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Performance comparison of indoor navigation and obstacle avoidance methods for low-cost implementation in wheelchairs

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ABSTRACT

Wheelchairs are a huge support for the movement of people who have disabilities. The wheelchairs that were traditionally moved using manual effort have given way to powered and smart wheelchairs with various controlling methods. When powered wheelchairs are used indoors, navigation and avoiding obstacles become challenging and tricky for a disabled user. To address these challenges there have been implementations of expensive and high-end systems to make the wheelchair move autonomously but as a result such a wheelchair is not economically viable for many users. Thus, there is a need for an alternative low cost method for users to be able to navigate and move in an indoor environment. The paper reviews low-cost methods for implementing indoor navigation systems, weighing their performances to validate if these methods can be used as a viable alternative to the high-cost systems for autonomous navigation in an indoor environment.

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1. INTRODUCTION

Wheelchairs have been used by the physically challenged for movement for many years. The simple manually operated wheelchairs have in recent years given way to powered wheelchairs, with various modes of control. These powered wheelchairs though make the movement simpler for the user, and also come with the difficulty of navigating and avoiding obstacles, especially in crowded environments. Powered wheelchairs have been under constant research and development with various methods being tested to achieve better navigation, control, and ease of use. Research by Bastos-Filho *et al.* [1] discuss the automation of wheelchair navigation using complete automation or supervised automation to allow users with different levels of disabilities to use the wheelchair. Research by Arnay *et al.* [2] describe the use of laser combined with video camera for detection of obstacles in front of wheelchairs in indoor as well as outdoor environments to ensure easy movement of the wheelchair in different environments. Research by Sanders [3] describes the control of a wheelchair using a joystick, by the user or using sensory inputs, allowing the user to have complete control over the wheelchair based on the surrounding environment in which the wheelchair is being driven. Research by Masud *et al.* [4] present a vision-based control of a wheelchair, allowing the users to have complete control of the movement of the wheelchair using their eyes. This allows users even with multiple disabilities to be able to control the wheelchair independently with no assistance from anyone. Research by Carlson and Demiris [5] present a way to assist the users with the help of collaborative control mechanisms. The system predicts the intentions of the user and adjusts the control signals based on the requirements. Research by Lei *et al.* [6] present an intention prediction-based point-to-point navigation system with control assistance to the users as needed. The system helps users navigate even in complex environments and provides ease of navigation and obstacle avoidance. Research by Tawil and Hafez [7] presents a deep learning based approach to avoid obstacles and help in the navigation of the wheelchair using a single camera and imaging technique. The papers [8], [9] present a machine learning based technique using computer vision to help wheelchair users navigate autonomously in various environments. Adámek *et al.* [10] discuss e vector field histogram+(VFH+) and dynamic window approach (DWA) algorithms to enhance the obstacle avoidance and navigation of a smart wheelchair. Research by Kawaguchi *et al.* [11] present a fuzzy-based predictive model for controlling a wheelchair in crowded environments allowing obstacle avoidance based on the prediction of behavior and other factors. In [12]-[20] authors describe various techniques, voice control, IoT, hand movements, movement of the head, blink-of-an-eye use of artificial intelligence, and other modes to control the movement of a wheelchair for easy navigation.

Candiotti *et al.* [21] discussed the advantages and challenges of a powered wheelchair for indoor and outdoor navigation, concluding that a semi-autonomous system with a good user interface is more beneficial for users. Research by Uganya *et al.* [22] implement a machine learning-based algorithm optimized using a stochastic gradient descent algorithm to achieve better autonomous indoor navigation. Research by Mascetti *et al.* [23] present the idea of smart wheels to identify the various features that wheelchair users need to navigate through in an urban landscape. The smart wheels were proposed to make the process easier for the users with automatic identification with no inputs required from the user. Research by Sivakanthan *et al.* [24] have done a detailed review of how robotic wheelchairs have developed over the years, and even though there have been many technological advances in the robotic wheelchairs, many of the advances have not reached the market successfully yet.

Research by Bandara *at al.* [25] discuss the need for wheelchairs to employ a hybrid navigation system where the user and the wheelchair both have control over the system and navigation is decided based on the scenarios and the inputs received. Hisham *at al.* [26] discussed a customized indoor navigation system for wheelchairs using 3D mapping of the location. Research by Lakmal *et al.* [27] discuss the implementation of a Lidar and 2D mapping based implementation of indoor navigation for wheelchairs.

Afonso and Ferreira [28] discussed the implementation of autonomous navigation in wheelchairs using deep learning and reinforcement along with the help of computer vision. Kobayashi *et al.* [29] discuss the implementation of a navigation system based on various factors to identify the shortest path to a desired destination using Dijkstra's algorithm. The proposed method uses a digital twin to develop the path and achieve the desired navigation. Mohamed *et al.* [30] developed an assistive navigation system for visually impaired wheelchair users using deep learning algorithms providing users with information about their environment and the path to be taken to reach the destination. The various implementations discussed fully autonomous wheelchairs employ technologies which make them economically expensive for an average user to buy and maintain. The paper attempts to compare two low cost options which can be employed to achieve autonomous navigation with obstacle detection and avoidance in an indoor environment also bringing out the advantages and challenges in the same.

2. PROPOSED SOLUTION

Wheelchairs, when used for indoor navigation, have to be very precise in identifying the objects around it as an indoor setup might have multiple obstacles at closer distances. Two of the main functions that the wheelchair used for indoor navigation should be able to perform are automatic detection of obstacles, taking the necessary action as required and the second being able to reach a destination as requested by the user. The obstacle avoidance and the navigation systems need to work in sync with each other to ensure effective and proper movement of the wheelchair.

2.1. Obstacles detection

Using infra red (IR) and ultrasonic sensors: IR sensors have the ability to detect the presence of objects in front of it using the reflection of the IR waves emitted by its transmitter. These sensors are low cost and are effective in identifying the presence of objects in front of them at close distances. Four such sensors were placed on the wheelchair, two on the handles and two near the wheels, to be able to detect the presence of any obstacle in the path of the wheelchair. The signals from each of these sensors was monitored by the controlling unit continuously to be able to detect the presence of any obstacle in the path on which the wheelchair was moving. The drawback of using only IR sensors was that these sensors could not give the distance at which the obstacle was present. Figure 1 shows the block diagram of integration of the IR sensor with the wheelchair.

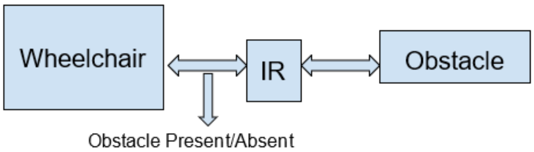

Figure 1. IR sensor and wheelchair

To be able to identify the distance of the obstacle from the wheelchair ultrasonic sensors were also added to the wheelchair. The ultrasonic sensors work by calculating the time taken for the ultrasonic waves to travel from the wheelchair to the obstacle and bounce back. Calculating the distance of the obstacle from the wheelchair allows the system to take appropriate action to ensure that the wheelchair does not collide with the obstacle. Two ultrasonic sensors were installed on the wheelchair, one in the upper portion and one in the lower portion of the wheelchair to be able to detect obstacles of all heights. Figure 2 gives a block diagram of the interaction between the wheelchair and the ultrasonic sensor.

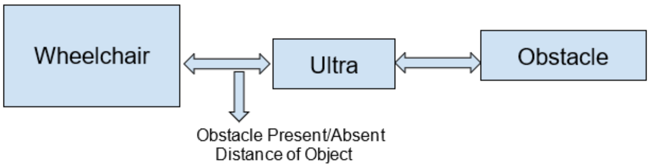

Figure 2. Ultrasound sensor and wheelchair

The combination of IR and ultrasonic sensors were capable of not only detecting the presence of obstacles in time but also provide the distance of the obstacle so that the system can take the necessary action in time to avoid the obstacle. Image-based method: the second method attempted was using a camera to take photos of the objects in front of the wheelchair and use the image to calculate the distance. The image by itself was capable of detecting the object's presence and its distance of the object from the wheelchair. The object detection and distance calculation were done using a YOLOv4 algorithm. The algorithm works by using pre-trained images to identify the object. The dimension of the object also would be fed as part of the training. The algorithm is capable of identifying the object and its distance from the camera from the pre trained data. As the method is being proposed for indoor navigation the training of the objects and its dimensions would be required only once and can be done during the first installation after which the wheelchair can work autonomously using the camera to detect the images as well as calculate the distance of the object. Figure 3 gives the block diagram of the interaction between camera and the wheelchair.

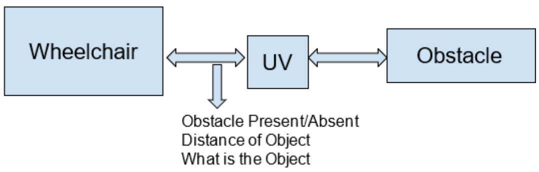

Figure 3. Camera based sensing

2.2. Navigation

Navigating to a desired location within the indoor space is also a major challenge for people using wheelchairs. The paper compares navigation using two simple low cost methods, one using IR sensors and second using images taken with a camera. Using IR sensors on wheels: to ensure the wheelchair can move from one location to another autonomously a distance based algorithm was used. The distances between locations are fixed in an indoor environment, for example distance between rooms will always be the same. Thus these fixed distances were fed as information into the system which would be used while navigating. Calculation of distance traversed by the wheelchair was done using an IR sensor installed on the wheels which would count the rotations of the wheel and in turn calculate the distance traveled. The starting point would be fixed as the entrance of the room, which the user can move to, using simple commands to move forward or backward. The fixed wheel diameter and fixed distances between locations in a home ensured that the calculation of distance was easy to compute and compare.

Using camera: the cameras used for detection of obstacles were also used for the navigation of the wheelchair. The path of the wheelchair from one location to another was mapped using known images or markers placed at proper places for the camera to identify. The turns of the wheelchair were configured based on the distance from these marked images. Once the path is identified and configured, the wheelchair would be trained to follow the path by looking for the images. The turns would be configured based on the distance from these set images. The camera would identify the image, and calculate the distance from the image using the YOLOv4 algorithm. The wheelchair would be made to turn at the appropriate distance from the image as trained, allowing the user to reach the desired location.

3. METHOD

Figure 4 gives a general flow of events adopted by the algorithm controlling the movement of the wheelchair. The system waits for the user to enter a command which could be the name of a destination location or a direction of movement. The command for movement can be issued using either voice, keypad or gestures. Once the system identifies the command the movement of the wheelchair begins. If the command is to move in a certain direction the wheelchair will continue to move till the user issues a stop command or an obstacle is encountered. If the command is to a specific destination, which is mapped already in the system, the wheelchair fetches the details of the movement required and will move in the corresponding directions unless it encounters an obstacle causing it to stop or move to avoid the obstacle.

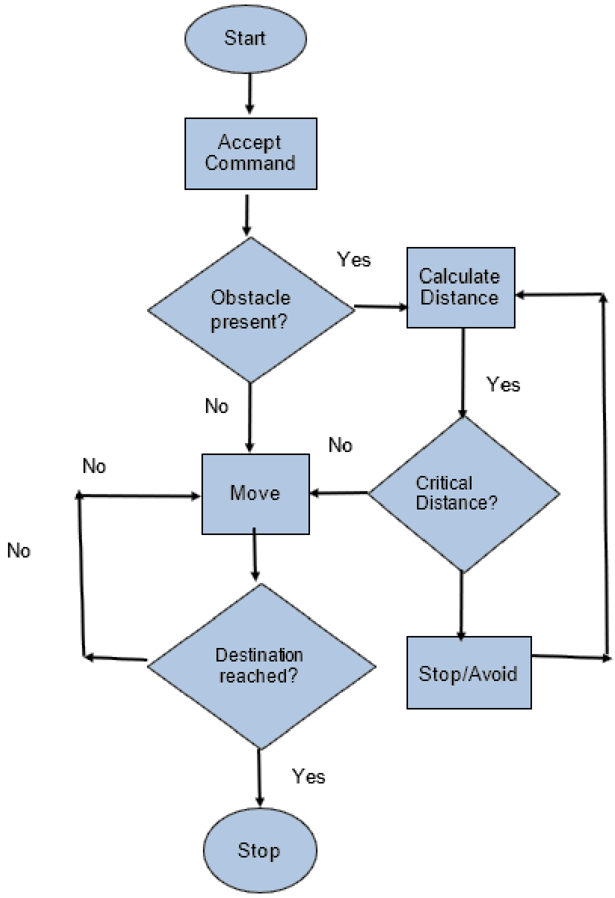

Figure 4. Movement of the wheelchair

The main difference between the two proposed methods are the system comprising the way of navigation to the destination and the obstacle detection systems. One system uses the IR and ultrasonic sensors for obstacle detection and the distance calculation using IR sensor for navigation. The second system uses a camera to achieve both obstacle detection and navigation.

In both the methods employed a predefined map of the indoor locations was fed using available data. In the case of the IR based navigation the distance to be covered and the distance of each turn during the navigation was stored in the system. Where as in the image based navigation the turns to be executed was identified distance from fixed images or markers placed in the indoor environment.

Figure 5 details the steps followed in an IR sensor based distance calculation setup. The control unit will receive the distance measured and then take the necessary action based on the command received from the user. Figure 6 details the steps followed by the image based system while calculating the distance of the object and updating the same to the control unit. Both the methods were implemented and tested on a wheel chair to demonstrate the ease of use and effectiveness of the approaches. Figure 7 is the image of the wheelchair on which the above mentioned algorithms were tested. Figure 8 shows a sample output of detection of the distance of a person from the wheelchair.

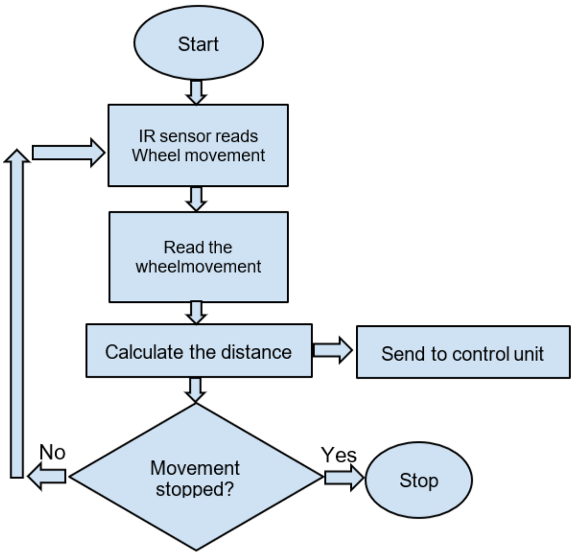

Figure 5. IR sensor based navigation

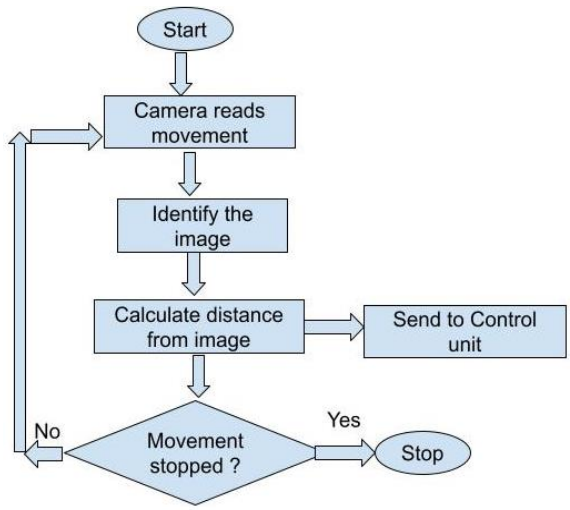

Figure 6. Image based navigation

Figure 7. Wheelchair model

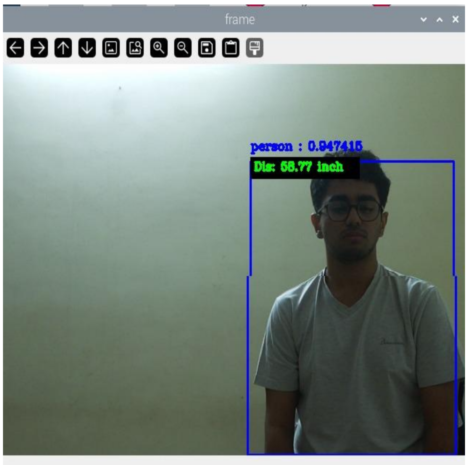

Figure 8. Distance and identification using camera

4. RESULTS AND DISCUSSION

The results below show the performance of the two algorithms on a real time wheelchair considering various scenations. Table 1 provides the results of performance in detected obstacles at certain distances. For distances greater than 0.5 m, both the methods proved not very effective but it would generally be acceptable in the case of indoor navigation as in an indoor setup 0.5 m is a large distance. In the range 0.5 m to 0.4 m the ultrasonic was able to detect and provide the distance but the level of accuracy obtained for this range was not very satisfactory, but the camera performed much better in this range compared to the ultrasonic systems. In the range of 0.4 m to 0.2 m the ultrasonic based system was very effective and accurate in providing the distance of the obstacle with an accuracy of 95%, the camera based system was also equally effective with 93% efficiency. In the range of 0.2 m-0.1 m, which is the general range of interest in the case of indoor navigation the accuracy of both the systems was very good and found to be above 95%. Thus, we can see that the camera based as well as the ultrasonic based systems both are effective tools for indoor obstacle detection, especially in close ranges.

Table 1. Distance based performance

Distance of obstacle (m)	Ultrasonic sensor	Camera
More than 0.5	Unable to detect	Very low accuracy
0.5-0.4	Low accuracy	Moderately accurate
0.4-0.2	95% accuracy	93% accuracy
0.2-0.1	98% accuracy	95% accuracy

During the movement of the wheelchair, it's not only detection of the obstacles, but avoiding them is also very important. Table 2 provides the results obtained with respect to the obstacle avoidance in each of the systems. As the number of obstacles reduced both the systems were effective in identifying and avoiding obstacles. The camera based system was less accurate with a larger number of obstacles. One of the reasons for the lower efficiency in a higher number of obstacles is that the processing time of the camera based system is higher than the ultrasonic system. Thus, the obstacle was not avoided due to delayed response from the detection system. Though this can be addressed with a faster processing power controller at the expense of higher cost of the system. Navigation: the navigation to the desired destination as commanded by the user is another factor that needs to be ensured for the wheelchair to be effective.

Table 2. Performance based on number of obstacles

Number of obstacles	Obstacles avoided with ultrasonic	Obstacles avoided with camera
10	9	8
6	5	5
4	4	4
2	2	2

The Table 3 gives the comparison of how the two systems performed with respect to the navigation. For longer distances, greater than 10 m the IR based system seemed to reach only about 8.5 m to 9 m the loss in the distance was attributed to the lack of accuracy of the sensing as well as due to minor deviations due to obstacles. The camera based system performed slightly better here reaching around 9 m while traveling to a destination of 10 m. As the distances of the destination reduced the performances of both the systems improved, with both of them achieving more than 95% accuracy for less than 2.5 m traversal. The navigation of above 10 m in a domestic indoor setup may not be a very common occurrence and hence the errors can be accommodated. The shorter distances are important for indoor navigation and that is being successfully navigated by both the systems to a high degree of accuracy.

Table 3. Performance on distance of navigation

Distance to be navigated (m)	Navigation accuracy with IR (%)	Navigation accuracy with camera (%)
Greater than 10	85	90
5-10	92	94
2.5-5	95	95
2.5-1.5	98	97

Table 4 compares the two methods proposed under various parameters. The IR and ultrasonic based system and the camera based system both are capable of identifying the obstacles as well as navigating based on distances. The major advantage of the camera based system is the ability to identify the obstacle and inform the user which the IR and ultrasonic based system is not capable of. But the camera based system has the drawback of being slower and requires more processing power as compared to the IR and ultrasonic based system.

Table 4. Comparison between the methods proposed

Description	IR ultrasonic based	Camera based
Obstacle detection	Possible	Possible
Identify object	Not supported	Supported
Speed of response	Faster	Slower
Processing required	Lesser	More

5. CONCLUSION

The results obtained indicate that wheelchair automation implemented using a combination of IR and ultrasonic or camera based sensors are both effective in practical scenarios. These variations are a lot more economical as compared to the more complex implementations based on technologies like lidar, radar, and machine learning, which are effective but make the wheelchair not affordable to many users. The work in the paper depicted that wheelchair automation for indoor navigation can be achieved using the low cost alternatives and be effective too. The IR and ultrasonic based system is more suitable where the user is not visually impaired making the requirement of obstacle identification unnecessary, but if the wheelchair is being used by a visually impaired individual then the feature of identification of the obstacle becomes very important, even at the the slight expense of slower movement.

These low cost alternatives might not be very effective in an outdoor environment as they rely on predefined maps and images fed into the system and operate based on these maps. But the independence offered to the user in the case of indoor navigation would be very helpful in ensuring that the disabled is able to self navigate and move around without the need for assistance from any helpers. The implementation can be further improved with the algorithms to be made dynamic in nature allowing them to adapt to a changing environment even in the indoor environment. This will make the usage of the wheelchair for the user hassle free and more efficient.

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