Turn Right: Analysis of Rotation Errors in Turn-by-Turn Navigation for Individuals with Visual Impairments

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ABSTRACT

Navigation assistive technologies aim to improve the mobility of blind or visually impaired people. In particular, turn-by-turn navigation assistants provide sequential instructions to enable autonomous guidance towards a destination. A problem frequently addressed in the literature is to obtain accurate position and orientation of the user during such guidance. An orthogonal challenge, often overlooked in the literature, is how precisely navigation instructions are followed by users. In particular, imprecisions in following rotation instructions lead to rotation errors that can significantly affect navigation. Indeed, a relatively small error during a turn is amplified by the following frontal movement and can lead the user towards incorrect or dangerous paths.

In this contribution, we study rotation errors and their effect on turn-by-turn guidance for individuals with visual impairments. We analyze a dataset of indoor trajectories of 11 blind participants guided along three routes through a multi-story shopping mall using NavCog, a turn-by-turn smartphone navigation assistant. We find that participants extend rotations by 17° on average. The error is not proportional to the expected rotation; instead, it is accentuated for "slight turns" (22.5°–60°), while "ample turns" (60°–120°) are consistently approximated to 90°. We generalize our findings as design considerations for engineering navigation assistance in real-world scenarios.

CCS Concepts

• **Human-centered computing** → **Empirical studies in accessibility**; • **Social and professional topics** → **Assistive technologies**, **People with disabilities** • **Information systems** → *Geographic information systems*, Sensor networks

Author Keywords

Visual impairments and Blindness; Navigation Assistive Technologies; Orientation and Mobility;

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INTRODUCTION

Turn-by-turn navigation represents routes as sequences of rotations and forward movements. Since this guidance method does not require any contextual knowledge about the surroundings [11], it is suitable for navigation assistance of blind or visually impaired (BVI) people. Furthermore, this paradigm can improve BVI mobility in unfamiliar environments through physical [34] or virtual [17] navigation. Sighted individuals using turn-by-turn guidance (e.g., GPS navigator), can correct small navigation errors through visual inspection of the surroundings. Instead, for BVI people, high accuracy in *acquiring* the position and the orientation is essential to compensate for the absence of the sense of sight.

Recently, navigation assistive technologies (NAT) capable of such accuracy have been proposed [31, 29]. However, even if the guidance itself is accurate, user can be imprecise when *following* turning instructions and thus impact the navigation process. Indeed, a small error during a rotation can lead to a significant distance offset during the following frontal movement, which in turn can result in the user taking an incorrect path. Selecting an incorrect direction can cause a delay in reaching the desired destination, it can make the user lose orientation and not being able to recover the navigation, or it can even lead the user towards a potentially hazardous area.

In this paper, we study the entity of *rotation errors* and their effect on turn-by-turn guidance for BVI people. By "rotation error" we intend the difference between the rotation instructed by the navigation assistant and the rotation performed by the user. We analyze a log dataset collected during a user study with 11 visually impaired participants traversing a trafficked shopping mall while guided by NavCog, an open-source turn-by-turn navigation assistant (see Figure 1), which uses Bluetooth signals and motion data for accurate guidance [31, 39]. We discover that participants were more precise in performing "ample turns" (60°–120°) than "slight turns" (about 22.5°–60°). We relate the higher rotation errors during "slight turns" to a greater occurrence of guidance issues at 45° intersections, as previously hinted [39]. Furthermore, for "ample turns", we notice that participants tend to rotate by 90°, regardless of the instructed turning angle, with shorter stopping delay compared to "slight turns". These findings suggest that participants are more capable and used to perform 90° rotations. Based on our findings, we discuss design considerations to improve turn-by-turn navigation assistive tools for BVI people.

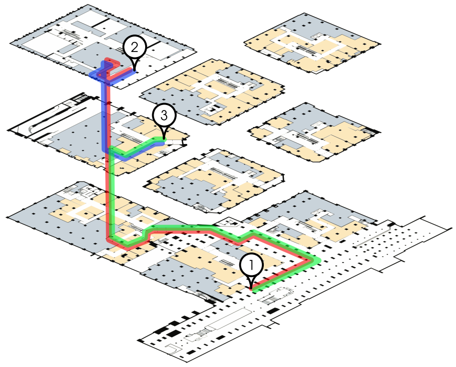


Figure 1: Experimental environment and routes. Route 1 (red) goes from the underground station to the cinema on the third floor. Route 2 (blue) continues towards a sweets shop on the first floor. Route 3 (green) returns to the start.

RELATED WORK

Long range visual inspection is commonly used to examine the environment and enable autonomous way-finding [24]. In absence of sight, BVI people map their surroundings through auditory, haptic, and vestibular sensing [16]. This process results in similar way-finding capabilities between visually impaired and sighted individuals [40]. However, non-visual sensing has a lower accuracy and sensory range, and therefore it is slower and more cognitively demanding [42]. Through prolonged exploration, which is often associated to orientation and mobility (O&M) training [43], BVI people learn routes that they will traverse habitually. However, in unfamiliar environments, the lack of a mental model of the surroundings makes navigation for BVI people harder or even dangerous, and therefore autonomous way-finding is rarely attempted [27].

Preinstalled smartphone software are often used by BVI people for assisted navigation [35]. Specifically designed tools are also studied to complement BVI way-finding [8, 13, 26, 37]. Computer vision is used to expand user's sensory range and detect visual cues, such as pedestrian crossings [3] or traffic lights [29], that cannot be accessed audio-haptically. Other approaches provide points of interest (POI) and contextual knowledge from Geographical Information Services (GIS), such as pedestrian crossings [6], shops or restaurants [21]. Such approaches convey information through auditory or haptic feedback [33, 30] since visual confirmation cannot be used.

Turn-by-turn navigation translates a route into a graph of straight paths and turning points, which is useful for BVI people since contextual knowledge of the environment is not needed to follow navigation instructions [11]. The instructions are sequential, so the user does not need to memorize the route or constantly track the navigation progress. This approach is used for outdoor vehicular GPS guidance, but in indoor environments, GPS localization is inaccurate or unavailable. Thus, alternative methods have been studied for indoor guidance, such as WiFi [36] or Visual Light Communication [32]. In particular, Bluetooth beacons [4, 5, 23] can be used to achieve 1 to 2m localization accuracy [7, 31] using off-the-shelf infrastructure that can be easily installed [15, 14].

During turn-by-turn navigation, sighted users compensate for localization inaccuracy through visual inspection of the surroundings [45]. Instead, BVI people cannot perform visual corrections, and therefore errors due to veering [18] or rotation [19, 9], can impact the navigation outcome. In particular, after a turn, even small rotation errors can lead to a distance error that accumulates during the following forward movement.

Both sighted [38] and blind [28] individuals tend to misjudge rotations. In particular turning errors when following instructions are related, not only to *encoding* errors (i.e., remembering the turning angle), but also in *execution* (i.e., reproducing the turning angle) [9]. Chrastil et al. [9] suggest that turning errors are related to the amount of rotatation performed. In particular, rotations are signaled at 90° rate [2, 20] which suggests that such angles are easier to detect and track. Prior experiments [39] analyzed human annotated video data and discovered a higher occurrence of navigation errors in correspondence to 45° intersections than for 90° intersections. In the following contribution, we investigate the corresponding trajectory data and analyze rotation errors and their impact on the quality of the guidance during turn-by-turn navigation.

EXPERIMENT

We conducted an empirical evaluation with 11 BVI participants traversing the experimental environment along three routes while supported by a turn-by-turn navigation assistant.

Participants

All participants are white cane users and trained in O&M. Six are totally blind while others have unusable residual vision (lv. 3 blindness[1]). Four owned a smartphone for at least 3 years, and five had previous NAT experience (Table 1). Two of them previously visited other parts of the environment, but they never traversed the experimental routes before. All participants took part in the first session in which usage logs were collected. Three participants were videorecorded, while others, except P1 and P5, returned to collect navigation videos during a second session. Clearly, those participants already had experience of the routes. Consequently the video data was only used to formulate initial hypotheses that were then further investigated through the analysis of the log data.

Table 1: Participants' demographic information.

ID	Sex	Age	Visual Impairment Condition	Visual Impairment Since	Experience with Smartphone	Experience with NAT
P1	Male	65	Totally blind	12	No	No
P2	Female	42	20/2000	0	4 years	No
P3	Male	54	Totally blind	2	4 years	Yes
P4	Male	48	20/2000	28	3 years	Yes
P5	Male	38	Totally blind	5	No	No
P6	Female	40	Totally blind	20	No	Yes
P7	Male	42	20/500	1	No	No
P8	Female	46	20/500 right	0	1.5 years	No
P9	Male	33	Totally Blind	30	1 year	Yes
P10	Female	53	20/500 left	49	1 year	No
P11	Female	48	Totally blind	0	4 years	Yes

[1]Defined in International Statistical Classification of Diseases

Experimental Setting

The experimental environment is a shopping mall with an area of $21,000m^2$. It consists in a public basement level and three buildings, two having 4 floors and one having 3 floors. It was instrumented with 218 Bluetooth beacons positioned every 5-10m. The three routes are approximately 400m long, with 26 turns in total. They traverse the basement area and two floors in one building (see Figure 1). Information about beacons, paths and POI was manually inserted during system setup.

Apparatus

Participants were guided using NavCog, an open source[2] turn-by-turn navigation assistant, running on an iPhone 6 device carried by the participants. All participants were provided with Bluetooth bone-conducting headphones, which convey audio without blocking the sense of hearing.

NavCog computes the user's position based on Bluetooth beacons signals and smartphone movements. The user is informed about turning points, obstacles and nearby POI through vocal and audio-haptic messages. At every turning point, NavCog informs the user of the turning angle with a coarse verbal indication: "Turn slightly left" signals turning angles between 22.5°–60° and "Turn left" those between 60°–120° (analogous for right turns). The app informs the user to stop turning through accurate audio/haptic feedback (i.e., a chime and a vibration) when the user reaches the target orientation.

NavCog logged the instructions conveyed to the participants, the detected beacons signal, inertial motion unit (IMU) sensor data (accelerometer, gyroscope and magnetometer) and the estimated participant's pose (location and orientation). Examples of two trajectories extracted from the log data are shown in Figure 2. We analyzed the logs collected during the first session only which contains data from 286 turns from 11 participants (26 turns per participant). We denote each turn with the number of route and the index of the turn within that route. For example, 3.02 denotes the second turn of route 3.

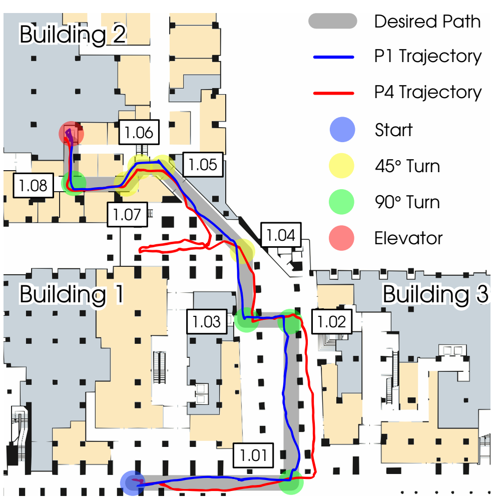


Figure 2: Floorplan of the basement area. Part of Route 1 and trajectories of P1 and P3 are traced on the map.

[2]Source code retrieved on Github

Procedure

First, we collected participants' demographic information (Table 1). We then provided a short training session (5-10 min.), during which the participants walked a training route to get familiar with the NavCog app. Finally, participants were asked to walk along three fixed routes in our testing environment as shown in Figure 1, following the navigation instructions provided by the app. The participants were instructed to walk the routes at their own pace, focusing only on reaching the destination. During the experiment, participants were at all times followed by an experimenter within a short distance to ensure their safety and provide assistance when needed. All experimenter interventions were annotated and the corresponding logged data were discarded from the following data analysis.

EVALUATION

We visually analyzed the video recordings, labelling the correctness of turns performed by the participants. This data was used to formulate initial hypotheses, which were then verified through a quantitative analysis on the collected log data.

Navigation Errors from Video Data

As a preliminary analysis, we examined the video data collected from 9 participants to label whether the turn was *correct* (i.e., the participant did not experience problems) or *incorrect*. The latter case was then categorized into three situations: *self corrected* if the participant managed to correct the direction autonomously, *system corrected* if the system provided instructions to correct the direction, and *failed* if the participant could not continue the navigation or required assistance. If the turn was not performed, for example due to an alternative route taken by the participant, the turn is labeled as *not available*.

Among the 26 turns in the three experimental routes, the *correct* ones were on average 22 ($SD = 2.8$) across all participants. Considering the *incorrect* turns only (12% of the total), 10% were labeled as *self corrected* and 47% as *system corrected*. In both cases the rotation error caused delays and fatigue but it was possible to continue the navigation. This is consistent with prior results [1], showing that not all navigation errors prevent the users from reaching the target. However, we also observed that 42% of the *incorrect* turns (i.e., 5% of total turns) were labeled as *failed*, and the navigation had to be stopped to avoid danger or because participants could not recover their orientation. For example, in two cases the navigation was stopped at turn 1.05 to prevent participants from walking into an incoming escalator. Thus, even with accurate guidance, **user errors in following the navigation instructions can affect the safety and the outcome of the navigation**.

Specific turning points had a consistently lower rate of correct turns (see Figure 3). For example, turning points *1.02* and *3.06* were easily traversed by all participants, while turning points *1.04* and *3.02* had frequent problems. We first examine the turning performance based on the intersection type at the turning point. We identify two types of intersections: 90° and 45° intersections. A paired t-test showed that the average rate of correct turns was significantly higher ($t_{(8)} = 2.63$, $p = .03$) for 90° intersections (88.3%, $SD = 12.0$) than for 45° ones (73.0%, $SD = 16.7$), which confirms prior findings [39].

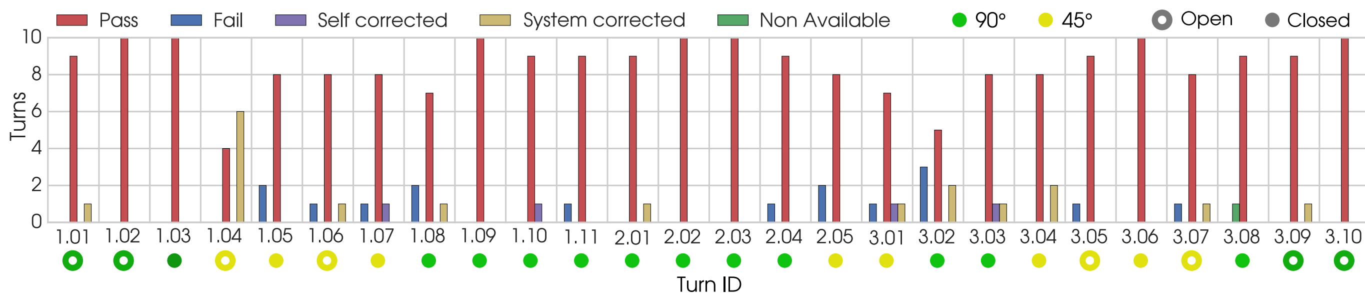


Figure 3: Type and incidence of errors for each turning point.

Rotation Errors from Log Data

Based on the preliminary video data analysis, we hypothesize that approximately 90° turns are less error prone than approximately 45° ones. We therefore analyze turning data from navigation logs of the participants, focusing on three factors: turn type (45° vs. 90°), spatial layout (narrow vs. open space), and participant characteristics. We assess each factor separately as no interaction effect was found between them.

Turn Type

We label approximately 45° turns (between 22.5° and 60°) as *slight turns*, and those close to 90° (between 60° and 120°) as *ample turns*, as used for NavCog audio feedback. We first examined the turning angle for each turn type (See Figure 4a). Slight turns were on average 56.2° (*SD* = 5.8°) while the average instructed angle was 39.46° (*SD* = 11.26°). Instead, ample turns were 90.4° on average (*SD* = 3.9°), very close to 90°, regardless of the actual angle that the participants were instructed to turn, which on average was 77.03° (*SD* = 10.97°).

We further evaluate participants' turning performance using two metrics. The **rotation error** is the difference between the turning angle performed by the user and the one instructed by the app. The **stopping delay** is the time difference between the moment the user is instructed to stop turning and when the user actually stops.

The average rotation error across all turns was 14.9° (*SD* = 9.9°). No directional bias was detected. For slight turns, it was 17.4° (*SD* = 4.0°), while for ample turns it was 13.4° (*SD* = 3.7°, see Figure 4b). A paired t-test revealed significant difference between the two cases ($t_{(10)} = 3.20$, $p = .010$, Cohen's $d = 0.37$). Similarly, the stopping delay (see Figure 4c) was greater for slight turns ($M = 0.72s$, $SD = 0.22s$) than for ample ones ($M = 0.58s$, $SD = 0.17s$). Again, a paired t-test revealed significant difference ($t_{(10)} = 2.29$, $p = .045$, Cohen's $d = 0.30$). These results support our intuition that **slight turns cause higher rotation error and longer delays.**

Spatial Layout

The average rotation error was 14.16° (*SD* = 10.18°) in narrow areas, and 16.43° (*SD* = 9.22°) in the open. A paired t-test revealed no significant difference between the two conditions. No significant differences emerge also for the stopping delay: $0.62s$ ($SD = 0.39s$) for narrow areas and $0.62s$ ($SD = 0.42s$) in the open. Thus, **we did not found statistical evidence that the spatial layout affects turning performance**.

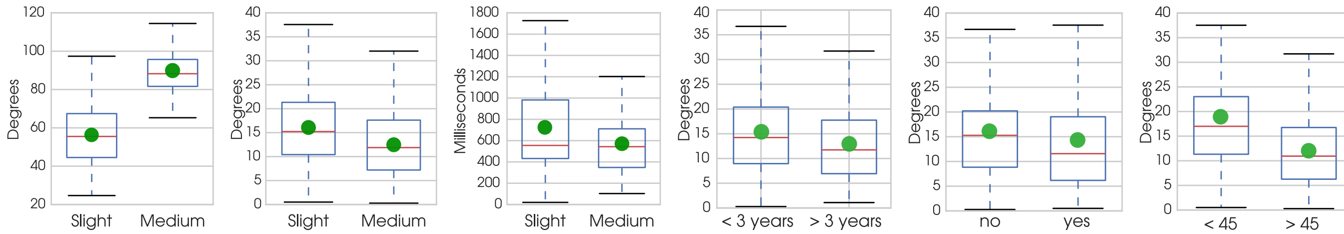
Participant Characteristics

Totally blind participants had an average rotation error of 14.96° (*SD* = 9.92°), while for others it was 14.46° (*SD* = 9.89°). No significant difference between the two groups was found, which was expected given the low visual acuity of the participants with residual vision. Similarly, the visual impairment onset age did not significantly influence the rotation error. Early onset [12] participants (onset age < 5), had an average rotation error of 14.21° (*SD* = 9.37°), while for late onset participants (onset age > 12) it was 15.01° (*SD* = 10.26°).

As expected, participants experienced with smartphones had lower rotation errors (See Figure 4d); $t_{(10)} = 2.05$, $p = .04$, Cohen's $d = 0.21$. Those with more than 3 years of smartphone experience had an average rotation error of 13.24° (*SD* = 9.62°), while others had 15.65° (*SD* = 9.97°). We also found a positive correlation between prior experience with NAT and turning accuracy (see Figure 4e); $t_{(10)} = 2.08$, $p = .03$, Cohen's $d = 0.23$. Participants who previously used NAT had an average rotation error of 13.46° (*SD* = 9.60°), whereas for others it was 16.03° (*SD* = 10.32°). Therefore, it emerges that **prior experience with smartphone and NAT positively affects turning performance**.

Age also influenced the rotation accuracy (see Figure 4f); $t_{(10)} = 4.92$, $p < .001$, Cohen's $d = 0.59$. Indeed, the average rotation error for participants under 45 years was 17.70° (*SD* = 10.84°), while it was 12.25° (*SD* = 8.26°) for others. Initially we speculated that lower rotation errors for participants over 45 years was due to a higher presence of expert smartphone users in this group. However even without those participants, the average rotation error was still significantly lower ($t_{(10)} = 4.43$, $p < .001$) for participants over 45 years ($M = 12.34°$, $SD = 8.32°$), than for the others ($M = 17.97°$, $SD = 10.81°$).

One possible motivation for the above result is that the stopping delay was significantly shorter ($t_{(10)} = 4.81$, $p < .001$, Cohen's $d = 0.53$) for participants over 45 years ($M = 0.52s$, $SD = 0.31s$) than for those under 45 years ($M = 0.75s$, $SD = 0.50s$). The starting delay was instead significantly higher ($t_{(10)} = 2.14$, $p = .03$, Cohen's $d = 0.24$) for participants over 45 years ($M = 0.79s$, $SD = 1.23s$) than for participants under 45 years ($SD = 0.54s$, $SD = 0.61s$). Conversely, total rotation duration was not significantly influenced by age. **Thus, participants over 45 years were not slower during rotation, but they were more cautious when starting to turn, and more reactive to the instruction to stop turning**.



(a) Total Rotation **(b) Rotation error** **(c) Stopping delay** **(d) Smartphone use** **(e) NAT experience** **(f) Participant age**

Figure 4: Total rotation, turning performance in relation to turn type and participants' characteristics.

DISCUSSION

Environment Layout

Video data analysis highlights that turn-by-turn guidance for BVI people is more likely to fail at specific turning points. We explored the commonalities among the most critical ones and we discovered that those diverging from 90° are consistently more error prone. Log data analysis supports this claim, showing higher rotation errors and stop delays for slight turns.

Instead, no substantial difference was observed between the turning performance in narrow and open areas. We were surprised by this result at first; we believed that turning in narrow areas would be easier because the participants could coast the walls with their cane. Guided by the quantitative results we analyzed the participants behavior in the video recordings and observed that none of the participants coasted walls while using NavCog. One reason which could explain this behavior was reported by one participant in a follow-up study: following walls attracts attention, which is a thing that BVI people tend to avoid, as previously noted in literature [41, 44]. Additionally, in crowded environments, it is difficult to reach and coast walls.

Human Factors

The analysis based on NavCog logs confirms that the participants were more accurate in performing turns close to 90° than ones around 45° [39], but it also reveals another interesting finding. Participants had a tendency to make accurate 90° turns when asked to perform ample turns, regardless of the actual turning angle. We believe that this behavior could be caused by multiple factors. Based on "Manhattan world" assumption [10, 22], which highlights that straight lines and 90° angles are prevalent in structured environments, we think that visually impaired people living in such environments are more used to perform, and habitually expect the turns of such entity during turn-by-turn navigation. It is also possible that the human body structure itself, being specular, makes 90° turns easier to perform than smaller and bigger ones.

As expected, prior experience with smartphones and navigation tools resulted in a higher rotation accuracy for our participants. Unexpectedly, younger participants seem to have worse turning performance than older participants. Indeed older participants are consistently more reactive to the audio/haptic feedback to stop rotating and thus they perform more accurate turns. This finding may suggests that **older users pay more attention to the instructions provided while turning.**

Design Considerations

One consistent result among all of our experiments was that almost the entirety of the turns performed by the participants were more ample than requested (of about 15° on average). In order to improve the accuracy of turn-by-turn navigation approaches, a possible design consideration is to compensate for the rotation errors by anticipating the stopping instruction by a given time offset or rotation distance with respect to the target rotation angle, similar to [25]. Turning compensation, however, should also consider how the rotation error is influenced by context, user's characteristics and turning amplitude.

This could be achieved using modern reinforcement learning approaches, that would personalize the turning compensation for each user and for different contexts on the go, based on the history of the interactions between the user and the system. Such technique would not be limited solely to this specific use case. It could also apply to any situation in which an instruction is followed by error prone user interaction (e.g., touchscreen gestures learning [33]).

The interaction paradigm used to convey turning instruction may also influence the rotation accuracy. We expect that different interaction approaches, such as sonification and musification, that use sound characteristics to provide a more fine-grained information on the required rotation angle [30], could result in users performing more accurate rotations.

CONCLUSIONS

While turn-by-turn navigation assistants can provide guidance to people with visual impairments while traversing unfamiliar environments, a small imprecision in following the navigation instructions, especially rotations, can lead to navigation failures. To examine this issue, we collected navigation trajectories of 11 participants with visual impairments using a navigation app to travel through a large shopping mall environment and we evaluated their turning performance

We show that the participants have the tendency to over-rotate the turns, on average 17° more than instructed, and that the rotation error is higher for slight turns than for ample turns. Ample turns instead are frequently approximated to 90°. Our findings also suggest that simply notifying the user when the rotation should be stopped is error prone and a different interaction is required, possibly predicting the over-rotation and hence compensating the rotation error, or by providing continuous feedback that helps the user to stop in the right direction.

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