SCIENCE ROBOTICS | RESEARCH ARTICLE

MEDICAL ROBOTS

Multimodal sensing and intuitive steering assistance improve navigation and mobility for people with impaired vision

Patrick Slade[1]*, Arjun Tambe[1], Mykel J. Kochenderfer[2]

Globally, more than 250 million people have impaired vision and face challenges navigating outside their homes, affecting their independence, mental health, and physical health. Navigating unfamiliar routes is challenging for people with impaired vision because it may require avoiding obstacles, recognizing objects, and wayfinding indoors and outdoors. Existing approaches such as white canes, guide dogs, and electronic travel aids only tackle some of these challenges. Here, we present the Augmented Cane, a white cane with a comprehensive set of sensors and an intuitive feedback method to steer the user, which addresses navigation challenges and improves mobility for people with impaired vision. We compared the Augmented Cane with a white cane by having sighted and visually impaired participants complete navigation challenges while blindfolded: walking along hallways, avoiding obstacles, and following outdoor waypoints. Across all experiments, the Augmented Cane increased the walking speed for participants with impaired vision by 18 ± 7% and sighted participants by 35 ± 12% compared with a white cane. The increase in walking speed may be due to accurate steering assistance, reduced cognitive load, fewer contacts with the environment, and higher participant confidence. We also demonstrate advanced navigation capabilities of the Augmented Cane: indoor wayfinding, recognizing and steering the participant to a key object, and navigating a sequence of indoor and outdoor challenges. The open-source and low-cost design of the Augmented Cane provides a platform that may improve the mobility and quality of life of people with impaired vision.

INTRODUCTION

More than 250 million people around the world have impaired vision ranging from moderate impairment to blindness, which affects their physical health, mental health, and quality of life (*1*–*4*). These health consequences are mainly due to reduced mobility and limited independent navigation. Impaired vision alters mobility by decreasing self-selected walking speed (*5*), reducing walking efficiency (*6*), increasing the likelihood of accidental injury (*7*), and increasing the risk of contracting communicable diseases such as coronavirus disease 2019 (COVID-19) because of reliance on public transportation and tactile navigation strategies (*8*). For people with impaired vision, mobility is related to quality of life (*3*). Improving mobility metrics like walking speed or efficiency increases the quality of life for patient populations—such as the elderly (*9*), stroke survivors (*10*), and people with multiple sclerosis (*11*)—and would likely provide similar benefits for people with impaired vision. In terms of independent navigation, 50% of people with blindness never make an independent journey (*12*), and 40% travel unfamiliar routes less than once a week (*13*), correlating to less physical activity and a more rapid decline in mobility (*7*). In the United States, impaired vision is associated with 68 billion dollars in health care costs each year (*14*). Thus, solutions that improve navigation and mobility for people with impaired vision could increase their independence and quality of life.

Navigating with impaired vision poses three main challenges: collision avoidance, indoor and outdoor wayfinding, and localizing key objects (*15*). Collision avoidance requires understanding the environment to avoid obstacles and accidents, such as tripping, which may cause injuries. Wayfinding is the process of navigating to a desired location. Wayfinding requires localization, where a person estimates and tracks their location as they travel in an indoor or outdoor environment. Orientation professionals teach wayfinding strategies to help people with impaired vision navigate known routes. For example, shorelining is a technique that uses a white cane to follow the right side of a sidewalk or wall (*16*). Wayfinding is especially difficult along unknown routes because localization requires visual cues to recognize key objects to navigate complicated environments, such as finding a crosswalk to safely cross a street (*17*), avoiding a construction zone, and locating a bus stop (*18*).

A white cane or guide dog are common tools that help people with impaired vision avoid obstacles, but neither can wayfind along unfamiliar routes. The most common navigational aid is a white cane, or long cane, which provides haptic information about the surface, elevation changes, and obstacles around the user (*16*, *19*). Standard white cane techniques help find a clear path of travel, negotiate terrain, and move around obstacles (*20*–*22*) but cannot detect obstacles beyond the length of the cane. Guide dogs perform collision avoidance by steering people around obstacles. However, the availability of guide dogs is limited because they cost about $42,000 to train and have a working life of 6 to 8 years (*23*).

Many assistive devices use sensors to perceive the environment and relay information to the user to address a subset of the navigation challenges (*15*). Electronic travel aids use distance measurements, inertial measurements, position information, or images to perceive the environment and convey that information to the user with audio or tactile feedback (table S1). For collision avoidance, some electronic travel aids rely on distance measurements from ultrasonic or light detection and ranging (LIDAR) sensors mounted to a white cane (*24*) or the user's body (*25*) to detect nearby obstacles, obstacles at head height (*26*), or drop-offs (*27*, *28*). Electronic travel aids can perform outdoor wayfinding with position information from GPS (*29*) or indoor wayfinding in specific locations with preplaced position

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[1]Department of Mechanical Engineering, Stanford University, Stanford, CA, USA.
[2]Department of Aeronautics and Astronautics, Stanford University, Stanford, CA, USA.
*Corresponding author. Email: patslade@stanford.edu

sensors (*30*, *31*) or environment maps (*32*, *18*). Simultaneous localization and mapping (SLAM) is a method for estimating the user's position while mapping unseen environments with a LIDAR (*33*) or camera sensor (*29*). Image classification allows electronic travel aids to recognize key objects (*18*, *15*), which can be fused with distance measurements for more accurate localization (*34*).

Walking speed is an objective mobility measure. Increasing walking speed correlates to improved independence and quality of life for patient populations like the elderly (*9*), stroke survivors (*10*), and people with multiple sclerosis (*11*). Most electronic travel aids evaluate performance based on metrics unrelated to the participant, such as obstacle detection rate (table S1), and decrease the participant's walking speed and thus mobility, compared with a white cane (*35*). Electronic travel aids may reduce walking speed because their method of feedback may increase the user's cognitive burden or require substantial training time to understand. The additional weight of the sensors and feedback modes may increase the physical burden of carrying the device. An electronic travel aid consisting of a white cane with a distance sensor decreased the walking speed of people with impaired vision by 36% during an obstacle avoidance experiment (*24*). Three electronic travel aids that used distance sensors (*25*) or cameras (*18*, *36*) worn on the body decreased the walking speed of people with impaired vision by 28, 47, and 37%. An electronic travel aid with distance sensors attached to a shoe increased walking speed by 11% during an obstacle avoidance task, but it required 9 hours of training (*37*). Another electronic travel aid enabled people with impaired vision to walk through hallways at fast speeds of up to 1 m/s, but was not directly compared with a white cane (*32*).

We present the Augmented Cane, a white cane with a set of comprehensive sensors and intuitive feedback methods that addresses the major challenges of navigating with impaired vision. We hypothesize that steering the user with grounded kinesthetic feedback will provide faster and more accurate guidance than vibration or audio feedback. We further hypothesize that participants navigating with the Augmented Cane will increase their walking speed compared with a white cane. To evaluate these hypotheses, we performed a series of four experiments: turning in place, indoor hallway navigation, indoor obstacle avoidance, and outdoor GPS waypoint tracking. We evaluate how the Augmented Cane could affect mobility and quality of life for people with impaired vision by comparing to the navigation capability of a standard white cane. We demonstrate that the Augmented Cane can perform advanced robotics techniques such as closed-loop planning to navigate to a desired indoor position, computer vision to steer toward key objects, and high-level planning to overcome combined indoor and outdoor challenges. The Augmented Cane offers an open-source and low-cost platform to enable researchers to focus on improving navigation for people with impaired vision.

RESULTS

Design of the Augmented Cane

The Augmented Cane is a white cane equipped with portable sensors to perceive the environment and feedback methods that assist the user with navigation (Movie 1). A white cane was selected as the base of the system to provide reliable obstacle avoidance in case of a system failure (*38*) and to provide physical feedback from tactile paving on street corners and train platforms. The sensors include a two-dimensional (2D) LIDAR, camera, GPS antenna, and inertial measurement unit (Fig. 1A), which provide information to address the navigation challenges people with impaired vision face (Fig. 1B and table S1). The sensors and motorized omni wheel on the Augmented Cane weigh 1 kg and have 2.5 times the moment of inertia of a white cane. Grounded kinesthetic feedback and audio instructions relay information to the user. Kinesthetic haptic feedback is the use of force or motion to guide a person's movements. In this application, grounded kinesthetic feedback is provided by a motorized omni wheel located at the end of the cane that steers the user to the left or right by applying torques to the ground. The feedback can be overpowered by the user or turned off with a push button. The omni wheel allows the user to freely select their forward walking speed. A portable microcontroller in the Augmented Cane receives sensor data, plans the navigation, and provides feedback in real time.


Movie 1. Summary of the Augmented Cane. The Augmented Cane uses a multimodal set of sensors to perceive the environment and provides grounded kinesthetic feedback to steer the participant. A series of experiments evaluated how novice and expert participants navigated when using the Augmented Cane or a white cane.

The Augmented Cane design was iteratively improved during three co-design sessions with a participant with impaired vision. The participant used the Augmented Cane to navigate an indoor hallway with and without obstacles. The participant used trial and error to select important parameters that defined how the Augmented Cane operated, including the rate at which the grounded kinesthetic feedback steered the user and the minimum distance from an obstacle before the cane steered the user. We also implemented additional features that the participant recommended, such as using the grounded kinesthetic feedback to sweep the cane in front of the user, comparing with audio feedback, and the ability to detect key objects such as a stop sign.

Grounded kinesthetic feedback was the most accurate and fastest method to steer blindfolded participants to reach a target heading angle during a turn-in-place experiment. For this experiment, blindfolded participants ($n = 12$) received grounded kinesthetic, vibrotactile, or audio feedback. Grounded kinesthetic feedback had the lowest final heading error (Fig. 2A) [two-way analysis of variance (ANOVA), random effect: participant; fixed effect: feedback mode; $P \leq 4 \times 10^{-4}$], reached the target angles in less time than vibrotactile feedback, and had the lowest error as a function of time (Fig. 2B). Grounded kinesthetic and vibrotactile feedback enabled participants to accurately reach the target heading angle, whereas audio feedback caused participants to turn past the target (Fig. 2C).

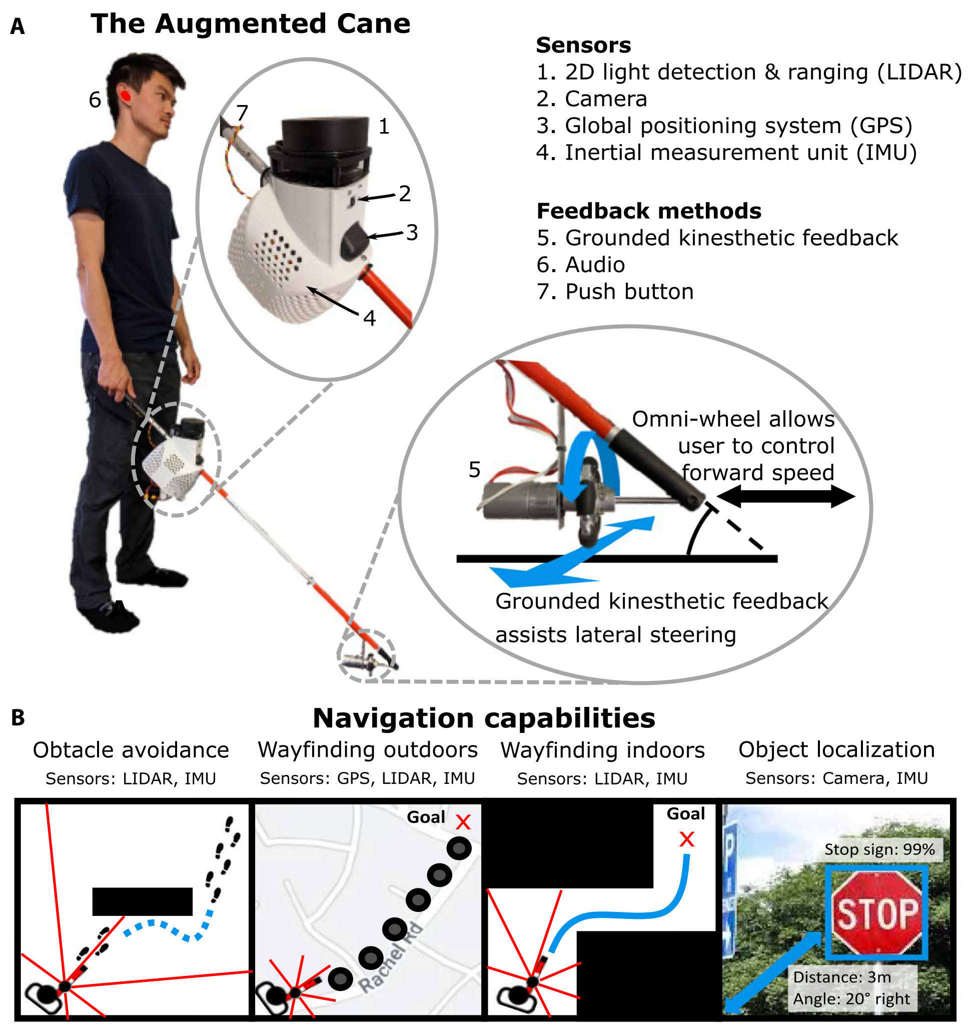


Fig. 1. Overview of the Augmented Cane. (**A**) The Augmented Cane helps people with impaired vision navigate by using sensors to understand the environment and feedback modes to help guide and inform the user. The user self-selects their walking speed, and a motorized omni wheel provides backdrivable steering assistance for guidance to the left or right. A portable microcontroller on the Augmented Cane receives the data from all sensors, processes the data, and controls the steering assistance. (**B**) The Augmented Cane uses its variety of sensors to overcome the challenges of helping a person with impaired vision navigate different challenges. The LIDAR measures distances to obstacles, the inertial measurement unit (IMU) provides orientation estimates, the GPS measures outdoor position, and the camera takes images.

Indoor and outdoor navigation experiments

Participants completed a series of indoor and outdoor navigation experiments to investigate how the Augmented Cane might change the mobility of a person with impaired vision compared with navigating with a white cane. We evaluated novice participants: blindfolded people with unimpaired vision and no experience using a white cane. We also evaluated expert participants: blindfolded people with impaired vision and several years of experience with a white cane (table S2). The Augmented Cane used an obstacle avoidance algorithm during the indoor experiments (fig. S1) and a GPS waypoint tracking (fig. S2) algorithm during the outdoor experiments.

During an indoor hallway navigation experiment, the Augmented Cane improved the mobility of novice ($n = 12$) and expert ($n = 12$) participants relative to a white cane (Movie 2). The center of mass of a representative novice participant swayed from side to side while navigating with a white cane and moved more smoothly with the Augmented Cane (Fig. 3A). A representative expert participant abruptly changed directions with a white cane, whereas they turned smoothly when using the Augmented Cane (Fig. 3B). Novice and expert participants navigating with the Augmented Cane walked through the hallways in less time, in a shorter distance, with a faster walking speed, and with fewer contacts with the environment than when using a white cane (Fig. 3, C to F). The Augmented Cane increased walking speed for novices by 38% (two-way ANOVA, random effect: participant; fixed effect: cane; $P \leq 2 \times 10^{-2}$) and experts by 22% (two-way ANOVA, random effect: participant; fixed effect: cane; $P \leq 5 \times 10^{-3}$), compared with a white cane.

Participants walking with a white cane decreased their walking speed for several seconds after the cane contacted the environment (Fig. 3G). The walking speed distribution for novice participants using the Augmented Cane had a similar shape but a higher average speed than using a white cane (Fig. 3H). The walking speed distribution for expert participants using the Augmented Cane was more uniform than using a white cane (Fig. 3I). The Augmented Cane increased the walking speed of all participants, except for two novices (table S3 and fig. S3A) and two experts (table S4 and fig. S3B).

During an indoor obstacle avoidance experiment, the Augmented Cane improved the mobility of novice ($n = 12$) and expert ($n = 12$) participants relative to a white cane (Movie 2). Navigating with the Augmented Cane resulted in a smoother center-of-mass motion for a representative novice participant (Fig. 4A). The Augmented Cane guided a representative expert participant away from obstacles earlier in the hallway than a white cane, smoothing the center-of-mass motion (Fig. 4B). The Augmented Cane improved all mobility metrics, although only some were significant (Fig. 4, C to F). The Augmented Cane increased walking speed for novices by 20% (two-way ANOVA, random effect: participant; fixed effect: cane; $P \leq 2 \times 10^{-3}$) and experts by 10% (two-way ANOVA, random effect: participant; fixed effect: cane; $P = 0.12$). The Augmented Cane increased the walking speed of all participants except for two novices (table S3 and fig. S4A) and two experts (table S4 and fig. S4B). One novice participant completed an additional indoor test navigating a circular hallway with either the Augmented Cane or white cane while measuring metabolic cost of walking with a mobile respirometry unit. Navigating with the Augmented Cane resulted

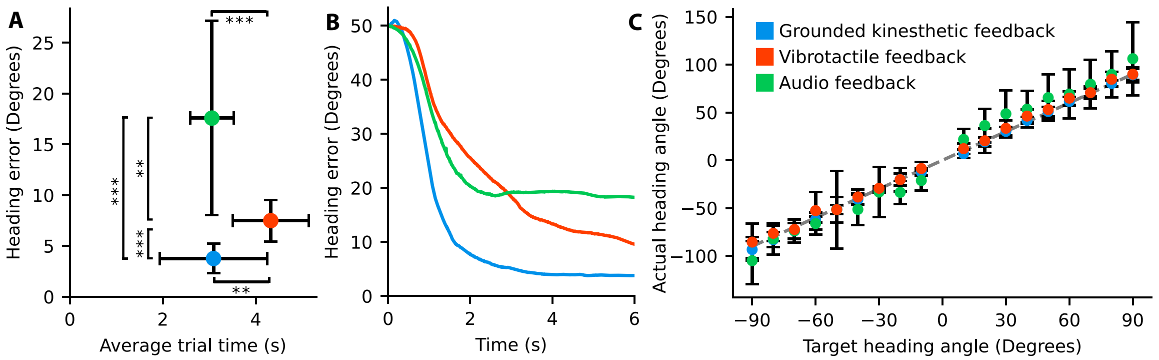
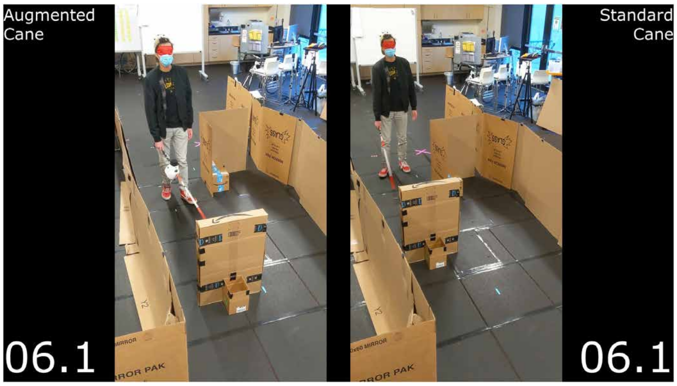


Fig. 2. Comparing haptic feedback methods with a turn-in-place experiment. (**A**) This experiment had novice blindfolded participants ($n = 12$) hold the Augmented Cane and turn in place toward a random sequence of target heading angles while receiving grounded kinesthetic, vibrotactile, or audio feedback. The grounded kinesthetic feedback had the lowest heading error averaged over all participants and was tied with audio feedback for the fastest trial time. A two-way ANOVA model with a random effect for the participant computed the significance of the effect of the feedback mode (**$P < 5 \times 10^{-3}$ and ***$P < 5 \times 10^{-4}$). (**B**) Plotting the heading error over time illustrates the fast and accurate response of the grounded kinesthetic feedback. (**C**) The audio feedback resulted in much larger actual heading angles than the targets, likely because a single audio prompt was given at the start of the trial, whereas the other methods provided continuous feedback. Error bars indicate one standard of deviation from the mean.



Movie 2. Comparison of the Augmented Cane and a white cane during indoor experiments. Example trials compare how a representative novice participant navigates with the Augmented Cane and a white cane during a hallway experiment and an obstacle avoidance experiment.

in a 14.1% increase in walking speed and a 12.0% decrease in the cost of transport, a measure for the energetic efficiency of walking. The cost of transport was 9.39 and 10.58 $\mathrm{J\ m^{-1}\ kg^{-1}}$ when navigating with the Augmented Cane and white cane, respectively.

During an outdoor navigation experiment, the Augmented Cane improved the mobility of novice ($n = 8$) and expert ($n = 4$) participants relative to a white cane with audio feedback (Movie 3). Both canes used the same GPS equipment and path waypoints. Participants using the white cane were provided audio feedback to turn a specific angle left or right toward the desired path every 10 s. The Augmented Cane helped a representative novice participant remain closer to the ground truth waypoints (Fig. 5A). This participant had a faster walking speed with lower variance when using the Augmented Cane (Fig. 5B). The Augmented Cane improved all mobility metrics, although only some were significant (Fig. 5, C to F). The Augmented Cane increased walking speed for novices by 46% (two-way ANOVA, random effect: participant; fixed effect: cane; $P \leq 0.02$) and experts by 23% (two-way ANOVA, random effect: participant; fixed effect: cane; $P = 0.33$). Participants had substantially lower heading error, the difference in the angle between the person's current direction and the next waypoint, when using the Augmented Cane (Fig. 5F). The Augmented Cane increased the walking speed of all participants, except for two novices (table S3 and fig. S5A) and one expert (table S4 and fig. S5B). Novice and expert participants using the Augmented Cane contacted the environment, on average, 7.1 and 9.3 times, lower than the 43.2 and 35.9 times when using a white cane.

The participants completed surveys after the experiments, comparing the Augmented Cane with a white cane in terms of usability (*39*), perceived workload (*40*), and their personal opinions. Novice participants gave the Augmented Cane and a white cane average usability scores of 65 and 74, corresponding to the 44th and 71st percentiles in a distribution of 5000 commercial and research devices (table S5) (*41*). Expert participants gave the Augmented Cane and a white cane average usability scores of 57 and 65 (table S6). The difference in walking speed when participants navigated with the Augmented Cane compared with a white cane was correlated to the difference in their reported confidence ($R^2 = 0.51$ for novices and $R^2 = 0.34$ for experts). There were no correlations ($R^2 > 0.3$) between any objective measures, including walking speed, trial time, and distance walked, and participant survey results, including confidence, ease of use, and level of inconsistency when comparing the Augmented Cane with white cane. Novice participants gave the Augmented Cane and a white cane relatively low perceived workload scores of 68.4 and 54.4, in the 91st and 51st percentiles of a distribution of 1000 devices (table S7) (*42*). Expert participants had similar perceived workload scores (table S8). In open-ended questions, expert participants reported that the Augmented Cane provided intuitive and helpful steering feedback but was heavy (table S9).

Demonstrations of advanced navigation capabilities

The Augmented Cane performed a closed-loop planning algorithm (Fig. 6A) to navigate a novice participant to a desired indoor position (Fig. 6B and Movie 4). The algorithm successfully guided the participant through a cluttered indoor environment in five successive trials. SLAM accurately estimated the participant's position with an average root mean square error (RMSE) of 0.26 ± 0.18 m compared with motion capture.

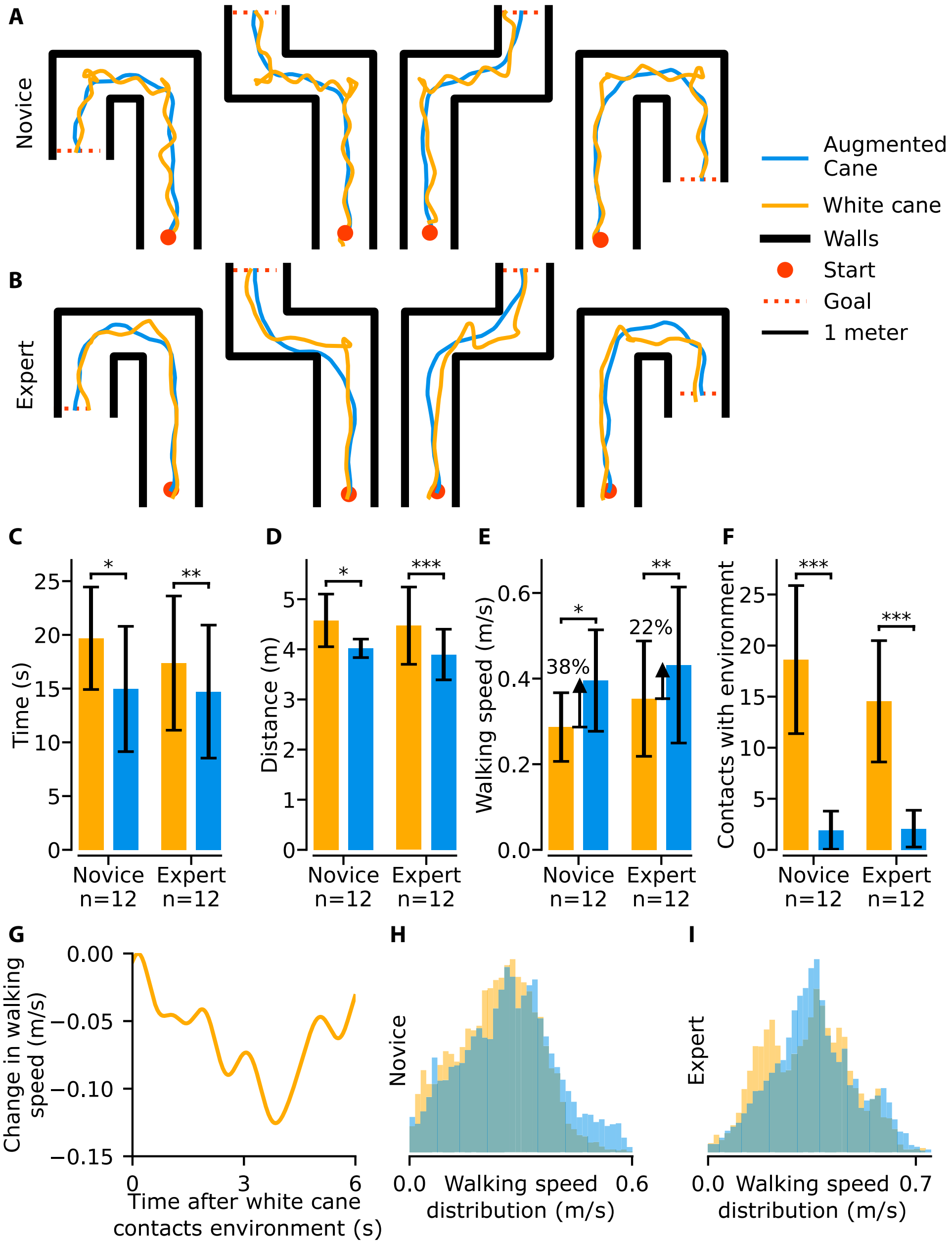


Fig. 3. Indoor hallway experiment. (**A**) The center of mass of a representative novice participant swayed from side to side while navigating with the white cane and moved more smoothly with the Augmented Cane. (**B**) A representative expert participant moved smoothly with the white cane but turned abruptly, yet turned more smoothly with the Augmented Cane. Novice and expert participants navigating with the Augmented Cane walked through the hallways (**C**) in less time, (**D**) by walking a shorter distance, (**E**) with a faster walking speed, and (**F**) with fewer contacts with the environment than the white cane. A two-way ANOVA model with a random effect for the participant computed the significance of the effect of using the Augmented Cane or a white cane (*$P < 0.05$, **$P < 5 \times 10^{-3}$, and ***$P < 5 \times 10^{-4}$). Error bars indicate one standard of deviation from the mean. (**G**) When the white cane came into contact with the environment, the participant's walking speed decreased for the following 3 s before resuming to their normal speed. The distributions of walking speeds averaged across all (**H**) novice and (**I**) expert participants show that the Augmented Cane distribution was shifted to faster speeds.

The Augmented Cane successfully recognized an example key object of a stop sign and automatically steered a participant toward the stop sign, a task known as visual servoing. Using images taken from the camera, the Augmented Cane could classify a stop sign at distances up to 10 m, depending on the angle the stop sign was facing (Fig. 7A and Movie 5). The Augmented Cane performed visual servoing at a rate of 1.4 Hz by taking an image with the onboard camera, classifying any stop signs in the image with a pretrained computer vision model (*43*), and steering the participant toward the stop sign by using grounded kinesthetic feedback (Fig. 7B). The visual servoing algorithm consistently guided the user to a stop sign located 7 m away from several starting angles (Fig. 7C). The Augmented Cane's linear regression model successfully estimated the distance to the stop sign with an RMSE of 0.89 m (Fig. 7D). A participant using the Augmented Cane successfully navigated a sequence of challenges including an indoor hallway, an outdoor path, and detecting and reaching a stop sign (Fig. 8).

DISCUSSION

The Augmented Cane enables people with impaired vision to overcome major navigation challenges and improves their mobility by increasing walking speed compared with a white cane. The Augmented Cane uses a comprehensive set of sensors to overcome more navigation challenges than previous electronic travel aids (table S1). Grounded haptic feedback steers participants more accurately and quickly than common methods of vibrotactile or audio feedback. Combining comprehensive sensing and intuitive guidance improves mobility metrics, such as walking speed and the cost of transport, for participants during indoor and outdoor experiments. The Augmented Cane also provides advanced navigation capabilities, enabling path planning techniques to help people with impaired vision navigate independently.

We attribute the increase in walking speed when using the Augmented Cane compared with a white cane to four factors: accurate steering assistance, reduced cognitive load, fewer contacts with the environment, and confidence in the device. First, the most accurate method of providing steering assistance for turning in place and during outdoor navigation was grounded kinesthetic feedback, which may have reduced the distance walked when completing the indoor and outdoor experiments (Figs. 3D, 4D, and 5D). Second, the Augmented Cane may have a lower cognitive load than the other electronic travel aids

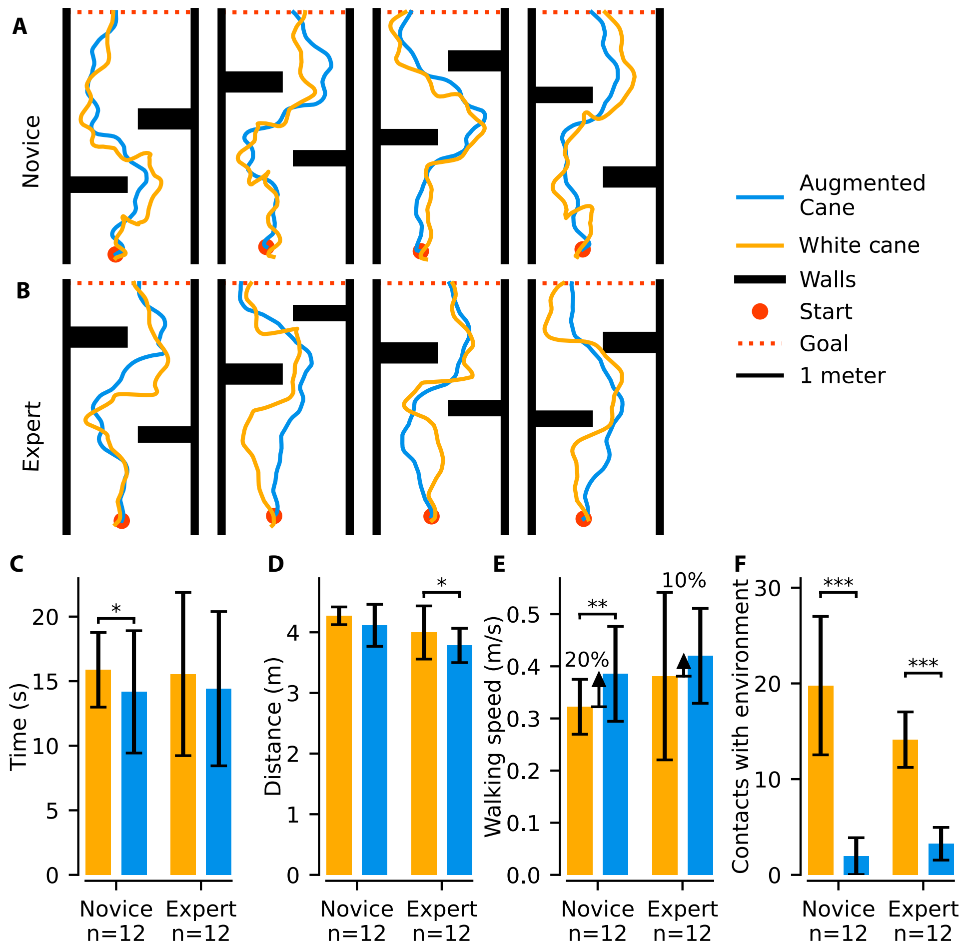


Fig. 4. Indoor obstacle avoidance experiment. (**A**) Visualizing the paths of a representative novice participant in the obstacle avoidance experiment illustrates that navigating with the Augmented Cane has a smoother center-of-mass motion than the white cane. (**B**) The Augmented Cane steered a representative expert participant away from obstacles before the white cane. Novice and expert participants navigating with the Augmented Cane completed the course (**C**) in less time, (**D**) by walking a similar distance, (**E**) with a faster walking speed, and (**F**) with fewer contacts with the environment compared with a white cane. A two-way ANOVA model with a random effect for the participant computed the significance of the effect of using the Augmented Cane or a white cane ($^{*}P < 0.05$, $^{**}P < 5 \times 10^{-3}$, and $^{***}P < 5 \times 10^{-4}$). Error bars indicate one standard of deviation from the mean.

Movie 3. Comparison of the Augmented Cane and a white cane during an outdoor experiment. A time lapse of a novice participant navigating an outdoor asphalt path with the Augmented Cane and a white cane with audio feedback.

because participants began turning after less time when provided grounded kinesthetic feedback, rather than vibrotactile or audio feedback (Fig. 2B). Previous electronic travel aids decreased walking speed when compared with a white cane, possibly due to vibrotactile feedback, which could require higher cognitive load than no feedback (*24*, *25*, *36*). Novice participants reported lower mental demand using the Augmented Cane (table S7). Third, the Augmented Cane reduced the participants' number of contacts with the environment in all experiments. An analysis of the motion capture data from the indoor experiments revealed that these contacts temporarily decreased walking speed (Fig. 3G). Fourth, there was a correlation between the difference in walking speed and confidence when participants used either the Augmented Cane or white cane. People with impaired vision prefer to use their white cane when learning to use an electronic travel aid because it increases their confidence (*38*). This may explain why a previous electronic travel aid without a white cane reduced the walking speed compared with a white cane (*25*). Using a white cane as the base of the Augmented Cane may have increased their confidence and walking speed.

Although the Augmented Cane increased the average walking speed of the novice and expert participant groups compared with a white cane, not all participants benefited (table S3 and S4). Additional work could investigate what factors affect the differences in individuals' benefits and whether additional training time might be helpful. Personalizing human-robot assistance to each user has improved performance in certain applications (*44*) and may further improve mobility metrics with the Augmented Cane.

The Augmented Cane is intuitive to use, improving mobility with minimal training time. Novice participants had a smoother center-of-mass motion and walked 35% faster across all experiments when navigating with the Augmented Cane than the white cane, even though they trained with each cane for the same amount of time. Unexpectedly, expert participants walked 18% faster across all experiments with the Augmented Cane than the white cane, despite having years of training with the white cane. The experts' experience using a white cane allowed them to walk faster than the novice participants, indicating that more training with the Augmented Cane could increase walking speed.

A few previous electronic travel aids also provided grounded kinesthetic feedback to steer the participants (*31*, *32*, *45*, *46*). These four electronic travel aids did not perform experiments that directly

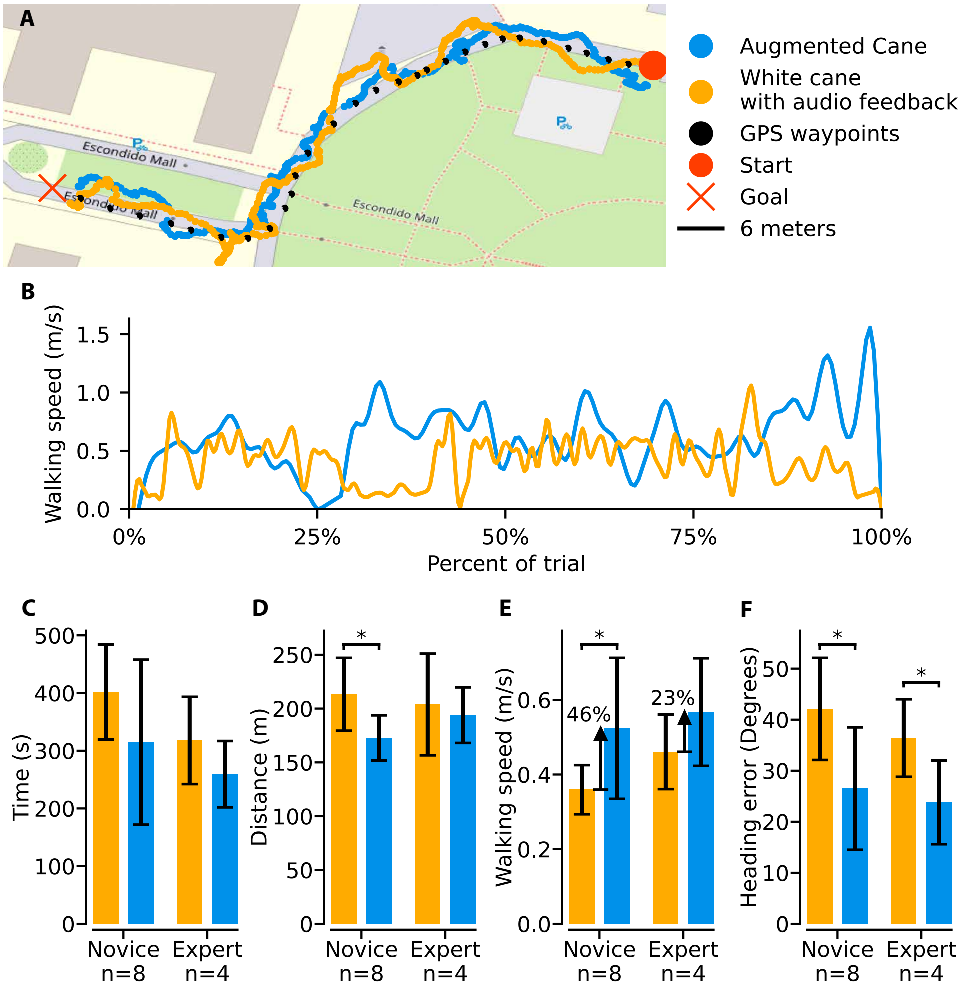


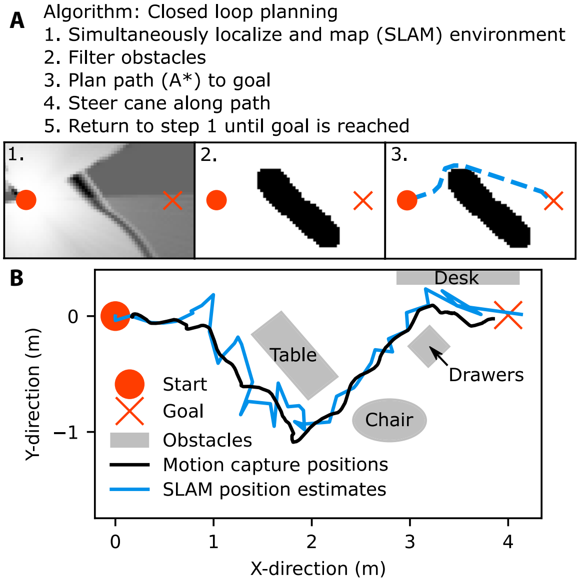
Fig. 5. Outdoor navigation experiment. (**A**) When a representative novice participant walked along an outdoor path with the Augmented Cane, they remained closer to the ground truth GPS waypoints than when using the white cane with audio feedback. (**B**) The participant walked faster and with less frequent changes in speed when using the Augmented Cane. Novice and expert participants navigating with the Augmented Cane completed the course (**C**) in less time, (**D**) by walking a shorter distance, (**E**) with a faster walking speed, and (**F**) with less heading error than a white cane. A two-way ANOVA model with a random effect for the participant computed the significance of the effect of using the Augmented Cane or a white cane (*$P < 0.05$). Error bars indicate one standard of deviation from the mean.

compare with a white cane; thus, their potential benefits to mobility are unknown. Several of the experiments only provided qualitative assessments of how the grounded kinesthetic feedback affected participants' navigation (*31*, *45*, *46*). One study reported that participants required minimal training with their device to walk at faster speeds than previous studies of white cane users (*32*), supporting the idea that grounded kinesthetic feedback is intuitive. However, these four devices may be challenging to extend to everyday use because they are designed only for indoor use, cost up to $6000 USD, and weigh 6 to 25 kg, whereas the Augmented Cane costs $400 USD and weighs 1.2 kg (table S1). Two previous electronic travel aids referred to as an "augmented white cane" used ultrasonic distance sensors and vibrotactile feedback to detect obstacles in front of the user (*47*) or at heights of the leg, trunk, and head (*48*). Despite the similar naming convention, these electronic travel aids only provide local collision avoidance and evaluate the effectiveness of their obstacle detection, rather than mobility metrics.

The advanced navigation capabilities of the Augmented Cane could increase independence for people with impaired vision by overcoming navigation tasks that were previously impossible. Closed-loop planning that combines SLAM and path planning eliminates the need for beacons (*31*) or an existing map (*32*) to navigate to a desired location in an indoor environment (Fig. 6). The desired locations of stores or other points of interest could be selected from a mapping platform for streamlined use. Recognizing and localizing key objects could help the participant better understand the environment through audio feedback and provide the capability of visual servoing directly to desired objects, such as doors, elevators, bus stops, and crosswalks. The accuracy of the pretrained object classification models depends on lighting (*43*) and orientation of the object. For example, rotating a stop sign by 60° substantially reduced classification accuracy (Fig. 7A). Thus, extensive evaluation and perhaps custom classification models may be necessary to accurately relay information about key objects to users. Although many of the experiments in this article evaluate navigation tasks independent of one another, fusing information from different sensors may improve the understanding of the environment. The Augmented Cane can assist many types of navigation, providing a platform to plan efficient routes that include a mixture of indoor and outdoor wayfinding, as well as public transportation.

Participants not only reported a higher confidence and a lower perceived workload when navigating with the Augmented Cane than the white cane but also found that the Augmented Cane had a lower usability due to the additional weight of the sensors. The expert participants were older than the novices, which may have contributed to them experiencing more challenges and reporting lower usability scores with either cane. Most expert participants noted that the Augmented Cane was too heavy (table S9), which may explain why the survey reported it as more cumbersome and physically demanding. Thus, weight and complexity are important factors to consider when designing electronic travel aids.

The Augmented Cane is a research prototype that would require substantial engineering improvements and extended experiments with a diverse group of people with impaired vision to be acceptable for everyday use. Although the design of the Augmented Cane is open-source, it requires mechanical assembly and soldering, which are challenging for people with impaired vision. The Augmented



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Algorithm: Closed loop planning
1. Simultaneously localize and map (SLAM) environment
2. Filter obstacles
3. Plan path (A*) to goal
4. Steer cane along path
5. Return to step 1 until goal is reached
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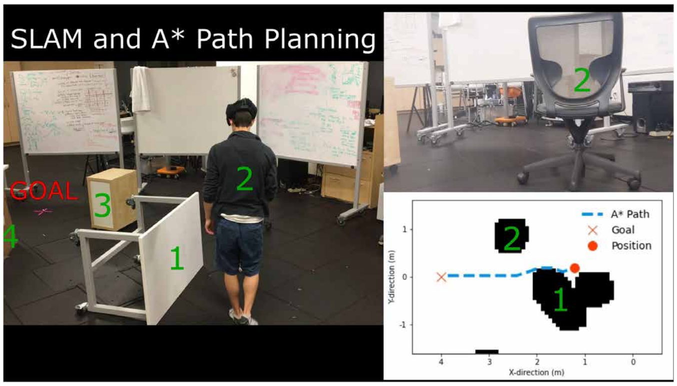
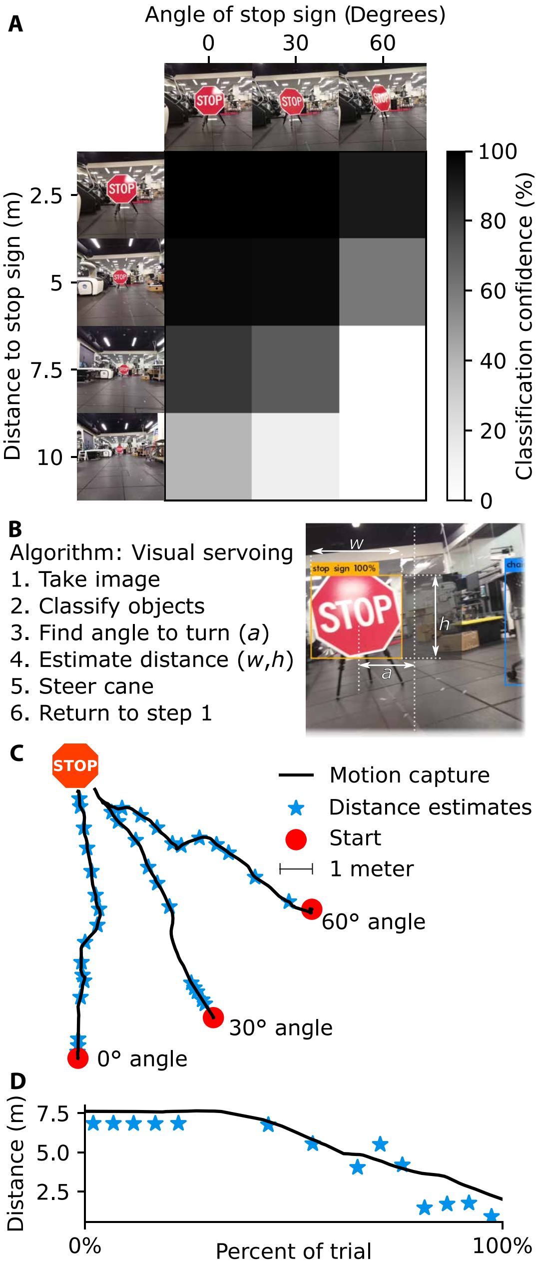
Fig. 6. Demonstrating closed-loop planning to navigate to a desired indoor position. (**A**) Each step of the closed-loop planning algorithm is listed and illustrated with example images. (**B**) One blindfolded novice participant used this algorithm and the Augmented Cane to navigate to a goal position 4 m away. The participant successfully reached the goal in five successive trials despite obstacles being less than 0.5 m apart. The Augmented Cane estimated the position of the participant and mapped the environment by using LIDAR-based SLAM. The SLAM position estimates compared with motion capture had an average RMSE of 0.26 ± 0.18 m across all trials. The trial represented in this figure had an RMSE of 0.28 m. The Augmented Cane contacted the obstacles three times during the trials.



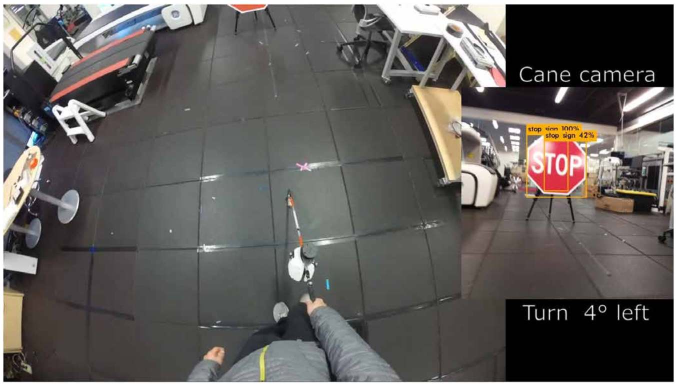
Movie 4. Demonstration of the Augmented Cane performing closed-loop planning to navigate to a desired indoor position in a cluttered environment. The Augmented Cane used LIDAR-based SLAM to determine the position of the participant and the environment. This map was then filtered to detect obstacles, and a path planning algorithm, A*, computed a trajectory to safely reach the desired position. The grounded kinesthetic feedback then steered the user along this trajectory.



```
Algorithm: Visual servoing
1. Take image
2. Classify objects
3. Find angle to turn (a)
4. Estimate distance (w,h)
5. Steer cane
6. Return to step 1
```

Fig. 7. Demonstrating visual servoing to a stop sign. (**A**) A computer vision classification model, YoloV3Tiny (*40*), classifies stop sign images taken at varying distances and angles. The classification confidence depends on the distance and angle to the stop sign. (**B**) The visual servoing algorithm implemented on the Augmented Cane is outlined with an example image. (**C**) One blindfolded novice participant successfully navigated to within 1 m of a stop sign while the Augmented Cane performed visual servoing for each of five trials starting at an initial angle of 0°, 30°, and 60°. (**D**). The linear regression model estimated the distance to the stop sign with an average RMSE of 0.89 m compared with motion capture.

Cane did not include specific sensors to detect vertical drops in terrain or head-level obstacles because previous electronic travel aids addressed those concerns with a single ultrasonic sensor (*26*, *24*), which could be easily integrated into the Augmented Cane. Replacing the sensors and microcontroller with a smartphone could simplify the assembly and reduce weight. The grounded kinesthetic feedback may be improved with an omni wheel that could roll over challenging environments and relay accurate information to the user. Experiments that evaluate the Augmented Cane with a larger number of participants during their normal daily activities would better represent use in the real world.



Movie 5. Demonstration of the Augmented Cane visual servoing to navigate to a stop sign. The visual servoing algorithm consists of taking an image, classifying the stop sign with a bounding box, computing the angle to turn toward the stop sign, estimating the distance to the stop sign using the height and width of the bounding box, and then using the motor to steer the Augmented Cane.

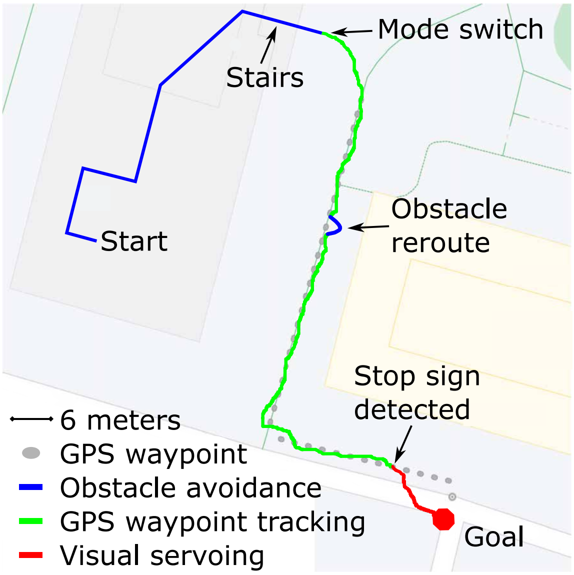


Fig. 8. The Augmented Cane enables navigation indoors, navigation outdoors, and visual servoing to a stop sign. One blindfolded, novice participant completed this course. The participant manually switched the navigation mode from indoors (obstacle avoidance algorithm) to outdoors (GPS waypoint tracking algorithm) by pressing the push button after descending the stairs. While navigating outdoors, the Augmented Cane provided obstacle avoidance and rerouted the participant about halfway through the waypoint tracking. The Augmented Cane automatically transitioned to visual servoing once the stop sign was detected.

The approach demonstrated by the Augmented Cane may offer a solution to help people with impaired vision overcome navigation challenges and improve their mobility or quality of life. The Augmented Cane increased walking speed for novice and expert participants during indoor and outdoor tasks, suggesting that it may provide substantial navigation and mobility improvements. A demonstration with one participant found that the Augmented Cane reduced the cost of transport, indicating that the increased walking speed reduces the metabolic energy needed to reach a destination. Increasing independence for people with impaired vision could provide clinically meaningful improvements to their physical health, mental health, and quality of life. The Augmented Cane's low cost and open-source design make it an accessible tool for researchers wanting to improve navigation for people with impaired vision. Future developments in sensors and portable computation offer exciting possibilities for improving environment understanding and planning to guide participants in complicated navigation. The demonstration of these advanced navigation capabilities illustrates the potential of the Augmented Cane to improve independence for people with impaired vision.

MATERIALS AND METHODS

Study design

The goal of this study was to design a device that could help people with impaired vision navigate more quickly and easily compared with a white cane. This study consisted of seven experiments: haptic feedback comparison, indoor hallway navigation, indoor obstacle avoidance, outdoor navigation, closed-loop planning to a desired position, visual servoing to a stop sign, and demonstration combining all the previous navigation experiments. The number of participants for the haptic feedback comparison and indoor navigation experiments was selected using a power analysis of data from one pilot participant. The power analysis (power of 0.9) recommended 9 participants, but 12 were selected to ensure that an equal number of participants completed each possible ordering of the three feedback modes. The number of novice participants in the outdoor experiment (eight) was selected with a power analysis (power of 0.9) of the results of the indoor hallway experiment (specifically, the difference in the walking speed of novice participants using the Augmented Cane versus a white cane in the indoor hallway experiment with turns). In the last three experiments, one participant was selected because the goal was to demonstrate the capabilities and consistency of the Augmented Cane, rather than evaluate how the Augmented Cane affected the person's mobility. All trials were completed successfully, and no participant's data were excluded. The GPS signal used during the outdoor experiment was rarely affected by the weather, in which case participants restarted the trial. Statistical significance between the participants' performance with the Augmented Cane and a white cane was evaluated using a two-way ANOVA that considered the independent factors of the individual participants and the type of cane (Augmented Cane or white cane).

Design of the Augmented Cane

The Augmented Cane was designed to meet the recommended design criteria for a navigation assistance device to be effective during everyday use (*16*, *49*). The device should be lightweight and use portable sensors. Assistance should not interfere with the mobility of the user, which includes excessive weight that could increase the energy expended while walking. Existing infrastructure, such as tactile paving surfaces used at crosswalks and railways, should be used for safety (*50*). Assistive devices should retain local obstacle detection, such as a white cane or guide dog, in the event of technology or power failure. Ideally, the device would provide navigation assistance in any location without requiring sensors to be placed in a specific environment (*49*). The initial design of the Augmented Cane was improved through three co-design sessions with a participant with impaired vision. The participant received instruction on how to operate the device and then used it to navigate indoor hallways and avoid obstacles. The sessions each lasted about an hour, with the participant providing suggestions and discussing observations with the researcher while evaluating the device.

An aluminum white cane was selected as the base of the Augmented Cane because it provided a platform to mount additional sensors and a motor. The white cane was 122 cm long, was made of aluminum, weighed 242 g, and had a pencil tip. These metrics are within the measurements of a typical cane, although the recommended length changes with the user's height and how the cane is used (*27*). The pencil tip allowed for more room to place the motor and grounded haptic wheel at the bottom of the cane. Other tips, such as marshmallow or roller, offer trade-offs in terms of sensitivity and environment interactions (*51*, *52*).

The Augmented Cane consists of lightweight, portable, and low-cost components that include a set of sensors, microcontroller, and hardware for providing grounded kinesthetic feedback. The total cost of the components is about $400 USD, and the parts list and design is available in a public repository (*53*). A 2D LIDAR (RPLIDAR-A1, Slamtec) provides rapid distance measurements around the user in the transverse plane. The LIDAR measures 360° with 0.9° between beams and samples the full revolution of measurements at a frequency of 5 Hz. A monocular camera (Camera Module V2, Raspberry Pi Foundation) provides high-resolution images. A GPS breakout board (Ultimate GPS Breakout, Adafruit) and an antenna provide position estimates with an accuracy of 3 m at 1 Hz. An inertial measurement unit, consisting of a three-axis gyroscope, accelerometer, and magnetometer, measures the relative orientation of the Augmented Cane (Precision NXP 9-DOF Breakout Board, Adafruit). A portable microcontroller (Raspberry Pi 4 Model B, Raspberry Pi Foundation) provides computation to perform sensing and feedback in real time. A motorized omni wheel applies torques to steer the user to the left or right while allowing the user to control their forward walking speed (Nexus Robot). The omni wheel provides effective grounded kinesthetic feedback when the Augmented Cane is held at an angle between 20° and 70° to assist participants with different heights. A brushed motor with a low gear ratio of 4.4 to 1 drives the omni wheel, allowing the user to overpower the motor if necessary while providing a peak torque of 0.078 N·m to turn the user up to 90°/s (Pololu). This motor also assisted in sweeping the cane back and forth at a frequency of 1.2 Hz to reduce the effort required by the user during normal operation. A rechargeable battery powered the microcontroller for up to 4.2 hours when using all sensors. A lithium polymer battery powered the motor for 5.2 hours on a single charge. A push button on the handle of the Augmented Cane enabled the participant to turn off the motor.

Experiment design

The research objective was to compare the Augmented Cane with a white cane in experiments that emulated a range of navigation tasks representative of free-living navigation for a person with impaired vision. All participants were volunteers and provided written informed consent before completing the protocol IRB-55295 approved by the Stanford University Institutional Review Board. The series of five experiments conducted in this study are detailed in the next five sections. These experiments consist of human participant tests in both indoor and outdoor environments. The experiments evaluated novice participants, or people without previous experience using a white cane, as well as expert participants, people with impaired vision who regularly used a white cane for navigation. The novice participants were young and healthy with an average age of 25.3 ± 2.8 years. The expert participants had an average age of 45.8 ± 16.1 years and had an average of 17.7 ± 10.8 years of experience using a white cane. Participant-specific information for the expert participants is provided in table S2. All participants wore blindfolds to control for the same level of vision, following previous studies (*25*, *32*, *17*, *54*). The code used to control the Augmented Cane and feedback modes during the experiments is available in the open-source Augmented Cane repository (*53*).

During experiments, the expert participants used their personal white canes and novice participants used a white cane identical to the base of the Augmented Cane. Novice participants were instructed in the most common white cane techniques: the two-point touch and constant contact (*27*). The two-point touch involves swinging the cane side to side, tapping the ground on just the ends of the swing at about the width of the shoulders. Constant contact sweeps the cane side to side while maintaining contact with the ground. The novice users were shown three grip styles: standard, pencil, and traditional (*55*), as well as several positions to hold the cane: in front of the body above the waist (centered high), below the waist (centered low), and to the side (off-center) (*21*, *56*). All novice participants chose to use the standard grip and off-center position. They were also instructed to move the cane with the wrist only, following expert training advice (*19*). All participants were required to hold the Augmented Cane below the waist (centered low) with a traditional grip and explore the environment with constant contact.

Several mobility metrics were collected to compare navigation with the Augmented Cane and white cane for each trial: distance, duration, average walking speeds, and number of contacts with the environment. Distances during the indoor experiments were computed either with an optical motion capture system (OptiTrack) that measured the positions of a set of five markers on a hat and a set of three or four markers placed on the white cane or Augmented Cane at 100 Hz or by integrating inertial measurements using a zero-velocity update (*57*) at 100 Hz. Preliminary tests found that the difference in distance estimates using optical motion capture and inertial measurements was less than 4%. Outdoor experiments used GPS positions to compute distance. The average walking speed was computed by dividing the total length of the course by the time the participant took to complete the course. The number of contacts with the environment was counted as any individual strike or slide of the cane along a portion of the environment other than the floor. The metabolic energy expended, while walking was estimated with a mobile K5 respirometry unit (COSMED) that measured oxygen and carbon dioxide.

Comparison of haptic feedback modes

We compared the accuracy of grounded kinesthetic, vibrotactile, and audio feedback in allowing users to accomplish a turn-in-place task. This experiment used a white cane attached to a vertical rod with a connecting bracket that allowed the cane to be held in a comfortable position and rotated in place (fig. S6). A potentiometer mounted at the top of the rod measured the angle as the participant turned in place to an accuracy of 0.1° at a rate of 100 Hz. The experiment consisted of a blindfolded participant turning to the left or right to reach a randomized target angle while receiving feedback. Once the participant thought they reached the target angle, they pressed the push button on the cane handle, returned to their initial position, and pressed the button to receive the prompt for the next target angle. For each feedback mode, participants received 5 random target angles for practice and then completed 18 target angles, ranging from 90° left to 90° right at increments of 10°. Participants were instructed to reach the target angle as accurately and quickly as possible. Expert white cane users do not regularly receive any of these modes of feedback, so we assumed that the novices and experts would perform similarly and selected novices to complete the experiment.

The feedback modes provided information to the user to help them reach the target angle. Earbuds provided audio feedback to relay verbal instructions to "Turn X degrees to the left (or right)," for a target angle of X degrees. Heading angles were recorded starting immediately after the verbal instructions finished. The motorized omni wheel on the Augmented Cane provided grounded kinesthetic feedback by turning the tip of the cane. Hardware details are included in the previous section on the design of the Augmented Cane. The grounded kinesthetic feedback used a proportional controller, where the torque applied by the motorized omni wheel was linearly related to the error between the current and target angle. The vibrotactile feedback used two vibrating coin motors (Precision Microdrives) placed on the back of the hand holding the cane at the distal index and small metacarpal bones on the hand and driven with a breakout board (DRV2605L, Adafruit). A proportional controller linearly mapped the error between the current and target angles to vibrations in the left or right vibrating motor, similar to previous electronic travel aids that provided vibrotactile feedback (*25*).

Indoor and outdoor navigation experiments

Indoor navigation was evaluated with two experiments, where 12 novice and 12 expert participants were blindfolded and walked through hallways constructed with cardboard (Movie 2). Because of the increased COVID-19 risks that people with impaired vision face (*8*), we performed this test in easily accessible locations near four of the expert participants' homes. Participants were instructed to navigate as accurately and quickly as possible. The indoor hallway experiment had participants navigate a hallway with two 90° turns. The hallway was rearranged between trials to form all four possible combinations of two turns (left or right) (fig. S7A). The hallway was 1.2 m wide, with 1.8 m between turns. The indoor obstacle avoidance experiment had participants walk through a straight cardboard hallway that was 1.8 m wide and 4.3 m long while avoiding two obstacles (fig. S7B). The obstacles had widths of 0.6 and 0.8 m and were 0.8 m long and 1 m wide. The obstacles were evenly spaced along the width of the hallway and positioned randomly along the length, at least 0.5 m from the start to end. Whether participants completed the experiment with the augmented or white cane first was randomized, with the same number of participants completing each method first. The ordering of turns and obstacle placements was also randomized. The number of contacts with the environment was counted manually during the experiments. The white cane motion capture data were also used to detect the times when the contacts with the environment occurred to understand the change in walking speed before and after the contact. These contacts were detected by finding decelerations of the white cane that were at least three times larger than normal sweeping.

The Augmented Cane used a simple obstacle avoidance algorithm to provide grounded kinesthetic feedback to steer away from obstacles (fig. S1). The obstacle avoidance algorithm used the LIDAR distance measurements to determine whether an obstacle was within 1.8 m and 20° from the position and orientation of the Augmented Cane. These distance and angle thresholds were experimentally selected to allow a person walking at 1 m/s to turn 60° before contacting the obstacle. If an obstacle was detected, the Augmented Cane steered the participant toward the LIDAR heading angle with the longest distance measurement to an obstacle. The algorithm operated at 10 Hz to quickly react to obstacles.

A single participant performed an additional indoor test to evaluate the cost of transport when walking with the Augmented Cane or the white cane. The participant walked in a circular hallway with a radius of 2.5 m and a hallway width of 1.2 m. Both canes were evaluated three times in alternating order. The motion of the participant was recorded with motion capture while simultaneously measuring the metabolic energy expended with respirometry. The cost of transport was computed as the metabolic energy consumed per unit distance.

The outdoor navigation experiment had eight novice and four expert participants walk about 200 m along an asphalt path with two sets of bollards (fig. S8 and Movie 3). The participants tracked a series of GPS waypoints that acted as the ground truth positions along the path. The participant navigated to within 5 m of each waypoint along the route, relying on either the Augmented Cane or a white cane with audio feedback. The Augmented Cane used a proportional controller to provide grounded kinesthetic feedback to steer the user toward the next waypoint, using a GPS waypoint tracking algorithm (fig. S2). If the obstacle avoidance algorithm detected an obstacle, the Augmented Cane played an audio file saying "obstacle ahead" through an earbud. The white cane provided audio feedback every 10 s telling the participant to turn left or right the appropriate number of degrees toward the next waypoint. The current heading of the participant was computed with a magnetometer, and the heading to the next waypoint was computed using the direction from the current GPS location to the waypoint. The same number of participants completed the experiment using the Augmented Cane or white cane first.

Demonstrations of advanced navigation capabilities

The Augmented Cane performed closed-loop planning to navigate to a desired indoor position using LIDAR measurements (Fig. 6A and Movie 4). This algorithm operated at 1.4 Hz relying on a fast SLAM implementation (*33*) that was sufficient for real-time use. Obstacles were detected from the gray scale SLAM map using a Canny edge detector (with sigma = 4). One blindfolded novice participant navigated a cluttered indoor environment to reach a goal position 4 m directly in front of their starting position. The obstacles included a table, chair, desk, and set of drawers. These obstacles were placed between the starting and goal positions with at least 0.5 m between obstacles.

The Augmented Cane performed a visual servoing to steer the participant toward a stop sign. The visual servoing algorithm (Fig. 7B) operated at a rate of 1.4 Hz. A pretrained computer vision model, YoloV3Tiny (*43*), classified the stop sign and any other objects detected in pictures taken by the camera mounted on the Augmented Cane. YoloV3Tiny is a real-time object detection model that uses a deep convolutional neural network to rapidly find multiple objects in an image from a set of 80 object classes (*43*). The distance to the stop sign was estimated using a linear regression model based on the width and height of the bounding box that detected a stop sign in an image. This linear regression model was trained from stop sign training images consisting of five images taken at each combination of a set of distances (2.5, 5, 7.5, and 10 m) and angles (0°, 30°, and 60° from directly facing the sign) (Fig. 7A). The stop sign's center pixel location detected by YoloV3Tiny was linearly related to the horizontal camera field of view of 62.2° to find the angle to steer the participant toward the stop sign. The stop sign was selected as a representative object from signs and key objects that are important for wayfinding. One blindfolded novice participant walked toward a stop sign placed 7 m away in an unobstructed indoor environment. The stop sign was rotated 0°, 30°, and 60° from directly facing the person, and the experiment was conducted five times for each angle. The person started at a randomized initial heading angle between 30° to the left or right to ensure the stop sign would be within the camera's field of view.

One novice participant used the Augmented Cane to complete a complicated route: navigating an indoor hallway, then tracking outdoor GPS waypoints, and finally performing visual servoing to reach a stop sign (Fig. 8). The participant first navigated a known path along indoor hallways while the Augmented Cane provided obstacle avoidance. Once outside, the participant descended a flight of stairs and pressed the push button to switch to outdoor operation. The Augmented Cane steered the participant to follow a series of GPS waypoints while also avoiding obstacles when they were detected by the LIDAR sensor. The camera on the Augmented Cane performed object recognition to detect stop signs. When a stop sign was detected, the cane switched to visual servo toward the sign. The course was completed when the participant was less than 1 m from the stop sign.

SUPPLEMENTARY MATERIALS

www.science.org/doi/10.1126/scirobotics.abg6594
Figs. S1 to S8
Tables S1 to S9
References (*58–60*)

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