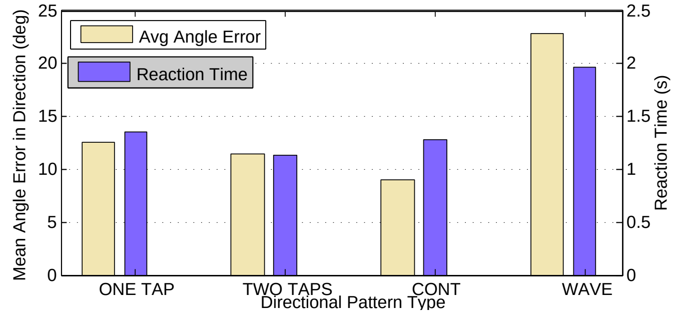

Figure 4: Average recognition error and reaction time of directional patterns.

6.1.2 Recognition accuracy w.r.t. applied direction

The confusion matrix for RA of the applied directions is given in Table 1.

Applied Direction \ Perceived Direction	1	2	3	4	5	6	7	8
1	0.97	0.03	0	0	0	0	0	0
2	0	0.59	0.38	0	0.03	0	0	0
3	0	0.1	0.55	0.3	0.05	0	0	0
4	0	0.04	0.04	0.76	0.16	0	0	0
5	0	0.02	0	0.09	0.81	0.02	0	0
6	0	0.02	0	0.02	0.04	0.84	0.08	0
7	0.02	0	0	0	0	0.26	0.65	0.06
8	0.03	0	0	0	0	0.03	0.14	0.80

Table 1: Confusion matrix of recognition accuracy directional patterns.

Our results show that the recognition accuracy is highly dependent on the applied direction. The subjects recognized the front direction with highest RA (%97) whereas Direction 3 (right) had the least RA (%55).

We expected the directional RA to be symmetrical around the belt, meaning that the accuracy of right and left directions should be equally sensitive to haptic feedback. However, there is at least %10 accuracy difference for all 3 such pairs. This could be due to imperfect alignment of motors in the belt prototype.

6.2 Rotational Patterns

6.2.1 Recognition accuracy and RT w.r.t. pattern type

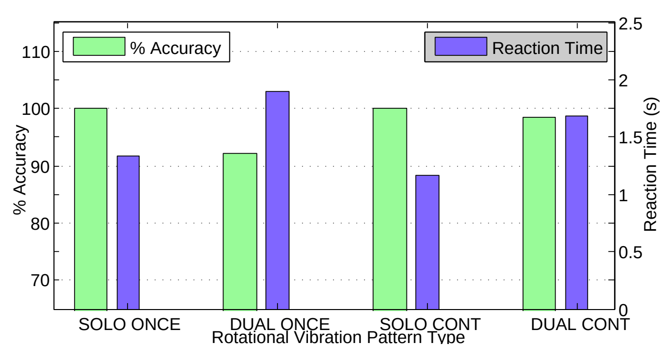

Figure 5: Accuracy and reaction time of rotational patterns. Two measures with different units are plotted together for better visualization.

A total of 256 rotational pattern samples were tested Studies I and II. Results are in Figure 5.

Subjects recognized **SOLO ONCE** and **SOLO CONT** patterns with %100 accuracy, whereas had **DUAL ONCE** had %92 RA. **SOLO CONT** had the least RT by 1.16 seconds. It is interesting to note that this reaction time is almost identical to the directional pattern with the least RT (1.13s).

6.2.2 Effect of intermediate directional patterns

We observed no significant effects of the intermediate directional signals between rotational patterns. The comparison of Study III and IV results is given in Table 2.

	Accuracy		Reaction Time (s)	
	w/ random pattern	w/o random pattern	w/ random pattern	w/o random pattern
SOLO ONCE	%100	%100	1.18	1.49
DUAL ONCE	%93.7	%90.6	1.59	2.19
SOLO CONT	%100	%100	1.19	1.12
DUAL CONT	%96.8	%100	1.70	1.66

Table 2: Recognition accuracy of rotational patterns, conditioned on whether or not a intermediate directional patterns are applied.

6.3 Usability

Subjects thought that it was fairly easy to move while wearing the belt (M=9.2). Most subjects thought that the belt was comfortable (M=8.3) and it fit their waist well (M=8.4). The vibration motors were not found very silent (M=6.8). Actual questions in the post-study survey results are shown in Figure 6.

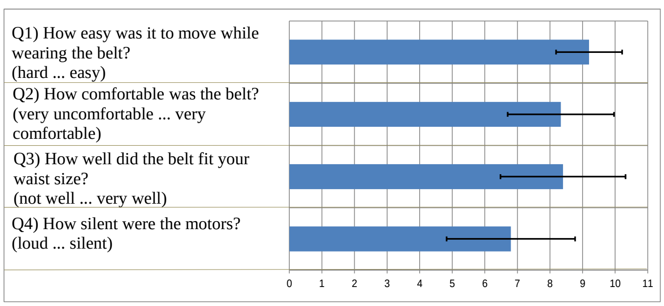

Figure 6: Results of post-study survey.

7 Discussion

Among directional patterns, **TWO TAPS** had the least RT and was found the most intuitive by our usability study. When asked which directional pattern they would prefer, 10 out of 15 subjects chose **TWO TAPS**, 3 chose **CONT** and 2 selected **ONE TAP** and no one chose **WAVE**. Although **CONT** have less recognition error, most subjects preferred **TWO TAPS** probably because people didn't feel comfortable when the vibration lasted for a long time. This supports our first hypothesis that continuous patterns would not be found preferable.

7 out of 15 subjects preferred **SOLO ONCE**, 7 preferred **SOLO CONT** and 1 preferred **DUAL CONT** in the post-study survey. Our results show that subjects rarely made mistakes in recognizing rotations and using a single motor for rotation patterns is preferable over using two motors. Therefore an application may use either of the **SOLO** patterns.

Our second hypothesis did not hold, as we found that application of other pattern between rotational patterns did not deteriorate the recognition rate.

8 Conclusion and Future Work

We successfully demonstrated usage of vibration patterns that induce direction and rotation on a haptic belt interface. Encoding directions is common practice for outdoor navigation assistance but not sufficient in cluttered indoor environments where maneuvering is needed. We believe the incorporating rotational motions will provide better indoor navigation assistance. Our usability studies with 15 subjects showed that applying two intermittent pulses is preferable over continuous vibrations for encoding directions. For rotational motion, patterns that activate a single motor consequently was favored. We also found that intermediate vibrations between tested rotational signals did not affect performance. Post-study survey showed that the tactile belt was found to be comfortable.

An immediate future step of our work will be to integrate the described tactile belt into a mobile robot in order to guide a blind user from one location to another. Our future work will focus on finding safe paths for both the human and robot, and controlling the blind user using the vibration patterns we have evaluated in this work.

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