RAIS: Towards A Robotic Mapping and Assessment Tool for Indoor Accessibility Using Commodity Hardware

Xia Su
Allen School of Computer Science
University of Washington, USA
xiasu@cs.uw.edu

Daniel Campos Zamora
Allen School of Computer Science
University of Washington, USA
danielcz@cs.uw.edu

Jon E. Froehlich
Allen School of Computer Science
University of Washington, USA
jonf@cs.uw.edu

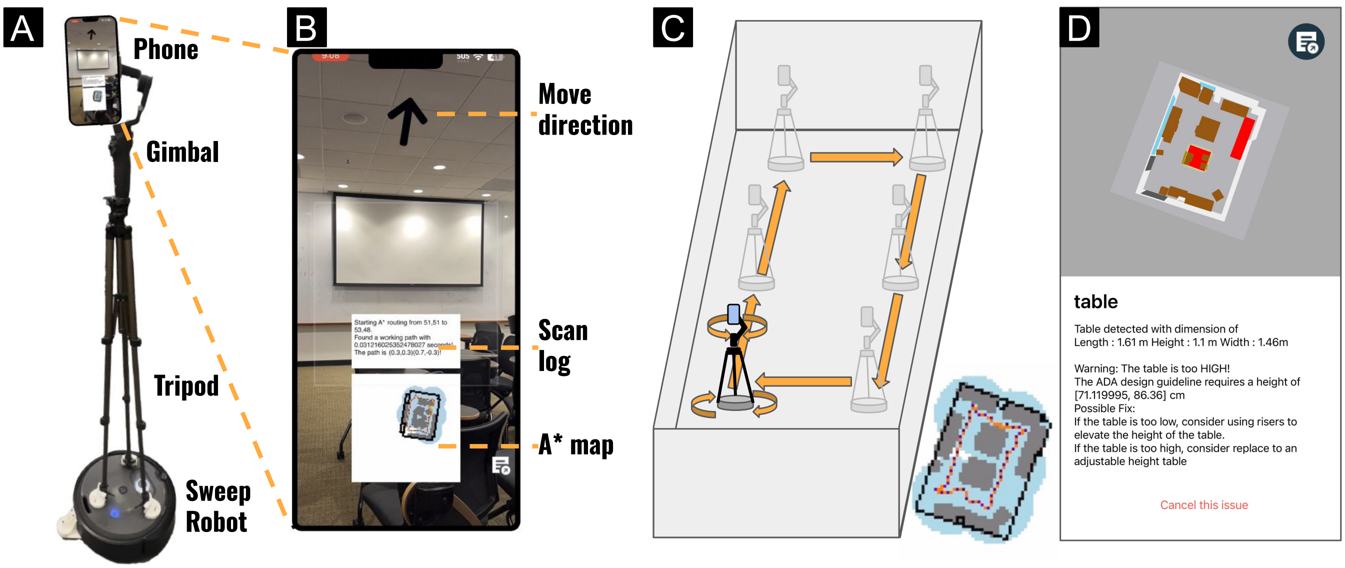

Figure 1: We introduce the *Robotic Accessibility Indoor Scanner* (RAIS), an automated indoor mapping and accessibility assessment system constructed with off-the-shelf components. (A) The RAIS hardware prototype, (B) scanning interface, (C) scanning process with a 2D generated map, (D) and autogenerated 3D parametric model with detected accessibility issues in red.

ABSTRACT

Mapping, assessing, and creating personalized routes of indoor spaces for people with disabilities remains a grand challenge in accessibility research. Drawing on recent work in robotics as well as emergent work in smartphone-based mapping, we introduce *RAIS* (*Robotic Accessibility Indoor Scanner*), a robotic-based indoor mapping and accessibility assessment system. As a rapid prototype, RAIS is constructed with off-the-shelf components including a vacuum robot, smartphone, and phone gimbal along with a modified version of our previous LiDAR-based accessibility scannar *RASSAR*. In a preliminary evaluation of three indoor spaces, we demonstrate RAIS's ability to autonomously scan spaces, produce detailed 3D reconstructions, and find and highlight accessibility issues.

ASSETS '24, October 28–30, 2024, St. John's, Newfoundland and Labrador

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM...$15.00
https://doi.org/https://doi.org/10.1145/3663548.3688512

CCS CONCEPTS

• **Human-centered computing → Accessibility systems and tools**.

KEYWORDS

Indoor accessibility mapping, LiDAR, computer vision, map generation, indoor accessibility assessment

ACM Reference Format:
Xia Su, Daniel Campos Zamora, and Jon E. Froehlich. 2024. RAIS: Towards A Robotic Mapping and Assessment Tool for Indoor Accessibility Using Commodity Hardware. In *Proceedings of The 26th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '24).* ACM, New York, NY, USA, 5 pages. https://doi.org/https://doi.org/10.1145/3663548.3688512

1 INTRODUCTION

Despite significant recent progress [4, 23, 27, 29, 31, 36], mapping, assessing, and creating personalized routes of indoor spaces for people with disabilities remains a grand challenge in accessibility research [10, 28]. With advances in photogrammetry, camera hardware, and laser scanning, emerging companies such as *Matterport* [15], *Metareal* [16], and *EyeSpy360* [13] can create precise and fully immersive 3D reconstructions of indoor spaces for virtual tours and other mapping applications. Others have designed push-carts equipped with scanning sensor suites such as FARO's *Focus Swift* [2] or large wearable "backpack" systems such as the NavVis *VLX 3* [19]. While offering high-fidelity scans useful for blueprint generation, construction tracking, and virtual walkthroughs, the focus has not been on understanding and evaluating indoor space accessibility (*e.g.,* narrow hallways, staircases, lack of assistive aids). Moreover, these hardware systems are costly and the scans are time consuming, expensive, and often require professional training. Thus, scaling such systems to identify and track accessibility problems in large indoor buildings such as offices, airports, and train stations is cost prohibitive.

Drawing on recent work in robotics for automated indoor scanning and inspection [14, 25] as well as emergent work in smartphone-based indoor accessibility mapping [30, 31, 36], we introduce *RAIS* (*Robotic Accessibility Indoor Scanner*), a robotic-based indoor mapping and accessibility assessment system (Figure 1). As a rapid prototype, RAIS is made with off-the-shelf components, including a vacuum robot, smartphone, and phone gimbal, and runs an indoor accessibility 3D reconstruction and auditing application called RASSAR [31]. Although preliminary, RAIS is able to independently navigate unknown indoor and detect potential accessibility issues in real time. RAIS generates parametric 3D map reconstructions, which support both *in-situ* and *post-hoc* accessibility audits of scanned spaces.

To evaluate RAIS, we performed a pilot study in three indoor environments: a maker space, a classroom, and an office. We placed RAIS in random positions, started the scanning session, and let RAIS independently conduct the indoor reconstruction and accessibility scan. Our preliminary evaluation shows RAIS is able to complete fully automatic scans, efficiently generate a 3D reconstruction including architectural features (walls, doors, windows) and furniture, and highlight accessibility issues in the space.

In summary, this poster paper contributes a new, low-cost robotic mapping and indoor accessibility assessment prototype made of commodity hardware. Our overarching goal is to develop new automated indoor mapping techniques that prioritize accessibility and support remote visit planning, *in situ* navigation support of accessible routes, and infrastructure maintenance.

2 RELATED WORK

To collect indoor accessibility data, current practices predominantly rely on manual efforts, such as home assessments conducted by occupational therapists [17] or the use of accessibility checklists [6, 8, 22, 32, 34]. Research indicates a scarcity of professional assistance [24], suggesting that digitizing indoor accessibility evaluation methods could expand their reach. Recent work, such as *RASSAR* [31] and *AccessLens* [18], has explored the feasibility of using smartphones to conduct indoor accessibility scans. However, these digital solutions still require manual intervention, making large-scale and long-term data collection challenging.

In contrast, fully automatic indoor mapping and modeling methods have long been implemented [12]. With SLAM (Simultaneous Localization and Mapping) [37], robots can explore unknown spaces and construct maps. As this research field matures, recent work has introduced a variety of robotic platforms [1, 26, 33] and sensors [21, 38, 39], greatly expanding the potential for application tasks, including accessibility-oriented tasks like guidance robots [4, 5, 11] and assistive robot walkers [7]. We envision such robotic methods being applied to indoor accessibility data collection.

Building on this prior work, our RAIS system aims to combine smartphones' proven capability for indoor accessibility mapping with the maneuverability of indoor vacuum robots to create the first fully automatic indoor accessibility mapping system. By rapidly building and testing a technical prototype, we demonstrate feasibility and describe future work in the Discussion.

3 THE RAIS PROTOTYPE

To examine the feasibility of creating an robotic-based indoor mapping plus accessibility scanning system, we rapidly constructed a hardware-software prototype using off-the-shelf components. Below, we enumerate the key design components before describing how the RAIS mapping and scanning process works.

3.1 Design & Components

As a rapid prototype, RAIS is built with commodity hardware and software components:

LiDAR-equipped smartphone: To scan and reconstruct 3D environments, we use a LiDAR-equipped smartphone (*iPhone 13 Pro Max*). The real-time reconstructed map also guides the robot path control.

Robot: To autonomously navigate and map indoor environments, we use a wheeled vaccum robot (*iRobot Create 3*).

Motorized phone gimbal: To control the capture angles of the smartphone and ensure maximum coverage, the phone is mounted on a motorized gimbal (*DJI Osmo Mobile 6*) which is controlled to rotate left, right, up, and down during scan.

Tripod: We elevate the gimbal and phone with a tripod to improve capture of indoor objects.

Software: The 3D reconstruction and real-time accessibility barrier scanning is conducted by our previously published system called RASSAR [30, 31], a custom iPhone application that identifies, localizes, and visualizes indoor accessibility and safety issues such as inaccessible table height or unsafe loose rugs using LiDAR and a custom-trained computer vision model. In addition, we wrote custom iPhone software to help route the RAIS robot and control the gimbal, which we describe below.

3.2 Scanning Process

To enable RAIS to explore and scan unknown indoor spaces, we implemented SLAM and a routing strategy. We use *Apple's ARKit* and *Roomplan API* [3] to create real-time 3D reconstruction of indoor spaces and locate the 3D coordinates of the robot. For the exploration and navigation algorithm, we implemented two methods: (1) a strategy to guide the robot into unknown spaces, (2) and an A* pathfinding algorithm to avoid obstacles.

For the former, we use the classic wall-following algorithm [35]. First, the robot is placed in a position away from the wall where the phone performs an initial scan to recreate a partial map. RAIS picks the nearest wall to follow at a constant distance of 1.2 meters. When a new wall is detected within 1.2 meters, RAIS chooses this

Algorithm 1 RAIS Wall Following Strategy

```
while not back at initial position do
    if further than 2.5m from already scanned positions then
        Rotate robot and gimbal to perform scan at current position
    end if
    if not following any wall then
        Find nearest wall and start following it
    end if
    Move along the following wall
    if new wall detected within 1.2m then
        Follow the new wall
    else if left-side wall ends then
        Turn left, move forward until a new wall to follow is found.
  Follow this new wall.
    end if
end while
end algorithm
```

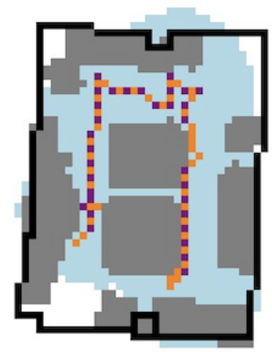

Figure 2: Example of RAIS's A* routing. Grid cells are 20cm × 20cm. Black indicates wall, gray for furniture, blue for scanned space, orange for path, and purple for stopped positions.

new wall to follow. This strategy continues until the robot returns to its initial position and closes its moving trajectory loop (*i.e.,* the scanning process is declared complete). See Algorithm 1.

Since objects such as furniture and clutter may obstruct the robot's path, we employ the well-established A* pathfinding algorithm to avoid obstacles [9]. As the RoomPlan API provides the real-time 3D reconstruction of the scanned space, we rasterize this information to create a grid map. The current location and the moving goal are projected onto the grid map to conduct A*. The resulting path is then executed by the robot. An example of such routing process is shown in Figure 2.

3.3 Scanning Result

After the scan, the layout of the room as well as the indoor objects (*e.g., tables, chairs*) are represented as a 3D parametric model. This model includes architectural features like walls, doors, windows, and also furniture like tables and chairs. An example of the room reconstruction is shown in Figure 1D. This visualization interface is reused from RASSAR [31] but the model could be downloaded and viewed by other CAD programs in the future. By further applying accessibility rubrics, potential accessibility issues can be detected in the scanned space either during the scan or in *post-hoc* analysis.

For this initial prototype, we adopt four accessibility rubrics from ADA design guidelines [20]. (1) *door width:* if doors are wide enough—more than 32" (81.3 cm)—for wheelchair to pass; (2) *table or counter height:* if tables and counters have proper height—between 28–34" (71.1–86.4 cm); (3) *cabinet height:* if cabinets are placed low enough—below 27" (68.6 cm)—to reach; (4) *Routing Space:* if indoor paths/corridors are wide enough for wheelchair to pass—more than 36" (91.4 cm). Issues 1,2 and 3 can be automatically detected in real-time during the scan process, while Issue 4 is currently filtered from scan results manually and will be automated in the future.

4 PRELIMINARY EVALUATION

To evaluate the RAIS's performance, we performed test scans in three indoor environments: a makerspace, a classroom, and an office (Table 1). For each space, we deployed RAIS at a random location and started an automatic scan. The RAIS robot then maneuvered within the space, generated a 3D reconstruction and 2D map, and conducted an accessibility scan. The entire scanning process was timed and recorded. For comparison, we also conducted a manual inspection to determine ground truth. The space details, scan time, as well as accessibility issue detection stats are shown in Table 1. We also show corresponding pictures of the indoor spaces, the generated maps, and RAIS' scan route in Figure 3.

Overall, we found that RAIS could successfully complete indoor scans in all three indoor spaces. The scans took approximately 8.5 minutes. RAIS detected 75% of accessibility issues, including inaccessible table and counter heights in the makerspace and office as well as narrow corridors in the classroom and office; however, RAIS missed identifying an inaccessible cabinet in the makerspace. While preliminary, these results demonstrate feasibility.

5 DISCUSSION AND FUTURE WORK

RAIS addresses the challenge of indoor accessibility mapping data collection. The data collected, as parametric 3D reconstructions, could promote accessible infrastructure and provide information and directions for people with disabilities. We built RAIS to explore the feasibility of automatically creating, updating, and maintaining indoor maps focused on accessibility. The preliminary evaluation demonstrated RAIS' potential and is a promising step towards addressing the grand challenge of indoor accessibility maps.

RAIS, being fully automated and capable of exploring unknown indoor spaces, is ideal for deployment in constantly changing environments that require regular accessibility maintenance, such as malls and public transportation stations. By conducting regular scans, RAIS can provide continuously updated indoor accessibility maps at a low cost. These scan results can also assist building managers in improving other aspects of the space, such as cleanliness and safety.

As a proof-of-concept prototype, RAIS demonstrates scanning capabilities but leaves several research questions unanswered. For

Table 1: The RAIS test spaces and results. Accessibility issues are indicated by their index in Section 3.3.

Space	Space Size (Sqm)	Scan Time (Min)	Time Per Sqm (Sec/Sqm)	Issues in Space	Issues Detected
S1: Makerspace	40	10	15	i2, i2, i2, i3	i2, i2
S2: Office	32	6.5	9.75	i2, i2, i4	i2, i2, i4
S3: Classroom	48	9	11.25	i4	i4

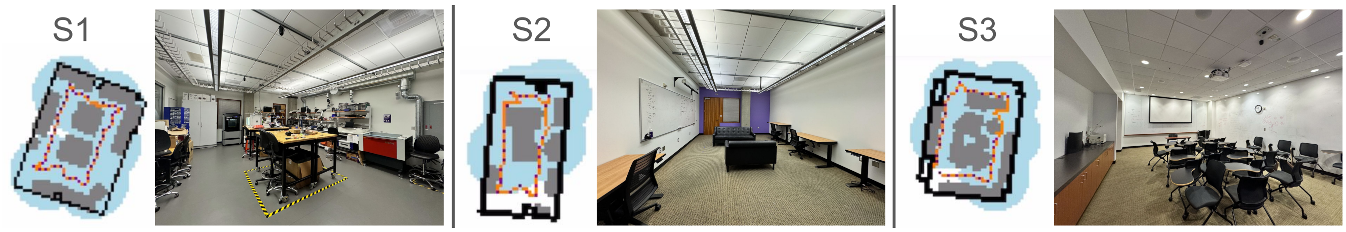

Figure 3: We conducted a preliminary evaluation of RAIS in three indoor spaces: a makerspace (S1), an office (S2), and a classroom (S3). We show images of each space as well as the autogenerated 2D map created by RAIS and RAIS's scanning route.

instance, can RAIS's scanning devices integrate with other widely applied indoor robots, like floor scrubbers? Can RAIS robustly and efficiently scan larger indoor spaces such as malls and train stations? Additionally, how can the scan results be inspected, tracked, archived, and shared to enhance understanding of indoor accessibility while supporting space maintenance? We plan to conduct future implementations and studies to address these questions.

6 CONCLUSION

In this paper, we present RAIS, a step towards the first fully automated indoor accessibility mapping system. RAIS can scan and reconstruct unknown indoor environments, create 3D parametric reconstructions and 2D maps, and identify potential accessibility issues using LiDAR and computer vision. Our preliminary evaluation in three indoor spaces demonstrates RAIS's potential. We believe that RAIS represents the future of indoor accessibility auditing, where fully automated systems can conduct regular scans of indoor spaces without manual control, maintaining a constantly updated accessibility map that can benefit indoor navigation and facility maintenance.

ACKNOWLEDGMENTS

This project was funded by the Center for Research and Education on Accessible Technology and Experiences (CREATE) at the University of Washington.

REFERENCES

[1] Wilayat Ali, Li Sheng, and Waleed Ahmed. 2021. Robot Operating System-Based SLAM for a Gazebo-Simulated Turtlebot2 in 2d Indoor Environment with Cartographer Algorithm. *International Journal of Mechanical and Mechatronics Engineering* 15, 3 (Feb. 2021), 149–157. https://publications.waset.org/10011916/robot-operating-system-based-slam-for-a-gazebo-simulated-turtlebot2-in-2d-indoor-environment-with-cartographer-algorithm

[2] Aniwaa. 2020. FARO Focus Swift. https://www.aniwaa.com/product/3d-scanners/faro-focus-swift/ Accessed: 2024-08-15.

[3] Apple. 2022. RoomPlan - Augmented Reality. https://developer.apple.com/augmented-reality/roomplan/

[4] Shaojun Cai, Ashwin Ram, Zhengtai Gou, Mohd Alqama Wasim Shaikh, Yu-An Chen, Yingjia Wan, Kotaro Hara, Shengdong Zhao, and David Hsu. 2024. Navigating Real-World Challenges: A Quadruped Robot Guiding System for Visually Impaired People in Diverse Environments. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 44, 18 pages. https://doi.org/10.1145/3613904.3642227

[5] Yanbo Chen, Zhengzhe Xu, Zhuozhu Jian, Gengpan Tang, Liyunong Yang, Anxing Xiao, Xueqian Wang, and Bin Liang. 2023. Quadruped Guidance Robot for the Visually Impaired: A Comfort-Based Approach. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, London, United Kingdom, 12078–12084. https://doi.org/10.1109/ICRA48891.2023.10160854

[6] Teresa Chiu and Rosemary Oliver. 2006. Factor analysis and construct validity of the SAFER-HOME. *OTJR: Occupation, Participation and Health* 26, 4 (2006), 132–142.

[7] Daisuke Chugo, Shohei Kawazoe, Sho Yokota, Hiroshi Hashimoto, Takahiro Katayama, Yasuhide Mizuta, and Atsushi Koujina. 2017. Pattern based standing assistance adapted to individual subjects on a robotic walker. In *2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, Lisbon, 1216–1221. https://doi.org/10.1109/ROMAN.2017.8172459

[8] Lindy Clemson. 1997. *Home Fall Hazards: A Guide to Identifying Fall Hazards in the Homes of Elderly People and an Accompaniment to the Assessment Tool, The Westmead Home Safety Assessment (WeHSA)*. Co-ordinates Publications.

[9] Basem M. ElHalawany, Hala M. Abdel-Kader, Adly TagEldeen, Alaa Eldeen Elsayed, and Zaki B. Nossair. 2013. Modified A* algorithm for safer mobile robot navigation. In *2013 5th International Conference on Modelling, Identification and Control (ICMIC)*. 74–78.

[10] Jon E. Froehlich, Anke M. Brock, Anat Caspi, João Guerreiro, Kotaro Hara, Reuben Kirkham, Johannes Schöning, and Benjamin Tannert. 2019. Grand challenges in accessible maps. *Interactions* 26, 2 (Feb. 2019), 78–81. https://doi.org/10.1145/3301657

[11] João Guerreiro, Daisuke Sato, Saki Asakawa, Huixu Dong, Kris M. Kitani, and Chieko Asakawa. 2019. CaBot: Designing and Evaluating an Autonomous Navigation Robot for Blind People. In *The 21st International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, Pittsburgh PA USA, 68–82. https://doi.org/10.1145/3308561.3353771

[12] Mehmet Gunduz, Umit Isikdag, and Melih Basaraner. 2016. A review of recent research in indoor modelling & mapping. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 41 (2016), 289–294.

[13] EyeSpy360 Inc. 2024. EyeSpy360: 360 Virtual Tour Software. https://www.eyespy360.com/en-us/. Accessed: 2024-08-15.

[14] HP Inc. 2024. HP SitePrint - Robotic Layout Solution. https://www.hp.com/us-en/printers/site-print/layout-robot.html Accessed: 2024-08-15.

[15] Matterport Inc. 2024. Matterport: 3D Capture Platform. https://matterport.com/. Accessed: 2024-08-15.

[16] Metareal Inc. 2024. Metareal: Virtual Tours Made Simple. https://www.metareal.com/. Accessed: 2024-08-15.

[17] Susanne Iwarsson. 1999. The Housing Enabler: An Objective Tool for Assessing Accessibility. *British Journal of Occupational Therapy* 62, 11 (Nov. 1999), 491–497. https://doi.org/10.1177/030802269906201104 Publisher: SAGE Publications Ltd

STM.
[18] Nahyun Kwon, Qian Lu, Muhammad Hasham Qazi, Joanne Liu, Changhoon Oh, Shu Kong, and Jeeeun Kim. 2024. AccessLens: Auto-detecting Inaccessibility of Everyday Objects. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–17.
[19] NavVis. 2024. NavVis VLX 3. https://www.navvis.com/vlx-3 Accessed: 2024-08-15.
[20] U.S. Department of Justice. 2024. 2010 ADA Standards for Accessible Design. https://www.ada.gov/law-and-regs/design-standards/. Accessed: 2024-08-15.
[21] Hesham Ibrahim Mohamed Ahmed Omara and Khairul Salleh Mohamed Sahari. 2015. Indoor mapping using kinect and ROS. In *2015 International Symposium on Agents, Multi-Agent Systems and Robotics (ISAMSR)*. IEEE, Putrajaya, Malaysia, 110–116. https://doi.org/10.1109/ISAMSR.2015.7379780
[22] Alexandre Patry, Claude Vincent, Christian Duval, and Emmanuelle Careau. 2019. Psychometric properties of home accessibility assessment tools: A systematic review. *Canadian Journal of Occupational Therapy* 86, 3 (June 2019), 172–184. https://doi.org/10.1177/0008417418824731
[23] Siyou Pei, Alexander Chen, Chen Chen, Franklin Mingzhe Li, Megan Fozzard, Hao-Yun Chi, Nadir Weibel, Patrick Carrington, and Yang Zhang. 2023. Embodied Exploration: Facilitating Remote Accessibility Assessment for Wheelchair Users with Virtual Reality. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA) *(ASSETS '23)*. Association for Computing Machinery, New York, NY, USA, Article 37, 17 pages. https://doi.org/10.1145/3597638.3608410
[24] Marnie Renda and Jennifer E Lape. 2018. Feasibility and effectiveness of telehealth occupational therapy home modification interventions. *International journal of telerehabilitation* 10, 1 (2018), 3.
[25] Marvelmind Robotics. 2024. Automated Scanning and Inspection. https://marvelmind.com/solution/automated_scanning_and_inspection/ Accessed: 2024-08-15.
[26] Bruno M. F. da Silva, Rodrigo S. Xavier, and Luiz M. G. Gonçalves. 2019. Mapping and Navigation for Indoor Robots under ROS: An Experimental Analysis. https://doi.org/10.20944/preprints201907.0035.v1
[27] Walter C. S. S. Simões, Guido S. Machado, André M. A. Sales, Mateus M. de Lucena, Nasser Jazdi, and Vicente F. de Lucena. 2020. A Review of Technologies and Techniques for Indoor Navigation Systems for the Visually Impaired. *Sensors* 20, 14 (2020). https://doi.org/10.3390/s20143935
[28] Julian Striegl, Claudia Loitsch, Jan Schmalfuss-Schwarz, and Gerhard Weber. 2020. Analysis of Indoor Maps Accounting the Needs of People with Impairments. In *Computers Helping People with Special Needs*, Klaus Miesenberger, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Peňáz (Eds.). Springer International Publishing, Cham, 305–314.
[29] Xia Su, Ruiqi Chen, Richard Weiye Zhang, Jingwei Ma, and Jon E. Froehlich. 2024. A Demo of DIAM: Drone-based Indoor Accessibility Mapping. In *Extended Abstract Proceedings of the 2024 ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA). 3 pages.
[30] Xia Su, Kaiming Cheng, Han Zhang, Jaewook Lee, Wyatt Olson, and Jon E. Froehlich. 2023. A Demonstration of RASSAR: Room Accessibility and Safety Scanning in Augmented Reality. In *The 25th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, New York NY USA, 1–4. https://doi.org/10.1145/3597638.3614504
[31] Xia Su, Han Zhang, Kaiming Cheng, Jaewook Lee, Qiaochu Liu, Wyatt Olson, and Jon E Froehlich. 2024. RASSAR: Room Accessibility and Safety Scanning in Augmented Reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–17.
[32] Bonnielin K. Swenor, Andrea V. Yonge, Victoria Goldhammer, Rhonda Miller, Laura N. Gitlin, and Pradeep Ramulu. 2016. Evaluation of the Home Environment Assessment for the Visually Impaired (HEAVI): an instrument designed to quantify fall-related hazards in the visually impaired. *BMC Geriatrics* 16, 1 (Dec. 2016), 214. https://doi.org/10.1186/s12877-016-0391-2
[33] Sumegh Pramod Thale, Mihir Mangesh Prabhu, Pranjali Vinod Thakur, and Pratik Kadam. 2020. ROS based SLAM implementation for Autonomous navigation using Turtlebot. *ITM Web of Conferences* 32 (2020), 01011. https://doi.org/10.1051/itmconf/20203201011 Publisher: EDP Sciences.
[34] Machiko R. Tomita, Sumandeep Saharan, Sheela Rajendran, Susan M. Nochajski, and Jo A. Schweitzer. 2014. Psychometrics of the Home Safety Self-Assessment Tool (HSSAT) to Prevent Falls in Community-Dwelling Older Adults. *The American Journal of Occupational Therapy* 68, 6 (Nov. 2014), 711–718. https://doi.org/10.5014/ajot.2014.010801
[35] P. van Turennout, G. Honderd, and L. van Schelven. 1992. Wall-following control of a mobile robot. In *Proceedings 1992 IEEE International Conference on Robotics and Automation*. IEEE Computer Society, Los Alamitos, CA, USA, 280,281,282,283,284,285. https://doi.org/10.1109/ROBOT.1992.220250
[36] Chris Yoon, Ryan Louie, Jeremy Ryan, MinhKhang Vu, Hyegi Bang, William Derksen, and Paul Ruvolo. 2019. Leveraging Augmented Reality to Create Apps for People with Visual Disabilities: A Case Study in Indoor Navigation. In *Proceedings of the 21st International ACM SIGACCESS Conference on Computers and Accessibility* (Pittsburgh, PA, USA) *(ASSETS '19)*. Association for Computing Machinery, New York, NY, USA, 210–221. https://doi.org/10.1145/3308561.3353788
[37] Khalid Yousif, Alireza Bab-Hadiashar, and Reza Hoseinnezhad. 2015. An Overview to Visual Odometry and Visual SLAM: Applications to Mobile Robotics. *Intelligent Industrial Systems* 1, 4 (Dec. 2015), 289–311. https://doi.org/10.1007/s40903-015-0032-7
[38] Ying Zhang, Juan Liu, Gabriel Hoffmann, Mark Quilling, Kenneth Payne, Prasanta Bose, and Andrew Zimdars. 2010. Real-time indoor mapping for mobile robots with limited sensing. In *The 7th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2010)*. 636–641. https://doi.org/10.1109/MASS.2010.5663778 ISSN: 2155-6814.
[39] Qin Zou, Qin Sun, Long Chen, Bu Nie, and Qingquan Li. 2022. A Comparative Analysis of LiDAR SLAM-Based Indoor Navigation for Autonomous Vehicles. *IEEE Transactions on Intelligent Transportation Systems* 23, 7 (July 2022), 6907–6921. https://doi.org/10.1109/TITS.2021.3063477