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Eyes on the Road: Wrist-worn Vibrotactile Navigation System for Cyclists to Reduce Distractions in Traffic

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Abstract. Mobile navigation systems are getting more and more common, and with the rise of smartphones, nearly everyone has access to them via mobile phone apps. Despite the widespread use of mobile apps for navigation, only few solutions for bicyclists exist. These solutions however rely on the user to either look at their phone screen or wear headphones. This poses a risk to the user's safety by taking away attention from the road conditions. Prior studies have suggested that a vibrotactile navigation system can perform similarly to already existing visual and auditory solutions. Such a system also seems to be less distracting than existing ones. This study presents a working prototype than can be used to navigate urban environments on a bicycle.

Keywords: Cyclist, Navigation System, Wayfinding, Wearable Vibrotactile Interface, Tangible Interaction Design

1 Introduction

Smartphones are becoming more and more common in recent times, with almost everyone having one. This opens the door for using them as navigation devices when commuting through cities in cars, on foot or on bicycles. The most common way of showing the route to the user is through visual instructions, showing a map and the route on the phone's screen. Another widespread modality is using audio instructions to inform the user of when and where to turn. When used while riding a bicycle, using the visual method is suboptimal, as it requires a special handlebar mount for the phone. In the case of bike sharing services, where shared bikes don't have a phone mount, the user needs to always hold the phone in their hands. Even with a mount, having to look at the screen frequently can distract the rider from possible traffic hazards, leading to an unsafe ride. Utilizing spoken instructions requires wearing headphones, which is also dangerous, as the rider might not hear other vehicles or pedestrians approaching. For this reason, it would be advantageous to have a system that uses tactile feedback to convey navigation instructions to the rider. Tactile instructions have been found to be not only effective in guiding the user to their destination, but they are also less distracting than other modalities [1].

This study therefore aims to design and build a system that conveys navigation instructions to bicycle riders through tactile vibration feedback. The wearable device will aid its user with their wayfinding process in an unintrusive way. By not blocking the visual or auditory channel the system aims to reduce the amount of attention needed for wayfinding allowing for better situational awareness. The system will aim to improve traffic safety for bicyclists by adopting a tactile approach to delivering navigation instructions, therefore allowing them to focus on road and traffic conditions. The specific characteristics of bicycle movement will be taken into consideration and the navigation will be tailored to this mode of transportation.

2 Background and related work

2.1 Wayfinding and Spatial Cognition

Wayfinding was defined by Downs and Stea in 1977 as someone's movement from one point to another point and the solving of problems resulting from this [2].

In their paper about a tactile wayfinding system, Heuten et.al. [3] describe four steps that make up the process of wayfinding, including 1) Orientation in the environment; 2) Choosing a route; 3) Keeping on track; and 4) Recognizing that the destination has been reached. In the context of bicycle navigation, this means there needs to be a way for the user to find themselves on a map, input a destination (choosing a route can be done by the app), being aware of the route during the trip, and getting a signal if they reached their destination.

Spatial cognition is another aspect of wayfinding. It deals with acquiring and recalling knowledge about one's spatial environment. It can be divided into three types. The first type of spatial cognition is called landmark knowledge. Knowing about the position of certain landmarks helps a person orient themselves in an environment. The name of the second type is route knowledge, which consists of the ability to recall specific routes between two points. Finally, there is survey knowledge, which refers to having a global frame of reference, allowing for example for shortcuts to be taken, because the person is not constrained to single routes [3].

By using a nonintrusive way of navigation, the tactile navigation system aims to increase spatial knowledge compared to visual and auditory navigation systems. A user study by Steltenpohl and Bouwer evaluating their tactile navigation system finds that participants using their system have better recollection of pictures taken along the route than those using a visual system [1]. This could lead to a better landmark knowledge when using the tactile system.

2.2 Use of Mobile Navigation

Mobile GPS navigation devices have become increasingly popular in recent times. In the past, people who wanted to make use of GPS navigation had to buy a separate device. Through the rise of smartphones, however, GPS navigation has become accessible to a broad range of people through mobile phone applications like Google Maps or Waze. Almost all people have used one of these navigation apps. According to a survey conducted in 2015, 90% of adults in the United States of America have used a navigation app at least once before [4].

However, these applications are mostly focused on people driving cars very few exist that fulfil the needs of people riding bicycles, such as finding routes that are safe or pleasant to take as a vulnerable traffic participant. With bicycles becoming increasingly common amongst daily city commuters, this is becoming a problem, as road safety is important.

The most used navigation app is Google Maps. The app's main mode of navigation is an audiovisual one, with a map displaying on the screen on which the route and the user's current position are marked. Turn by turn instructions are also displayed on screen as well as given via spoken instructions. Google Maps' navigation can also be used with the screen turned off, in which case the spoken turn by turn instructions are sufficient for navigation. The user can also opt to turn off the spoken instructions completely, using only the visual navigation cues [5].

One app that is specifically designed for bicyclists is Bike Citizens. Bike Citizens allows for visual navigation as well as turn-by-turn auditory instructions. Users can choose to take the fastest or a more pleasurable route. The app utilizes their users' GPS movement data to find shortcuts and fast routes, that may not be accessible to cars. This movement data is voluntarily provided by users, who can opt-out of tracking their movements. The app itself is available on the Apple App store and Google Play for free, but users have to pay for accessing each cities' individual maps. One region can be unlocked by using the app to ride a certain distance within the first trial period [6].

2.3 Safety Considerations

Visual navigation systems require the user to look at their mobile phone screen relatively often, which takes their attention away from road conditions and can be distracting. In the study conducted by Haska Steltenpohl and Anders Bouwer, bicyclists using visual navigation spent 28% of their time looking at their mobile phone screens. Using a mobile phone while riding a bicycle has been found to be detrimental to spatial awareness, leading to potential safety risks [1].

Another factor contributing to the safety issues with using visual navigation systems on bicycles is that a bike mount for the phone is pretty much a requirement, as the rider would otherwise have to always hold their phone in their hand, steering and braking with one hand only. Many bicycles don't have such mounts, however. Bike sharing bikes, which are nowadays deployed by many cities, often come with a basket and a bell, but typically without a phone mount.

Using turn-by-turn navigation instructions given via headphones circumvents the need to use a phone mount and look at the phone while biking, however the use of headphones can also be dangerous. In a 2011 study, Dick DeWaard et.al. found that listening to music via headphones worsened bicyclists' response time to auditory signals and led to an overall worse auditory perception [7].

2.4 Tactile Feedback

Jones and Sarter (2008) found that of the four available ways to provide information through vibration (frequency, intensity, location, and duration), location and duration of the stimulus are the most promising ones [8]. Duration can mean either length of a single vibration, or speed and number of multiple pulses of vibration. When using position of tactors to convey information, the spacing of the vibration motors must be sufficiently large, otherwise the correct identification rate drops significantly.

A tactile illusion that can be used to convey information using position is called “sensory saltation”. When actuators are vibrating in succession (e.g., three pulses on first motor, then three pulses on second), the vibrations are not perceived as independent events, but rather as one, the vibration seems to hop from place to another. The interstimulus interval should be between 20 and 300ms, with 50ms being the optimal interval length [8]. This illusion could be used by a tactile navigation system to convey direction of the upcoming route to the user by using multiple motors in different locations and letting the route hop along them.

In their paper about tactile feedback, Bolton et.al. identify the wrist as a good location for tactile feedback, as it is already well established and widely used in the form of smartwatches [9]. This points to the wrist or forearm being a suitable location for the navigation system.

2.5 Tactile feedback in navigation

The use of tactile feedback for navigating an urban environment has been explored already by many researchers. Several studies have been conducted developing and testing wearable tactile feedback for indoor as well as outdoor navigation, utilizing different body parts for placement of the tactile devices, as well as different ways of communicating information. Possible locations for tactile devices include the waist, wrists, head, or feet [1][10][11][12]. Tactile feedback has also been found to be effective and useful as an assistive technology for visually and auditory impaired pedestrians [12][13]. Though most studies focus on pedestrians, there are some that focus on navigation in the context of bicyclists.

One of these studies is Vibrobelt by Haska Steltenpohl and Anders Bouwer. Their bicycle navigation system uses a set of vibration motors located on a belt that is worn around the waist. The belt conveys turn-by-turn instructions by vibrating in the direction of the next turn. It also always shows the direction of the endpoint, regardless of the user’s position on the route. The system proved effective compared to visual navigation. Participants did not all like the endpoint information, as it was perceived as confusing rather than helpful by some. Other findings from this study, that are useful for the development of future navigation systems, are that participants liked to get feedback that shows the application is still active during the navigation and that they wished for an overview of the route like the one a visual system provides [1].

The need for a route overview is also addressed by Luca Chittaro, who suggests including a map in any navigation system. He notes that the wayfinding process often includes a planning phase, for which a map is a necessary tool which the user needs.

For this reason, a multimodal solution is desirable, and most probably include a visual component, as displaying a map in a non-visual way proves to be rather difficult [14].

GentleGuide is a system designed by S. Bosman et.al., that is intended for indoor pedestrian navigation. It uses vibration motors placed on the user's wrists that give instructions to turn left, right, when to turn around (wrong direction), and when the destination is reached. This method for giving instructions was found to be effective and easy to understand during a user study the researchers conducted. Through iterative design, the researchers found out that wearing one output device on each wrist is more intuitive to use than only using a single device [10]. Though this study was tested only indoors and with pedestrians, it is reasonable to assume that using two devices rather than one is beneficial also for tactile bicycle navigation.

NaviRadar by Sonja Rümelin, Enrico Rukzio, and Robert Hardy uses only a mobile phone to provide vibration feedback. Directions are given using a radar sweep analogy, vibrating at the current walking direction and the direction of the next turn. The researchers compared different ways of coding the information on direction and distance using only one device. After considering different combinations of duration, rhythm, and intensity, they decided to use rhythm and intensity of vibration for their prototype. They found their navigation method to perform comparably well to audio navigation. One finding from their study that is relevant to this research is that rhythm paired with intensity is the most effective way to code distance using vibration feedback [15].

2.6 Design Implications

Both visual and audio-based navigation systems introduce some level of distraction from what is happening on the road, leading to potential safety issues. Tactile feedback does not do so and has been shown to be equally effective in supporting users during the process of wayfinding and leading them to their destination. A wearable interface makes the most sense for tactile feedback, because riding a bicycle requires the use of both hands. Through the literature review, several design suggestions were identified. The first is, that when using turn-to-turn instructions, the forearms provide a suitable location for this wearable interface, as users are through the prevalence of smartwatches already accustomed to receiving vibration feedback from there. Furthermore, it is better to wear two devices, one on each arm, rather than just one. The two pieces of information that need to be communicated to the user, distance to and direction of the next turn, can efficiently be coded using location, frequency and pattern of the vibration feedback. To make the wayfinding process as easy as possible, the navigation system should give some information on future turns. For this, a tactile illusion called "sensory saltation" can be employed. To produce this illusion, the system needs to consist of several vibration motors in different locations. Using a mobile app with a visual map interface similar to Google Maps to select a route allows the user to get a quick overview of the route before starting their trip. The signals given to the user on arrival at the destination, as well as the route previews need to be clearly distinguishable from regular turn instructions.

3 Prototype Design

The navigation system consists of three parts: two wrist-worn vibration devices and a mobile phone app. The vibration devices receive navigation instructions from the phone app via a Wi-Fi connection and translate them into vibration patterns to be interpreted by the user. The information flow is illustrated in Fig.1.

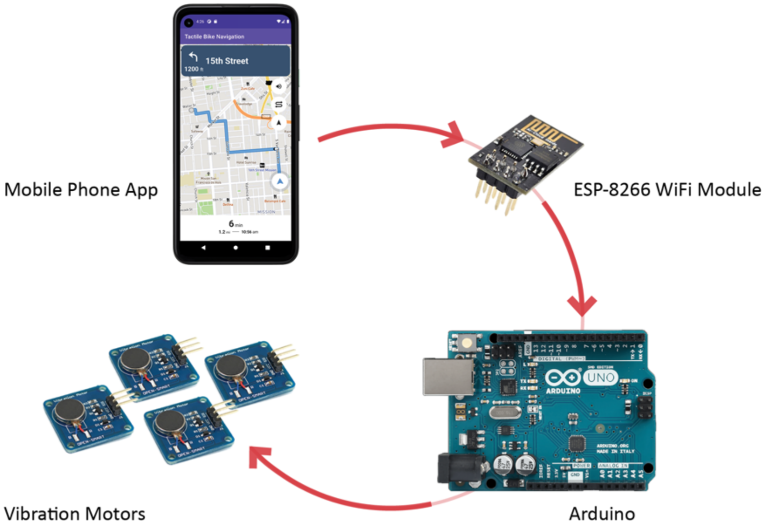


Fig. 1. System information flow

3.1 Wearable Devices

The wearable part of the system has two identical vibration devices. They each include an Arduino [16] with an ESP-8266 Wi-Fi module and two vibration motors and are powered by 4 AA batteries. The Arduino receives turn-by-turn instructions from the mobile phone app via Wi-Fi and converts them to vibration patterns to send to the two motors. The two vibration motors are located on opposite sides of the user's forearm: one is near the wrist and one near the elbow. The distance between the two motors is deliberately made as large as possible to facilitate distinguishing between a vibration of the front motor and a vibration of the back motor. The individual components are mounted on a cardboard sleeve that is worn on the user's forearms and fastened with Velcro straps as illustrated in Fig.3. Fig.2 shows the completed physical prototype. Cardboard was used for developing this prototype, however in the future a flexible fabric sleeve should be used for greater comfort and better durability. The cardboard prototype is also rather big, which is not something generally desired in wearable interfaces. Future iterations of this navigation system should improve on this aspect, by focusing on making the devices easy to put on and take off, and by making them smaller and generally less noticeable. Because the navigation devices would not be worn all day, but only during trips, it should be fast and easy to put them on and take them off. For better portability while not in use, they should also be as small as possible, so that they can fit in a small bag. The wearables should also be more durable and water-resistant, as bicyclists are generally exposed to the elements during their rides, and the sleeves could get wet or dirty easily.

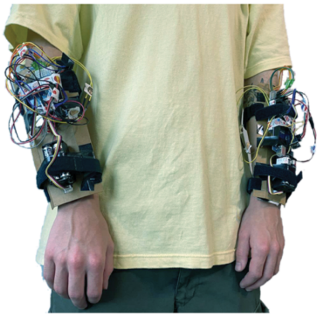


Fig. 2. Wearing the prototype

3.2 Mobile App

The mobile phone application makes use of the Mapbox API to calculate routes and generate turn-by-turn navigation instructions. This API is free to use, highly customizable and can be integrated with the prototype easily [17]. The entire navigation process is handled by Mapbox and only the instructions are forwarded to the wearable devices. The mobile phone, which the app is running on must have an activated Wi-Fi hotspot feature for the parts to be able to connect to each other. Wi-Fi was chosen over Bluetooth, because it allows the app to send messages to both wearables, while Bluetooth allows only one-to-one connections. The mobile app interface can be seen in Fig.3.

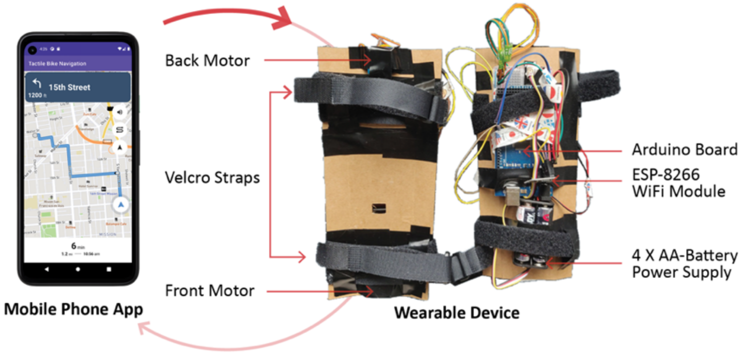


Fig. 3. Finished Prototype: Mobile app interface and wearable devices.

3.2 Functionality

The mobile application checks the user’s position along the route and constantly calculates the current distance to the next turn. Based on this distance, the app then forwards different commands to the two wearable devices. Fig.4 depicts an application flowchart detailing the navigation algorithm, according to which the instructions are given to the user.

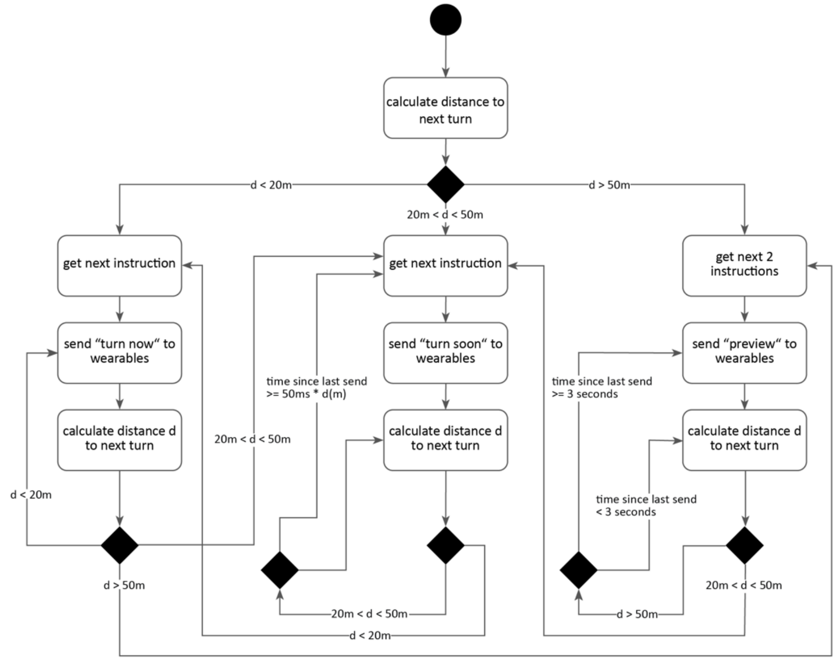


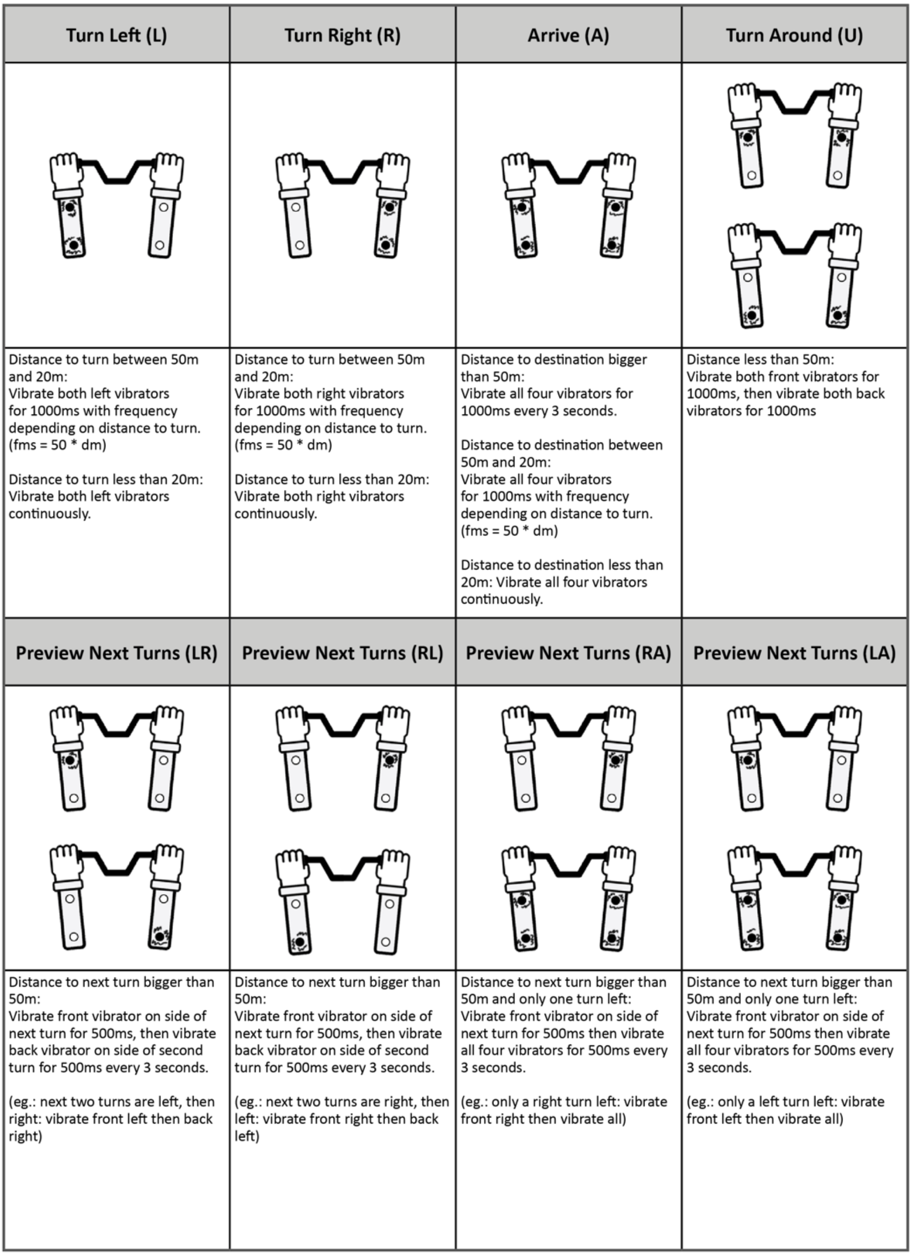
Fig. 4. Application flowchart.

know the system is still on and they are still on track. This should ideally work to reduce uncertainty about the route ahead and help with anticipating upcoming maneuvers.

If the distance is between 50m and 20m (maneuver upcoming), the motors on the side corresponding to the direction of the turn vibrate periodically. Vibration frequency is calculated as a function of the distance to the turn ($f_{ms} = 50 * d_m$). This has two purposes: it gives the user time to prepare for the upcoming turn, and also communicates the distance to said turn.

Once the distance to the next turn gets smaller than 20m, the sleeve vibrates continually to indicate a necessary maneuver. The vibration pattern is designed to be very noticeable, so the user does not miss or misinterpret the instruction.

If the user arrives at their destination, all motors vibrate, followed by a vibration of the motors on the side of the destination. A U-turn is indicated by first vibrating the two front motors and then the two back motors. The vibration patterns for all the instructions listed above are also illustrated in Fig.5.



Turn Left (L)	**Turn Right (R)**	**Arrive (A)**	**Turn Around (U)**
Distance to turn between 50m and 20m: Vibrate both left vibrators for 1000ms with frequency depending on distance to turn. (fms = 50 * dm) Distance to turn less than 20m: Vibrate both left vibrators continuously.	Distance to turn between 50m and 20m: Vibrate both right vibrators for 1000ms with frequency depending on distance to turn. (fms = 50 * dm) Distance to turn less than 20m: Vibrate both right vibrators continuously.	Distance to destination bigger than 50m: Vibrate all four vibrators for 1000ms every 3 seconds. Distance to destination between 50m and 20m: Vibrate all four vibrators for 1000ms with frequency depending on distance to turn. (fms = 50 * dm) Distance to destination less than 20m: Vibrate all four vibrators continuously.	Distance less than 50m: Vibrate both front vibrators for 1000ms, then vibrate both back vibrators for 1000ms
Preview Next Turns (LR)	**Preview Next Turns (RL)**	**Preview Next Turns (RA)**	**Preview Next Turns (LA)**
Distance to next turn bigger than 50m: Vibrate front vibrator on side of next turn for 500ms, then vibrate back vibrator on side of second turn for 500ms every 3 seconds. (eg.: next two turns are left, then right: vibrate front left then back right)	Distance to next turn bigger than 50m: Vibrate front vibrator on side of next turn for 500ms, then vibrate back vibrator on side of second turn for 500ms every 3 seconds. (eg.: next two turns are right, then left: vibrate front right then back left)	Distance to next turn bigger than 50m and only one turn left: Vibrate front vibrator on side of next turn for 500ms then vibrate all four vibrators for 500ms every 3 seconds. (eg.: only a right turn left: vibrate front right then vibrate all)	Distance to next turn bigger than 50m and only one turn left: Vibrate front vibrator on side of next turn for 500ms then vibrate all four vibrators for 500ms every 3 seconds. (eg.: only a left turn left: vibrate front left then vibrate all)

Fig. 5. Vibration patterns corresponding to the upcoming navigation.

The navigation system aims to improve the previously developed ones mentioned in the literature review by combining the aspects that were found to be intuitive and desirable, while omitting the disliked ones. It also introduces the concept of the route preview shown through spatial cues on the forearms. This preview projects a simplified tactile map of the upcoming route onto the users' forearms, providing an intuitive way for the user to orient themselves.

If the distance to the next turn is bigger than 50 meters (no maneuver currently needed), the next two turns are displayed on the sleeves as a preview, to let the user

4 Field Test

A field test was conducted by the researcher (system developer) to test the prototype before conducting the user test with the recruitment of the public. The test took place on the campus grounds of National Taiwan University in Taipei, and Taipei's YouBikes were used (Fig.6). Multiple routes were navigated by the researcher himself to adequately test all features of the navigation system. This field test serves only as a pilot study confirming the general functionality of the new system. It should show if the prototype reliably gives instructions and highlight any big problems that can easily be identified. For reliably testing the efficiency and usability of the system full user study needs to be conducted in the future.

The prototype was found to be generally effective in providing navigation instructions, however some adjustments were made following the field test. The routes navigated are shown in Fig.7, with the locations at which the problems occurred marked in different colors.

The first problem identified was that it was hard to distinguish between route previews and actual instructions, because the two types of feedback were very similar. This led to uncertainty especially on long stretches without turns. The points where this problem occurred are marked in the illustration in yellow color. To fix this issue, the commands were changed so the vibrations for turn instructions are now 1000ms long, which is twice as long as the ones for previews (500ms).

The second point of confusion was noticeable right before turns. The old command could be a little unclear sometimes, because the vibration suddenly stopped right before a turn. Occurrences of this are shown in blue color on the illustration. The "turn now" command was changed from vibrating for 3 seconds with 5 second pauses to continuous vibration to improve clarity when a turn is needed.

Distances for the turn commands were found to be a bit too short, which lead to several times where a turn was almost missed. The directions were adjusted to start earlier, so they start early enough for the bicyclist to prepare for the upcoming turn, but late enough that they can not be misinterpreted. Points where turn commands came too late are marked on the map in red color.

At one point, one of the connectors on the Arduino came loose and had to be reconnected. This is marked in pink on the map.

Overall, the field test proved successful in identifying the weak points in the prototype design and helped with understanding ways to fix these issues.

Fig. 6. Field test at NTU campus.

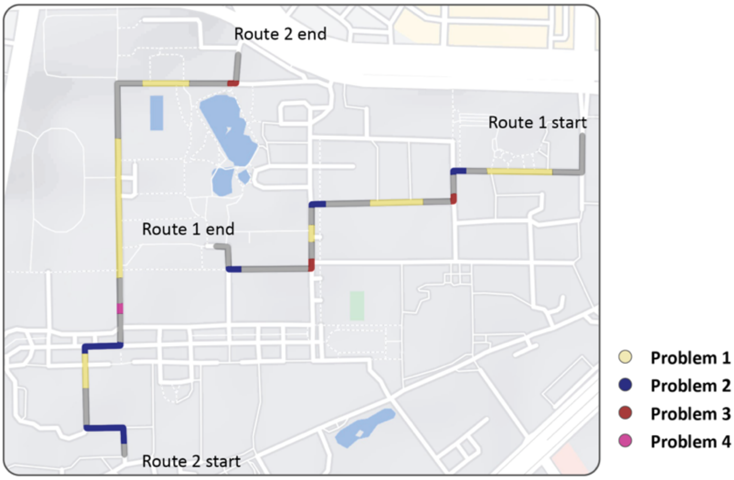


Fig. 7. Field test routes.

5 Conclusion and Future Work

In this paper, we have introduced a tactile system that allows bicyclists to navigate unknown environments without occupying their vision or hearing. The system is designed with the specific needs and requirements of bicyclists in mind. Intuitive and easily understandable instructions are given to the user via vibration feedback. Based on findings from the literature review, the system is expected to work as well as currently existing navigation solutions, such as Google Maps.

This research leaves much room for future work. As a next step, the prototype should be tested in a user study with multiple participants. Such a study could determine the efficiency of the tactile navigation system compared to visual or auditory ones. Factors to test for include speed of navigation, error rate and number of accidents. The impact of using the new system on spatial knowledge and route recollection could be measured in a separate study.

We hope that this system will leave the user free to focus their attention on the road and traffic conditions. By leaving the visual and auditory channels out of the navigation process, the user can keep watching and listening to traffic while receiving turn instructions. The effect this has on mental load and on traffic safety needs to be measured in a future study.

Furthermore, the wearable part of the system in its current form is not very desirable. It needs to be improved to be smaller, more durable and easier to put on and take off to be suitable for use under real road conditions.

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