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ENHANCING SAFETY IN COLLABORATIVE WORKSPACES: DEFINING ATTENTION AND AVOIDANCE ZONES USING PATH PLANNING WITH MOBILE ROBOTIC SYSTEMS

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ABSTRACT

Ensuring the safety of human workers who work alongside mobile robots is extremely important. This study defines and delineates attention zones and avoidance zones for human workers to include both visual and audible aspects. Attention zones aims to keep workers aware of potential hazards. Specifically, visual attention zones focus on field of view and audible attention zones consider noise levels in the workspace. By establishing these zones, mobile robots can generate warning signals as human workers approach to minimize the risk of collisions. After determining optimal attention zones, researchers identify path planning strategies that can be adjusted based on visual and audible warnings to avoid potential accidents. The proposed attention zone-based warning system and the contact avoidance zone represent a critical advancement in enhancing worker safety in collaborative workspaces to promote a safer workspace.

Keywords: Safety, mobile robots, modeling and simulation, robotic systems

1. INTRODUCTION

Prioritizing worker safety in collaborative workspaces where mobile robots and industrial vehicles operate is paramount. Defining human workers' visual attention zones and using this information to identify areas to be avoided by moving robots is crucial to prevent potential collisions and injuries. Utilizing various indoor localization techniques such as Wi-Fi based positioning and visual odometry helps to accurately identify these zones. Additionally, methods like kinematic analysis [1] and vision-based detection [2] help define avoidance zones in collaborative workspaces.

In a collaborative human-robot workspace, the attention zone enables robots to issue effective warning signals when human workers are within potential collision areas. By defining an attention zone, robots can recognize areas where human presence is likely and adjust movement accordingly, reducing the risk of hazardous events. To define an attention zone, it is important to consider factors such as the field of view [3], audible range [4], [5], and environmental conditions [6] to establish boundaries that the robot should be cautious around. Therefore, understating the locations where human workers are present and where robots should steer clear is critical for establishing effective operational guidelines to ensure worker safety. With knowledge of the positions of collaborating human workers and existing obstacles, the control unit of a mobile robot can develop movement strategies to avert potential collisions.

Path planning algorithms and vision-based approaches further enhance safety by identifying human presence and facilitating collision-free navigation. Path planning, as introduced by Ajeil et al. [7], optimizes robot movement in both static and dynamic environments, resulting in shorter, smoother, and collision-free paths. Additionally, vision-based approaches have been employed to detect human presence within workspaces and update workspace maps for mobile robots, facilitating path planning [8]. Timely updating of workspace maps when robots relocate ensures accurate adjustment of avoidance and attention zones. This method combined computer vision and indoor localization techniques, allowing collaborative and mobile robots to adjust their trajectories as needed. This approach also actively enhanced robot safety by preventing collisions between robots, human workers, and surrounding obstacles, thus demonstrating its feasibility.

With the previous studies [7], [8], active avoidance approach strategy is anticipated to decrease the risk of injuries. Contemporary mobile robots deployed in various workspaces come equipped with an array of sensors designed to detect obstacles and humans in their vicinity. Robots use the data gathered from these sensors to determine their position, facilitate communication with other robots and machines, and effectively plan movement trajectories [9]. Indoor localization techniques play a crucial role in enabling mobile robots to navigate their surrounding safely and avoid potential collisions or unexpected contact with human workers. This not only assists in pinpointing the robot's location but also enables the activation of alerts or safety protocols as needed, thereby enhancing the accuracy and reliability of attention zones and avoidance zones to bolster human safety.

This study outlines the integration of both an attention zone and avoidance zone into a path planning process for mobile robots. The objective is to define the attention zone of human workers and the avoidance zones for robots to effectively navigate movements in collaborative workspaces. Furthermore, the study delves into various factors that influence the design and implementation of these two different types of zones, including environmental conditions, human factors, and technological considerations to support the development of robust safety protocols.

This manuscript is structured as follows. Section two provides an overview of the existing safety regulations of robot operation, environmental conditions, and warning signals. Section three details how the attention zone and contact avoidance zones can be integrated. Section four explains the approaches of path planning with the consideration of both attention and contact avoidance zones. Section five discusses two navigation examples presented in the 2D plane to validate the effectiveness of the proposed framework. Section six provides a discussion and conclusions from the study results.

2. SAFETY REGULATIONS AND FUNCTIONS IN HUMAN-ROBOT INTERACTIVE ENVIRONMENTS

Over the past few decades, numerous industrial safety standards and government documents have outlined the necessary environmental conditions for different collaborative workspaces. These standards include specific safety regulations for robotic devices and applications. However, the field of mobile robot applications is still emerging with existing gaps that need to be addressed both in terms of regulations and safety functions.

2.1 Presence-Sensing Robotic Devices

Presence-sensing devices equipped on mobile robots serve to reduce risks and can include various types of sensors, such as opto-electronic, vision-based, pressure-sensitive, or other non-contact presence-sensing devices. These devices detect safety hazards, allowing the mobile robot to halt within the defined stopping distance without posing additional risks. If stopping distance varies with direction or slope, further tests may be necessary.

ANSI/RIA 15.08-1-2020 [10] outlines specific criteria for determining the stopping distance of a mobile robot, which is contingent upon factors such as its maximum-rated load, velocity, and the operating environment in which it is deployed. For example, if the robot's presence-sensing function to detect human workers can be bypassed outside the restricted area, the mobile robot must incorporate a safety function that restricts the velocity of any part of the mobile robot to below 300 mm/s when the presence-sensing functions are bypassed. Once the robot is confirmed to have entered a restricted area, it can only operate at speeds not exceeding 300 mm/s within that area while the presence-sensing functions are suspended. However, the determination of stopping distance must encompass the motions of all components, including the mobile platform and any attachments. Additionally, standards regulate the permissible moving speeds of the mobile robot, stipulating that it should operate at 33%, 66%, and 100% of its rated speed with corresponding rated load percentages.

2.2 Other Safety Functions

Assessing the operational environment where a mobile robot is deployed involves taking into account several specifications and safety functions. These include incorporating supplementary safety measures, providing visibility aids for workers collaborating with the mobile robot, determining minimum overhead clearance, creating a workspace diagram, defining load and velocity limits, and understanding the expected proficiency of workers who will be collaborating with the mobile robot.

Safety functions also include factors such as maximum permissible roughness of travel surface, depth and quantity of foreign materials on the floor, coefficient of friction, incline grade, and obstacle dimensions. Minimum ambient brightness, maximum permissible ambient noise, uninterrupted vertical line of sight, and obstacle tracking capabilities at varying distances are also vital considerations. To guarantee tracking capability, parameters like sensing range, navigation turning radius, obstacle avoidance reaction time, and clearance between obstacles must be clearly defined.

2.3 Environmental Conditions

The brightness level within the workspace stands as one of the most crucial factors influencing worker safety. Standards for brightness and noise levels are established for different work environments [11], [12] with light brightness requirements differing between common and industrial spaces. Consistency in illumination is essential, with consideration given to the fixture's luminous flux, measured in lumens, the international system of units (SI). Luminous flux, or lux, refers to the total light energy emitted from a fixture in all directions. The Illuminating Engineering Society of North America (IESNA) has outlined recommendations for lumen requirements across various workspaces [14]. For instance, Table 1 outlines the recommended luminous flux in different manufacturing facilities, influenced by the specific functions and products manufactured in each location.

In manufacturing facilities, noise exposure criteria have also been established by the Occupational Safety and Health Administration (OSHA) in the United States, outlined in OSHA 1910.95 [12], [13]. These criteria dictate the acceptable noise levels for workers over an eight-hour period. OSHA sets a maximum permissible exposure limit (PEL) of 90 dBA for individuals working a full shift, with these levels applying to an exchange rate of 5 dBA. Additionally, the National Institute for Occupational Safety and Health (NIOSH) recommends limiting a worker's equivalent noise exposure to 85 dBA over an eight-hour day to reduce the risk of hearing damage [16], [17]. Recent literature indicates that significant hearing loss can occur even when noise levels align with the OSHA PEL. NIOSH recommends a more stringent exchange rate of 3 dBA, whereby each increase of 3 dBA results in half the allowable exposure time.

Table 1: Required luminous flux of different manufacturing workspaces [14], [15].

Type of manufacturing	Tasks and required lumen
Glove manufacturing	• Knitting and sorting: 1000 – 2000 lux • Pressing, cutting, and sewing: 2000-3000 lux
Hat manufacturing	• Dyeing, cleaning, and refining: 500-750 lux • Forming, finishing, and ironing: 1000-1500 lux • Sewing: 2000-3000 lux
Jewelry and watch manufacturing	2000-3000 lux
Explosives manufacturing	200-300 lux
Leather manufacturing	• Cleaning, cutting, stuffing and stretching: 200-300 lux • Finishing and scarfing: 500-750 lux
Electrical equipment manufacturing	500-750 lux
Assembly Work	• Simple: 200-300 lux • Moderately difficult: 500-750 lux • Difficult: 1000-1500 lux • Very difficult: 2000-3000 lux • Extracting: 5000-7000 lux

2.4 Warning Signals

According to [10], it is important to mitigate associated risks when safety functions of a mobile robot are suspended or altered. In collaborative workspaces, warning devices must be provided to alert human workers of potential hazards associated with mobile robots. These warning devices can take the form of audible, visual, tactile, or a combination of signals. However, this document lacks specific guidelines regarding the range or intensity of these warning signals, which may depend on the environment.

Warning signals can come in various forms, each with its own advantages and disadvantages. Visual signals must be within the workers' attention area, which can be limited. Therefore, audible signals are valuable in mobile robot applications. Spatial hearing extends beyond the ability to distinguish whether a sound originates from the left or right; it also includes the perception of sounds coming from above or below, as well as from in front or behind. However, impaired hearing can make distinguishing between upper and lower sounds (or front and back) challenging or impossible, reducing spatial hearing to a one-dimension experience.

ISO 7731 [18] provides guidance on designing auditory warning signals for environments with high ambient or background noise levels, such as industrial workspaces. According to this standard, warning or danger signal should surpass the A-weighted sound pressure level of ambient noise by at least 15 dB and should not fall below 65 dB to ensure clear audibility. Furthermore, when measuring octave-band sound pressure levels, the standard recommends that the warning signal exceed the effective masked threshold by a minimum 10 dB in one or more octave-bands. The effective masked threshold can be calculated as follows:

$$L_{eff,\,i} = L_{amb,\,i}, \text{for } i = 1$$
$$L_{eff,\,i} = \max\left(L_{amb,\,i}, L_{eff,\,(i-1)} - 7.5\ dB\right), \text{for } i > 1, \qquad (1)$$

where $L_{eff,\,i}$ is the effective masked threshold for the i^{th} octave-band, and $L_{amb,\,i}$ is the ambient sound pressure level for the i^{th} octave-band. Frequency-wise, the standard suggests that danger signals should contain frequency components within the range of 500 Hz to 2,500 Hz. Concerning temporal characteristics, ISO 7731 also recommends using pulsating danger signals rather than signals that are constant in frequency, with repetition frequencies falling between 0.5 Hz and 4 Hz. Warning signals can exhibit various frequency contents, spanning from narrow-band periodic signals to alternating tones or continuously changing frequencies such as sirens. Additionally, the human ear, coupled with the brain, can localize the direction of incoming noises by leveraging auditory cues like interaural time difference (ITD), interaural level difference (ILD), and spectral cues.

Unfortunately, the current safety standard for mobile robot systems [11] does not address the brightness and noise level of the visual and audible warning signals. This gap is particularly concerning in environments where human workers may not be actively attentive to their surroundings. It is essential to establish zones where human workers can easily notice warning signals, as well as the zones where warning signals can effectively attract their attention. By defining these zones and obtaining information on the movement direction and speeds of collaborating human workers, mobile robots can adjust their movements to prevent injuries resulting from unexpected contact.

3. ATTENTION ZONES OF HUMAN WORKERS

To facilitate active avoidance among mobile robots and human workers in a collaborative workspace, it is necessary to determine the areas where humans are attentive and areas where the mobile robots should refrain from entering. This study established attention zones based on visibility and audibility of human workers.

3.1 Attention Zone Based on Human Vision

To establish the attention zone based on visual perception, we studied the field of view, which defines the extent of what external devices can observe during steady fixation. It is important to note that while eye movements are a part in defining the the field of view, they do not expand the observable range. The analysis in this study takes into account only the natural limitations of visibility, excluding any potential effects from eye movements.

In human vision, the visual field refers to the range of degrees within the visual angle during steady fixation. Humans have a forward-facing horizontal arc of slightly over 210°, which increases slightly with eye movements. The total vertical range of the human visual field is approximately 150°. Within this visual field, visual abilities also vary from person to person. Binocular vision, crucial for stereopsis and depth perception, spans 120° horizontally [3], [19], allowing humans to evaluate the distance of visible objects. In the peripheral 40° on each side of the visual field, only one eye can perceive the image, which prevents the formation of a stereo image of the visible objects.

Color vision distribution and the ability to perceive shape and motion also vary across the human visual field [20]. Both form perception as well as color vision are most concentrated in the central region of human visual field, whereas motion perception shows a slight decrease in sensitivity towards the periphery, where it retains a relative advantage. This variation is attributed to the higher density of color-sensitive cone cells and color-sensitive parvocellular retinal ganglion cells in the fovea, the central region of the retina. Moreover, there are functions more prominently represented in the visual cortex. Conversely, the visual periphery contains a higher density of color-insensitive rod cells and motion-sensitive magnocellular retinal ganglion cells, with a comparatively smaller representation in the cortex. Rod cells, known for their heightened sensitivity to low light levels, enhance peripheral vision's sensitivity during nighttime conditions compared to foveal vision, reaching peak sensitivity at ~20° of eccentricity [21].

Regarding distance vision, the average person typically has 6/6 vision (or corrected vision), indicating that in adequately illuminated conditions, individuals can perceive objects clearly from 6 m. Visual acuity, measuring the clarity of vision when observing an object at a specific distance, plays an important role in defining the range of vision. Considering both high sensitivity and binocular areas, along with the assumption of 6/6 vision, Figure 1 illustrates the proposed geometric shape and range synthesizing the attention zone based on the field of view on the horizontal plane. The shaded area represents where the human worker should have sufficient attention to visualize moving robots in the collaborative workspace. It is not advisable for the high sensitivity area to extend beyond 9 m, as objects or signals may become blurred at longer distances.

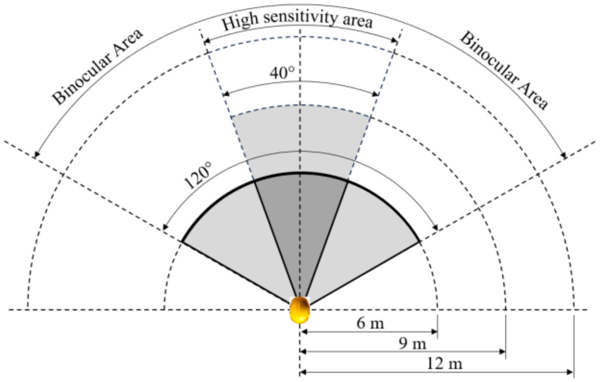

FIGURE 1: Field of view with high sensitivity and best attention.

To guarantee sufficient visibility, the luminous flux within the targeted manufacturing workspaces should be sufficiently bright to support the tasks. Additionally, it is recommended that visible warning signals, such as flashing red lights, surround the robotic device when it is within the range where adequate attention can be paid by the human worker.

3.2 Attention Zone Based on Audible Ranges

Audible signals serve as an important means in alerting human workers in collaborative workspaces, complementing visible signals. However, their effectiveness can be affected by environmental factors, such as background noise levels and the frequency spectrum of surrounding sounds. For instance, in noisy environments like construction sites where heavy machinery operates, noise levels typically range from 85 to 105 dBA [22], [23]. Therefore, careful design of audible warning signals is essential to ensure their detectability amidst such noise. In most industrial settings, sound levels often exceed 85 dBA, requiring employers to provide hearing protection to workers by law. Hearing protectors come into two main categories: over-the-ear hearing protectors, like earmuffs, and in-ear hearing protectors, such as ear plugs. While wearing hearing protection devices theoretically should not affect signal detection in noisy environments, an increase in the severity of hearing loss may reduce the detection of the desired signal [24].

Human hearing spans from 20 Hz to 20 kHz, with individuals capable of perceiving sounds as low as 12 Hz and as high as 28 kHz [25]. However, adults typically experience a threshold increase around 15 kHz, coinciding with the last auditory channel of the cochlea. The human auditory system is most receptive to frequencies between 2 kHz and 5 kHz, although individual hearing ranges may vary based on factors such as age and overall ear health. Thus, tailoring the frequency band of audible signals to suit the specific types of industrial settings is imperative. However, noise-induced hearing loss is gradual and accumulative, worsening over time with prolonged exposure to work-related noise within specific frequency bands [26]. Over 40% of audiometry results indicated hearing deterioration at acute frequencies corresponding to specific noises. Hence, designating the frequency of warning signals appropriately is vital to ensure worker attentiveness. It is also recommended to design warning signals with two frequency bands with the required signal-to-noise ratio (SNR) to maintain worker alertness. Improving communication between industrial devices and human workers relies on understanding the diverse characteristics of acoustic signals and the environment. A higher SNR improves the worker's capacity to distinguish signals from background noise.

To prevent potential hearing damage, the warning signal emitted by the mobile robot should be configured to be 85 dBA or lower in collaborative workspaces. By using the following equation [27], the sound intensity of a point source of sound can be calculated. That is

$$\beta = 10 \cdot \log_{10}\left(\frac{P_{source}}{4\pi d^2 \cdot I_0}\right), \qquad (2)$$

where β is the sound pressure at the targeted location, P_{source} is the acoustic power of the point source, d is the distance between the point source and the targeted position, and I_0 is the reference intensity. The reference intensity I_0 is $10^{-12}\ W/m^2$. With a point source emitting 0.05 watts of acoustic power, the sound pressure can reach 80.43 dBA at a distance of 6 m, making it suitable as a warning signal for a mobile robot for a 1 kHz sound signal.

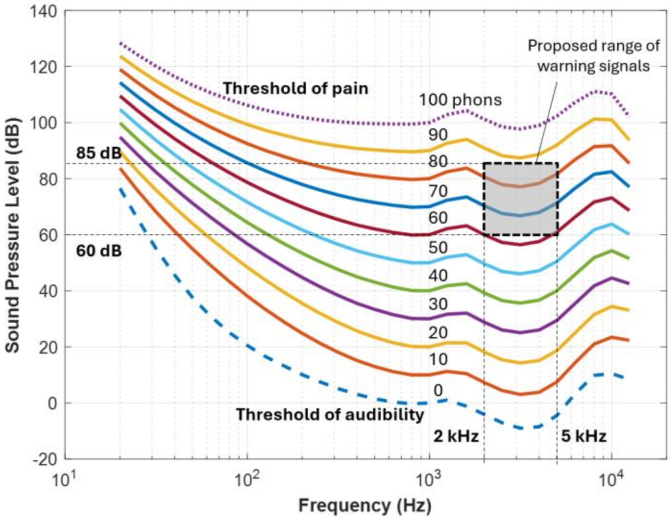

FIGURE 2: Equal loudness contours and recommended range of audible warning signals.

Figure 2 illustrates the equal loudness contours, including noise levels and frequency spans, alongside recommended audible warning signal ranges tailored for various industrial and manufacturing settings (ISO 266) [28]. The designated range for the warning signal is also indicated in Figure 2. In this Figure, the phon is a logarithmic unit used to measure the loudness level of tones and complex sounds. The loudness level of a sound, measured in phons, corresponds to the sound pressure level (in dB SPL) of a 1 kHz pure tone perceived as having the same loudness. On this scale, 0 phons at 1 kHz is set at 0 dB, which corresponds to the threshold of hearing at that frequency. The contour of the threshold of pain is set at 100 phons.

3.3 Suggested Attention Zone

Based on the details provided in the preceding sections, the attention zone of a human worker can be approximately delineated. The visible zone extends in a fan shape, spanning 40° in front of the worker and extending to a radius of 6 m. This configuration ensures that the worker maintains a clear and highly sensitive field of vision. Regarding the audible zone, it is recommended to cover a circular area with the same radius of 6 m with a 0.05 watts point sound source. Within this area, mobile robots should actively emit visible and audible warning signals. Figure 3 illustrates the shape of this proposed attention zone. Such a setup ensures that the warning signal remains audible regardless of whether the human worker is in motion or stationery. While careful design of warning signals in the audible zone can enhance human worker attentiveness, it is still recommended to meticulously plan the moving paths of involved mobile robots to avoid unexpected collisions.

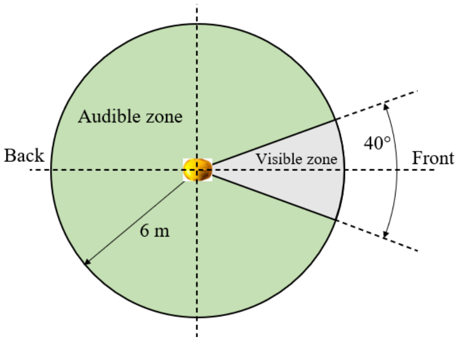

FIGURE 3: Recommended attention zone of human worker.

4. AVOIDANCE ZONES AND PATH PLANNING

This section delves into delineating the zones crucial for ensuring safety around mobile robots in the presence of human workers. After establishing the attention zone for human workers, the next step is to define the avoidance zone, where the mobile robot should steer clear to prevent unexpected contact and potential injuries. This designated area must account for whether the human worker is in motion or stationery.

4.1 Maps of Workspace

This study was conducted in an experimental area measuring 7.5 m in length, 7 m in width, and 2.5 m in height. In preparation for effective navigating and task execution within the targeted workspace, mobile robots rely on an always updated indoor map for path planning [8]. This map is essential for accurately depicting obstacles in three dimensions, marking out inaccessible or hazardous areas. Constructing such a map requires a thorough understanding of the robots' span and moving patterns. While the adopted mobile robots primarily operate in a two-dimensional plane, considerations must be given to obstacles and their spatial surroundings in three-dimensional space. To capture this spatial information, this study utilized an RGB-D camera to detect the existence of surrounding obstacles and their corresponding 3D information. The collected data was transformed into point cloud data, offering a representation of the experimental area and facilitating the recreation of the updated indoor map.

Figure 4 illustrates how the experimental area was converted into a planar map used for the navigation of the mobile robot. Since the robot's height did not exceed 1.2 m in this study, the map can be seamlessly converted into a 2D planar representation while the robot is in motion. After acquiring point cloud data, the data underwent processing and analysis to extract environment details, such as object locations and sizes, geometric configurations, and the presence of potential obstacles and human workers. The point cloud-generated map requires adjustments depending on the targeted applications to ensure the safe operation of the robots and avoid collisions. A safety buffer must be added around obstacles to prevent collisions caused by inaccuracies in the point cloud data measurements. This adjustment involved converting the point cloud into a spatial map by segmenting the workspace into gridded cells.

For efficient path planning, the obstacles within 3D operational workspace were projected onto a 2D planar map, which was then standardized into grids with dimensions of 100 mm × 100 mm on the plane. This resulted in a total of 75 × 70 grids to facilitate the robot's trajectory planning between locations. Figure 4 illustrates the occupancy and planar maps converted from the point cloud step by step. Grids already occupied were marked as unavailable on the planner map to prevent potential collisions. This map needed to be updated regularly, with the depth image recaptured to ensure the map remained current.

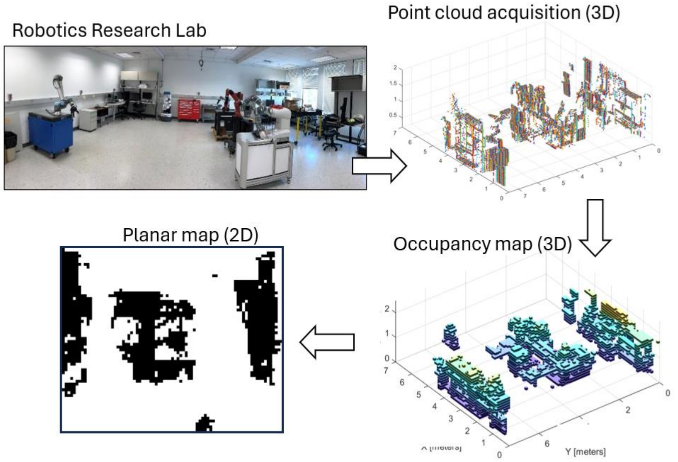

FIGURE 4: The experimental area and the corresponding 3D and 2D maps.

4.2 Workers with Avoidance Zones in the Workspace

When defining the contact avoidance zone for a human worker, it is critical to consider more than just the occupied cells. Predicting the worker's movement path is also essential, as human workers may find it challenging to alter their course due to their ongoing tasks when mobile robots are nearby. Accurately determining these zones requires estimating them while the worker is in motion, considering factors like speed and map update frequency. The average speed of a human worker ranges from 0.89 m/s to 1.79 m/s according to ISO/TS 15066 [29]. To simplify calculations, a fixed-size contact avoidance zone was applied in this study, based on an average human speed of 1.6 m/s.

In this study, the contact avoidance zones were updated every one-and-a-half seconds to ensure real-time safety during robot operation. To account for worker movement within this timeframe, the contact avoidance zone around the worker was extended by 2.4 m in all directions, with the assumption that workers move at a speed of 1.6 m/s for 1.5 seconds. Upon the mobile robot entering the attention zone of any worker, the map update rate was elevated to one second, accompanied by the activation of both visible and audible warning signals. This approach allowed for faster generation and application of the contact avoidance zones to robot operations. Figure 5 illustrates the application of the contact avoidance zone and the proposed attention zone in the 2D plane.

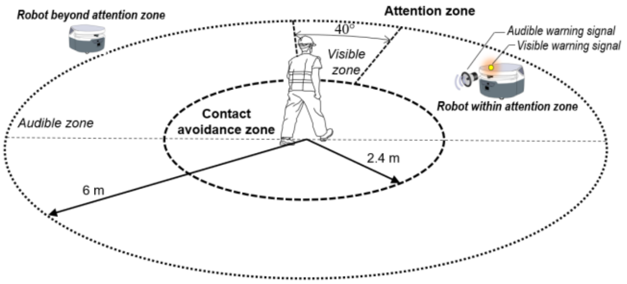

FIGURE 5: The proposed contact attention zone and avoidance zone on the 2D plane surrounding a human worker.

Supporting collision avoidance also involves defining a space between mobile robots and other structures where robots should not enter or operate. For mobile robots, this zone is created by expanding the range of occupied cells around obstacles in the 2D indoor map. This map was synthesized from 3D point cloud data by projecting points onto a 2D plane and then inflating them to form contact avoidance zones. In this study, a contact avoidance zone radius of 0.3 m was used and regularly updated to reflect the latest information. Figure 5 illustrates the application of both attention and contact avoidance zones. It is important to note that the attention zone beyond the 2.4 m range of the contact avoidance zone is accessible to the mobile robot. However, both visible and audible warning signals must be activated when the robot is traveling this area.

4.3 Path Planning of Mobile Robots

To strategize the movement of mobile robots within collaborative workspaces, it is essential to distinctly mark and continuously update the occupied regions with existing obstacles or human workers where applicable. In each operational cycle, the robot acquires a depth image to detect the presence of human workers and generate a 2D map to plan its path accordingly. In this study, the efficiency of continuously updating the map was evaluated using three methods: the A* algorithm, the rapidly-exploring random tree (RRT) algorithm, and the probabilistic roadmap (PRM) path planning algorithm.

The A* algorithm is a widely used pathfinding algorithm in robotics and artificial intelligence. It efficiently finds the shortest path between two points in a graph by considering both the cost of reaching a node and the estimated cost to the goal. A* utilizes a heuristic function to guide the search towards the goal while also ensuring that the path is optimal, making it suitable for applications requiring real-time path planning in environments with obstacles and varying terrain [30].

As to the RRT algorithm, it is also a popular motion planning technique that explores the configuration space by randomly sampling feasible states and incrementally growing a tree structure rooted at the initial state. This algorithm rapidly expands the tree towards unexplored regions while ensuring collision avoidance with obstacles. RRTs are particularly suitable for high-dimensional spaces and dynamic environments due to their probabilistic nature and ability to adapt to changing conditions [31].

The PRM path planning algorithm is a sampling-based method used to plan collision-free paths for mobile robots operating in complex environments. It works by generating a roadmap of the environment through random sampling of configurations and connecting them with collision-free paths. These paths are then used to efficiently navigate the mobile robot from its starting position to its goal while avoiding obstacles. PRM is particularly effective in high-dimensional spaces and environments with complex geometry, offering a robust solution for path planning in real-world scenarios [32].

In each approach, the mobile robot's path was recalculated upon reaching a designated waypoint using the newly obtained depth image. If a collision-free path could not be determined, the mobile robot was programmed to remain stationary until the depth image was refreshed and a collision-free path could be synthesized. Utilizing this specified update rate, the robot was able to dynamically navigate around existing obstacles and human workers by the updated information. The updated map also allowed the controller to promptly activate warning signals, triggering both visual and audible alerts when the mobile robot entered the attention zone of existing human workers. It is important to recognize that the map can only be updated during robot navigation using the acquired depth image. If human workers or obstacles are positioned beyond the detectable range of the RGB-D camera, the map cannot be updated.

5. SIMULATION OF PATH PLANNING BASED ON CONTACT AVOIDANCE ZONES

In this section, both PRM and RRT were utilized to address the effectiveness and efficiency of the real-time updates when a moving worker navigated through the laboratory workspace. In all methods, the turning radius of the mobile robot was fixed at 0.4 m and the avoidance range of existing obstacles was set to 0.3 m.

5.1 Stationary Human Worker

In this scenario, the mobile robot initiated its movement from a point where two human workers were situated at undisclosed locations, which were not initially documented in the workspace map. The presence and positions of the human workers could only be ascertained when the mobile robots reached certain waypoints, owing to the restricted field of view of the RGB-D camera they were equipped with. Due to the small size of the experimental area, only the RGB-D camera was employed, while the indoor location device was excluded due to its larger deviation.

Figures 6, 7, and 8 illustrate the paths generated from a specified initial location to a designated destination using A*, RRT, and PRM path planning methods. Upon reaching waypoints where the mobile robot can detect the presence of the human workers, the path was adjusted. The red dashed lines represent the planned path of the mobile robot based on the initial indoor map without considering the presence of human workers, while the blue solid lines depict the paths after the robot detects the presence and locations of human workers. As the Figures illustrate, when a human worker was detected, the mobile robot reprogrammed and adapted its moving path to avoid any potential collision.

Specific start and destination locations were defined in each scenario, with the human worker positioned along the original planned path. The black dashed boxes in these three figures represent the avoidance zones surrounding the human workers. All three path planning methods effectively adapted the mobile robot's path upon detecting the presence of human workers.

Table 2 compares the computation time required using a Ryzen 7 4700u processor with 16 GB memory. In this scenario, the path generated using A* changed from 73 waypoints to 144 waypoints. The path produced using RRT changed from 3000 nodes to 6000 nodes since the total number of nodes has been specified as a parameter, while the path generated using PRM changed from 20 waypoints to 35 waypoints. Following numerous trials wherein the avoidance zone around human workers was positioned at various locations on the map, the calculation times of both A* and PRM algorithms were compared to determine the optimal operation time for path planning. It is evident that if the workspace map is partitioned into a limited number of grids, PRM demonstrates superior efficiency in path synthesis in terms of time when adjustment of a planned path is necessary.

Based on the finding in this section, PRM method demonstrates quicker calculation time when adapting the path upon detecting the presence of human workers. Therefore, PRM was chosen to formulate the moving paths of the mobile robots when navigating around moving human workers, incorporating both attention and avoidance zones in the subsequent section.

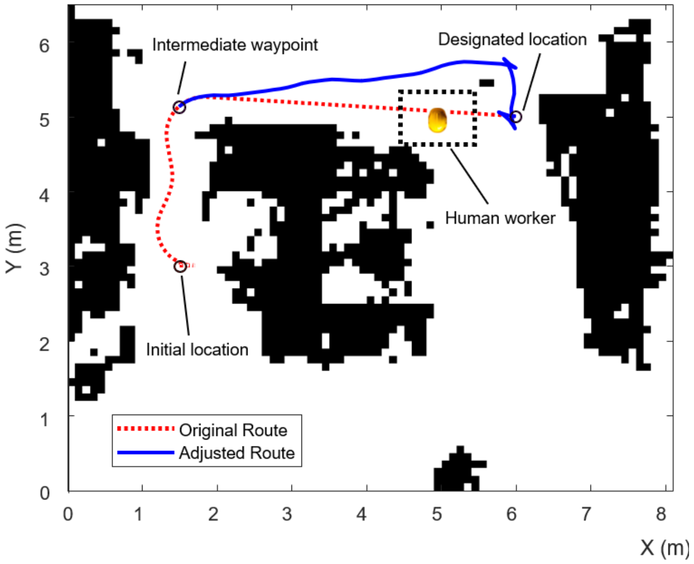

FIGURE 6: A* path planning method utilized to navigate around a stationary human worker detected along the original path.

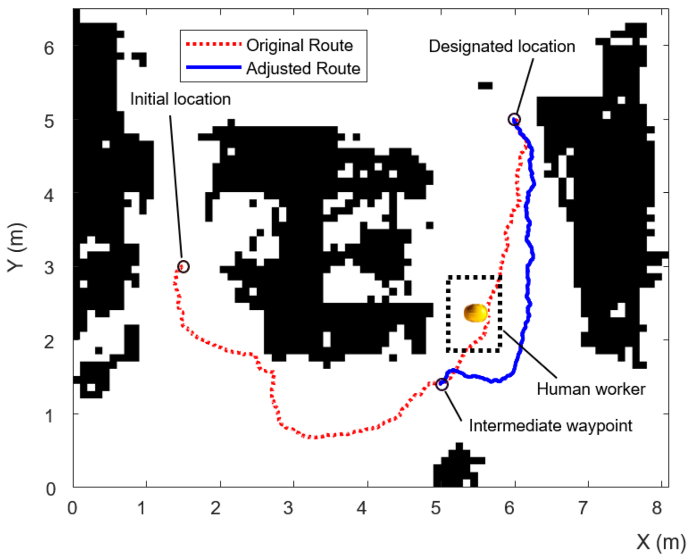

FIGURE 7: RRT path planning method utilized to navigate around a stationary human worker detected along the original path.

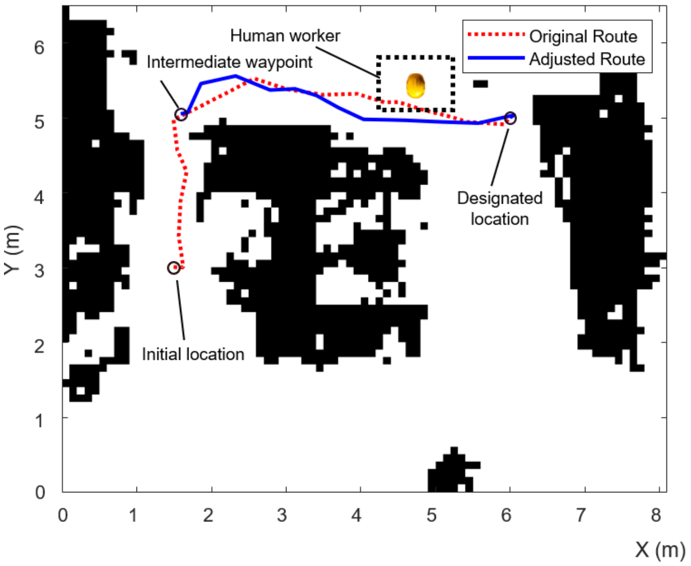

FIGURE 8: PRM path planning method utilized to navigate around a stationary human worker detected along the original path.

Table 2: Comparison of path-planning methods

Method	A*	RRT	PRM
Original map	73 waypoints	3000 nodes	20 waypoints
Process time	0.059 sec	1.24 sec	0.27 sec
Updated map	71 more waypoints	3000 more nodes	15 more waypoints
Updated time	0.559 sec	0.369 sec	0.27 sec

5.2 Moving Human Worker

In the scenario involving a moving human worker as opposed to being stationary, the workspace transitioned from the Robotics Research Lab area to an emulated warehouse setting, covering an 80 m × 100 m area. As two human workers began moving, a 2.4 m radius circle was integrated into the planning map upon identifying the presence of each individual human worker. The locations of two human workers were determined using both the equipped Bluetooth indoor localization device and the depth images captured by the RGB-D camera. Additionally, a 6 m radius circle was superimposed onto the workers' locations to represent their attention zones. Path planning was guided by the contact avoidance zones, with the mobile robot required to activate the warning signals upon transversing these attention zones.

To optimize calculation time for the robot controller in a warehouse workspace, the grid size of the indoor map was configured as 0.1 m, enabling a refresh rate of 1.5 sec. Leveraging its efficient calculation rate, the PRM could quickly synthesize the updated path within the refresh rate to prevent potential collisions. While the proposed refresh rate and avoidance zone afforded ample time to evade potential collisions, the robot promptly updated its path upon identifying a human worker within a 4 m radius. Moreover, upon entering the attention zone, both visible and audible warning signals were activated, allowing human workers sufficient time to avoid colliding with the mobile robot.

In Figure 9, the path adjustment of the mobile robot is illustrated as it transversed from its initial position to the designated location. Upon detecting a moving human worker within a predetermined distance, the mobile robot updated its path accordingly. Subsequently encountering a second worker, the robot adjusted its path again before it reached the designated location. Figure 9 also demonstrates the adapted paths of the mobile robot, carefully circumventing the contact avoidance zones around the human workers.

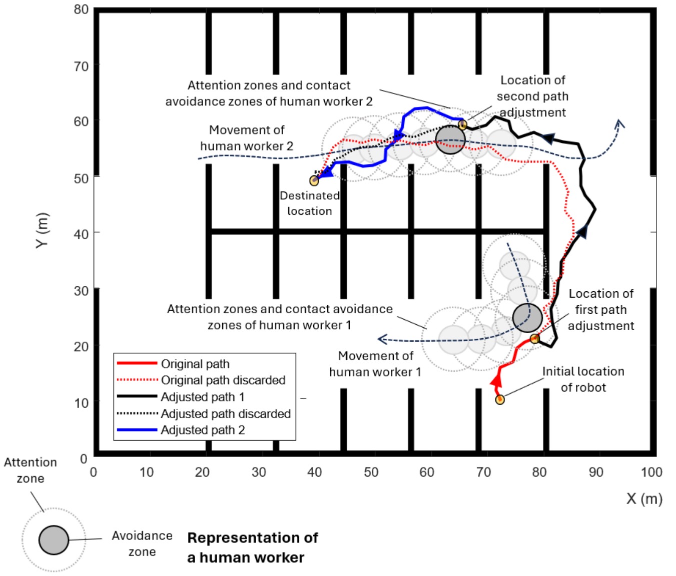

FIGURE 9: PRM path planning method utilized to navigate around moving human workers detected along the movement path.

In this scenario, the control unit of the mobile robot generated and updated paths within an average time of 0.87 seconds, with the longest calculation time recorded at 1.2 seconds. Consequently, the effectiveness of the PRM method in averting potential collisions with human workers is apparent. Upon encountering two human workers at distinct locations, the mobile robot adjusted its trajectory when it detected a worker within a 4-meter range, ensuring collision-free navigation. As the speed of the mobile robot was set as 3 m/s, the total distance traveled was 119.82 m, with a total duration of 42.56 sec based on the simulation, including both movement and path updating time.

6. CONCLUSION

This paper addresses the critical challenge of preventing collisions between mobile robots and human workers in collaborative workspaces. By proposing a comprehensive solution that integrates attention zones and avoidance zones into path planning for mobile robots, we have taken a significant step toward enhancing workplace safety. This study also introduces a methodology for delineating attention zones for human workers and avoidance zones for robots during navigation, thereby enabling effective path planning to prevent potential collisions and minimize the risk of injuries. Various factors influencing the design and implementation of these zones was explored, including environmental conditions, human factors, and technological considerations, to develop robust safety protocols.

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