DroneNavigator: Using Leashed and Free-Floating Quadcopters to Navigate Visually Impaired Travelers

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ABSTRACT

Although a large number of navigation support systems for visually impaired people have been proposed in the past, navigating through unknown environments is still a major challenge for visually impaired travelers. Existing systems provide navigation information through headphones, speakers or tactile actuators. In this paper, we propose to use small lightweight quadcopters instead to provide navigation information for people with visual impairments. Using a leashed or free-floating quadcopter, the user is navigated by the distinct sound that the quadcopter emits and a haptic stimulus provided by the leash. In a user with 14 visually impaired participants, we compared leashed quadcopter navigation, free-floating quadcopter navigation, and traditional audio navigation. The results show that compared to audio navigation, participants navigate significantly faster with a free-floating quadcopter and make fewer navigation errors using the quadcopter navigation methods.

CCS Concepts

•**Human-centered computing → Empirical studies in HCI; Accessibility systems and tools;**

Keywords

Navigation Aid; Visual Impairments; Quadcopter; Drones

1. INTRODUCTION AND BACKGROUND

In 2012, there were 285 million persons with visual impairments, including 39 million persons that were considered blind [17]. People with visual impairments face a number of challenges in daily life. Especially being able to navigate through known and unknown environments becomes challenging without vision. Today, the most common tools used by persons with visual impairments are the white cane and guide dogs. While both offer great support for fine navigation, they do not provide support for gross navigation - medium-term strategies including orientating, reaching waypoints, and following a path along a route.

Figure 1: A user is using a leashed quadcopter to navigate in unknown indoor environments. The user can perceive the directions both by hearing the auditory feedback that the quadcopter naturally emits and by feeling the tactile feedback on the handle.

A number of electronic mobility aids for people with visual impairments are commercially available (see Roentgen et al. for an overview [19]). An even larger number of approaches and systems has been proposed by previous research. Previous research focused on providing navigation information through auditory (e.g. [10, 16, 24]) or tactile feedback (e.g. [2, 8, 9]). Auditory feedback is typically provided through headphones [10] or bone-conduction headphones [24]. Using 3D audio to display waypoints can further improve blind users' navigation performance [4, 13]. Tactile feedback is provided by diverse systems and through various body parts. Common approaches include smartcanes [5, 23], tactile belts [9, 22], wheeled robots on a leash [15], and tactile vests [12, 21].

A novel approach that has recently been proposed is providing navigation information using small lightweight quadcopters [3, 14]. The work is mainly inspired by work on the use of quadcopters as companions for outdoor activities [6, 18, 20] and combining tactile and auditory modalities for navigating visually impaired travelers [11]. Similar to more traditional auditory navigation systems that use 3D audio to provide navigation information, quadcopters can provide

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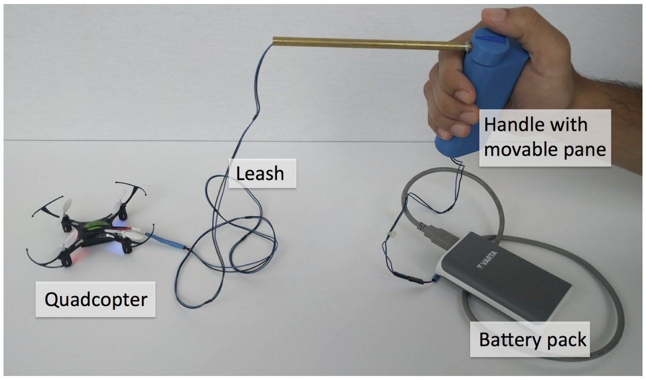


Figure 2: Our leashed quadcopter navigation prototype. The quadcopter is connected to a handle using an electric wire which acts as a leash. The handle has a movable pane with a 3D-printed arrow on top. This arrow can convey a direction as the leash lets the arrow always point into the direction of the quadcopter. Further, the handle is connected to an external USB battery pack, which can be carried by the user.

directional information through their position relative to the user and the sound they naturally emit. This was also used by previous work to guide two blind runners [1] in a Wizard of Oz study. Previous work, however, did not study if quadcopters can provide helpful information to blind users in everyday navigation tasks.

In this paper, we investigate the potential of quadcopters as navigation support for persons with visual impairments (see Figure 1). We extend previous work on quadcopters for visually impaired persons by providing tactile feedback in addition to the auditory feedback provided by the quadcopter's rotors. Through a leash that connects the user and the quadcopter the user can not only hear but also feel the direction of the quadcopter. In a study with 14 visually impaired participants, we compared leashed quadcopter navigation, free-floating quadcopter navigation, and traditional audio navigation. We show that the quadcopter-based approaches enable participants to significantly navigate faster and make fewer navigation errors.

2. DRONENAVIGATOR

We developed two prototypes of a multi-modal feedback system that provides navigation information for visually impaired users. The first prototype is a free-floating quadcopter which uses spatial audio to guide a visually impaired traveler. The second prototype uses a leashed quadcopter to combine advantages of auditory and tactile systems. Previous work typically provides spatial audio by positioning and rendering a virtual 3D sound relative to the user's position (e.g. [4, 13]). The resulting audio signal is conveyed through speakers, headphones, or bone conduction headphones. Instead, of using a virtual sound source for providing directional information, we provide directions through an actual sound source that can be moved in 3D. Therefore, our two prototypes use a quadcopter that can be freely moved in space (see Figure 1).

For both prototypes, we decided to use a small and lightweight quadcopter to ensure safe operation even in crowded environments. Therefore, we use an Eachine H8 Mini quadcopter, which is 13.5×13.5cm wide, 2.8cm high, and weighs 20 grams.

2.1 System: A Free-Floating Quadcopter

Similar to previous work [3], our free-floating prototype is an unmodified quadcopter, which provides auditory information through the sound the quadcopter naturally emits. We use a Wizard of Oz approach to fly the quadcopter at a distance of 1m in front of the participant. The quadcopter is flown at an altitude similar to the participants shoulders above the ground. If there are stairs up or down along the route, the quadcopter will change its height indicating that a change in altitude will follow soon.

2.2 System: A Quadcopter on a Leash

Our second system extends the prototype by Avila et al. [3] and makes it more durable by mounting a leash on the quadcopter. Using a leash has two main benefits. The first benefit is, that the leash is connecting the visually impaired traveler with the quadcopter, which creates a tactile feedback. Considering tactile feedback approaches, previous work relied on using multiple vibrotactors. Directional information can be provided by spatially arranging a discrete number of vibrotactile actuators (e.g. [9, 22, 23]. In contrast, we enable the user to also feel the position of the quadcopter to provide tactile feedback. To increase the tactile experience, we designed a handle that converts the pulling of the quadcopter into an appropriate tactile stimuli for the visually impaired traveler. To achieve that, we extended a handle with a pane, which is rotatable and has a 3D printed arrow on its tip (see Figure 2). Further, the tip of the handle is connected to a small pipe, which converts the direction in which the leash is pulled by the quadcopter into a rotation that is perceivable by the visually impaired traveler.

The second benefit of the leash is that it provides a connection to the quadcopter, which enables us to power it using an external battery. To extend the quadcopter's flight duration, we integrated an additional battery with $10,000mAh$ into the handle. The additional battery extends the flight time from 5-8 minutes to approximately 5 hours. Using an external battery further enables us to remove the original battery from the quadcopter, which compensates for the additional weight of the leash. For the leash, we use a standard insulated electric wire which is 1m long. Similar to the free-floating quadcopter navigation system, the leashed quadcopter also flies at an altitude similar to the participants shoulders and also indicates upcoming stairs using a change in altitude.

3. EVALUATION

For evaluating the two proposed quadcopter guidance approaches, we conducted a study with 14 visually impaired or blind participants. We compared the two approaches to state of the art audio navigation. In the following, we describe the method and the results of the study.

3.1 Design

The experiment follows a repeated measures design with the used guidance approach as the only independent variable with three levels (free-floating quadcopter, leashed quadcopter, and audio navigation). As dependent variables, we measure the Task Completion Time (TCT), the number of errors, and the Raw NASA Taskload Index (RTLX) [7]. To minimize learning effects we used 3 equally long and equally difficult routes as navigation task. We counterbalanced the order of the guidance approaches and counterbalanced the used routes according to the Balanced Latin Square.

3.2 Apparatus and Navigation Routes

The study compares the two quadcopter-based systems, to an audio navigation baseline. We designed the audio navigation according to state-of-the-art navigation systems and enhanced them with feedback about the current state. This results in three navigation instructions: *"continue straight"*, *"turn left"*, and *"turn right"*. The instructions to make a turn were presented 2 meters before the turn had to be made. Further, the *"continue straight"* instruction was presented every 5 meters. To ensure a perfect triggering of the auditory instructions according to the participants position, all instructions were triggered manually by a Wizard of Oz. Inspired by related work [25], we chose to present the auditory navigation instructions on bone conduction headphones in order to be able to additionally perceive the sound from the environment. For our study, we were using the Aftershokz Sportz M3[1] bone conduction headphones, which are connected via Bluetooth to a smartphone. The Wizard of Oz was carrying the smartphone and triggering the audio instructions using the Custom Soundboard[2] app.

We chose to conduct our experiment in an indoor navigation context. Therefore, we designed three routes that were equally long and equally difficult. The length was approximately 60m for each route. All routes contained a staircase with the same number of steps on the staircase and entering a door with the width of 95cm. Further, we made sure that all routes contained a reverberating and dull sounding environment. We made sure that there were no passersby when conducting the study. Therefore, the routes can be seen as a controlled study environment. Other type of routes might provide additional insights.

3.3 Procedure

After welcoming the participant and explaining the purpose of the study, we informed the participant about the data, which we collect during the study, and asked for a written consent. Then, we collected the demographics of the participants and gave a general introduction about the three navigation systems that we are using in the study. Due to counterbalancing, the order of the conditions was different across the participants. Before starting the first condition, we gave the participant some time to get familiar with the navigation system. Once the participant felt familiar, we started the experiment at a defined starting point of the current route. We instructed the participant to start following the instructions that are provided by the navigation system. However, we told them to additionally use their white cane. After the experimenter started the study, the TCT and the number of navigation errors were measured. The TCT is measured from the starting point to the end point of the route. As a navigation error, we counted when the participant was walking three or more steps with more than a 45° offset away from the target position. The errors were independently counted by two experimenters, who were walking behind the participant in a distance of 1m in all three conditions. For all conditions, the navigation instructions were triggered by one of the two experimenters, who was acting as a Wizard of Oz. After reaching the end position of the route, we asked the participant to fill an RTLX questionnaire. We repeated this procedure for the remaining two conditions. After all conditions, we were asking the participants for their opinion about the presented navigation systems through a semi structured interview.

[1]http://aftershokz.com/products/sportz-m3

[2]https://play.google.com/store/apps/details?id=ix.com.android.CustomSoundboard&hl=en

3.4 Participants

We invited 14 visually impaired participants for our user study. Thirteen of the participants were completely blind and one participant had a remaining vision of 5%. All of the participants were white cane users. The participants were aged from 21 to 74 years ($M = 51.69$ years, $SD = 15.09$ years). None of the participants was familiar with the quadcopter guidance systems, nor were they familiar with the routes that we used in our study. We recruited the participants using the first author's personal contacts to a social group for visually impaired and blind persons. As participating in our user study was on a voluntary basis, we did not compensate the participants for taking part in our study. The runtime of the study was approximately 45 minutes.

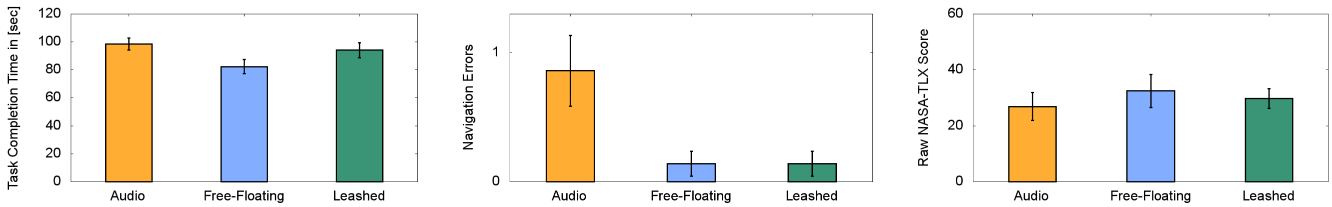
3.5 Results

We statistically compared the TCT, number of navigation errors, and the RTLX score using a one-way repeated measures ANOVA. Mauchly's test showed that the sphericity assumption was violated for the number of navigation errors ($\chi^2(2)$=10.208, p=.006). Therefore, we used the Greenhouse-Geisser correction to adjust the degrees of freedom (ϵ=.636 for the number of navigation errors). Further, we were using a Bonferroni correction for all post-hoc tests.

First, we analyzed the TCT, i.e. the time that the visually impaired travelers took to complete the routes (see Figure 3a). The participants were fastest using the free-floating quadcopter navigation ($M = 82.29$ sec, $SD = 18.97$ sec), followed by the leashed quadcopter ($M = 94.07$ sec, $SD = 20.58$ sec), and the audio navigation ($M = 98.57$ sec, $SD = 16.32$ sec). A one-way repeated measures ANOVA revealed a significant difference between the approaches, $F(2, 26) = 4.41$, $p = .022$. The post-hoc tests revealed a significant difference between the free-floating quadcopter and the audio navigation ($p < 0.05$). The effect size estimate shows a large effect ($\eta^2 = .254$).

When analyzing the number of navigation errors that the participants made during the study (see Figure 3b), the audio navigation led to the highest number of navigation errors ($M = .86$ errors, $SD = 1.03$ errors), followed by the free-floating quadcopter and the leashed quadcopter, which both had exactly the same average number of navigation errors ($M = .14$ errors, $SD = .36$ errors). A one-way repeated measures ANOVA revealed a significant difference between the approaches, $F(1.272, 16.53) = 6.25$, $p = .021$. The post-hoc tests revealed a significant difference between the audio navigation vs. the free floating quadcopter and the audio navigation vs. the leashed quadcopter (all $p < 0.05$). The effect size estimate shows a large effect ($\eta^2 = .325$).

Finally, considering the perceived workload that the participants experienced using the different navigation systems measured using the RTLX score (see Figure 3c), the participants rated the audio navigation as inducing the least



(a) (b) (c)

Figure 3: The results of the user study. (a) The Task Completion Time in seconds that was needed for each navigation method. (b) The average amount of navigation errors. (c) The perceived cognitive workload measured using the RTLX score. All error bars depict the standard error.

workload ($M = 26.93$, $SD = 18.83$), followed by the leashed quadcopter navigation ($M = 29.79$, $SD = 13.34$), and the free-floating quadcopter navigation ($M = 32.5$, $SD = 22.01$). A one-way repeated measures ANOVA could not reveal a significant difference between the conditions ($p > 0.05$).

In the semi-structured interview, we asked the participants which navigation system they considered being the best one in the study. 8 participants preferred the auditory navigation. This was followed by 4 participants who preferred the free-floating quadcopter navigation and 2 participants preferring the leashed quadcopter.

Participants' preferences for the auditory navigation was also visible in the answers to the questions of the semi-structured interview. However, the participants were suggesting to improve the auditory navigation as they found it was too *"coarse when giving the directions"* (P8) and therefore is *"inaccurate"* (P1, P3, P4, P8, P14). Also they would have liked to *"receive more accurate directions - e.g. in three meters turn to two o'clock"*. Compared to the two quadcopter conditions, participants mentioned that *"the auditory navigation condition is not continuous"* as feedback was not always present like in the quadcopter conditions.

Considering the free-floating quadcopter, the participants liked that they did not have to carry a device with them at all times. P11 stated that *"the free-floating quadcopter is great because I can focus completely on my white cane"*. However, other participants were skeptical because *"[they are] not sure if the free-floating quadcopter navigation will work in noisy environments"*. Two participants stated that on the one hand, they could *"precisely tell the position of the quadcopter but [are] having a hard time estimating the distance to the quadcopter"*. Some participants did not like the quadcopter because they found that *"the sound of the rotors is annoying after some time"* (P2, P5, P7, P12, P14) and would like to use a different frequency of sound when using a continuous auditory feedback.

When being asked about the leashed quadcopter, the participants were generally positive although only two participants considered it the best navigation system. Two participants liked that *"[they] can feel the distance to the quadcopter using the leash"* (P1, P11) and P4 especially liked the tactile component *"because this would also work in loud environments"*. Other participants liked how the handle was designed because they stated that *"it is nice to have an arrow in the hand that shows [them] the way every time"* (P1, P4, P6, P8). On the other hand, participants disliked that *"[they] had to carry an additional thing [referring to the handle] during the navigation while using the cane"* (P7, P12) as this occupies both of their hands.

4. DISCUSSION AND CONCLUSION

In this paper, we investigated using small light-weight quadcopters as a navigation device for visually impaired travelers. We extended previous work [3], which proposed using free-floating quadcopters as navigation systems, by presenting a quadcopter on a leash. Our leashed prototype extends the auditory navigation instructions that are emitted by the quadcopter with a tactile navigation through creating a tactile sensation on the quadcopter's handle. Through a user study with 14 visually impaired participants, we compared the free-floating quadcopter navigation system and our leashed quadcopter navigation system to a state-of-the-art audio navigation system.

The results reveal that participants using a free-floating quadcopter as a navigation system were significantly faster compared to the auditory baseline navigation system. Considering the number of navigation errors the participants made during the study, we found that the state-of-the-art audio navigation leads to significantly more navigation errors compared to both quadcopter navigation systems. The qualitative feedback revealed that the participants found the quadcopter navigation more accurate as it was giving a continuous feedback in the direction of travel. Main limitation of both quadcopter-based approaches is emitted sound which can be annoying and raises concerns considering the social acceptability of both quadcopter conditions.

One important direction for future work is the potentially annoying sound and the social acceptability when using a small quadcopter as a navigation device for visually impaired travelers. We envision a number of technical directions to potentially improve both aspects. Using quadcopters that produce less sound or integrating active noise control into the system could improve the social acceptability and the probability to be annoying. Unfortunately, a lower volume could make it harder to localize the quadcopter. Thus, there is a need to find a suitable sound design for quadcopter-based navigation systems. We are interested in exploring the use additional auditory feedback combined with active noise reduction. This would allow full control over the sound generated by the quadcopter that could be targeted only in the direction of the user.

Another direction we are interested in is how the acceptance of small quadcopters changes when the audience knows that it is an accessibility device. We expect similar effects as for guide dogs. While dogs are not necessarily socially acceptable in many situations, guide dogs are typically considered acceptable. Also, as safety of both visually impaired user and passersby are our priority, we want to work of a solution, where the quadcopter is protected with a cage.

5. ACKNOWLEDGEMENTS

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