Invisible Humans in Human-aware Robot Navigation

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***Abstract*— Human-aware robot navigation addresses the navigation of the robot in the presence of humans. Although significant research exists for addressing the visible humans, there is a need to address the humans that are not visible but can emerge anytime into the scene. While addressing such 'invisible humans', we have to make sure to avoid surprises or shocks for humans and the erratic behavior of the robot planner. In this work, we propose a novel approach to detect and integrate these 'invisible humans' into human-aware navigation planning. The experiments and the results presented show the advantage of the proposed idea.**

I. Introduction

With the rapid advancement in human-aware or social robot navigation, new frameworks [1], [2], [3], [4], [5] are required to address a variety of social navigation scenarios. However, most of these frameworks [6], [7] address only the visible humans and do not take into account the possible emergence of humans that are not visible currently. We believe that such invisible humans should be considered while developing a human-aware navigation framework to avoid any erratic behaviors of the robot planner when a human suddenly appears. Therefore in this work, we try to address these invisible humans in human-aware navigation planning.

There are not many works that address this problem in the field of human-aware navigation. However, there are some existing works in classical robot navigation that address similar issues. Particularly, this work is inspired by the pioneering work of M. Krishna concerning the ability of a mobile robot, based on the model of its perception functions, to assess from where in the close environment of the robot a human can emerge and prepare to react to ensure no-collision by adapting its path and velocity [8], [9], [10]. Some recent works like [11], [12] address the issues of robot navigation in occluded or unknown regions with a limited field of view. The work presented in [13] talks about the adaptive speed control of the robot in unknown environments and also talks about the occluded regions. The authors of [14] propose a methodology to mitigate or avoid collisions while navigating. In our case, we are trying to mitigate possible future collisions with a human.

As it is evident that the unknown or occluded region could cause issues with classical navigation, the same applies to social navigation. Hence, we propose the concept of 'invisible humans' in human-aware navigation planning through this paper. First, we briefly present a methodology to locate invisible humans while navigating a 2D map. Next, we integrate these invisible humans into our human-aware navigation framework, CoHAN [15], by introducing a new human-aware constraint into our optimization scheme, and a new modality to address the issues. The implementation and code can be found at `https://github.com/sphanit/cohan_planner_multi/tree/model`. Finally, we present a detailed analysis through a set of experiments that highlight the advantages of this idea.

The rest of the paper is organized as follows. Section II presents the estimation of the invisible humans. Section III shows how the invisible humans are integrated into CoHAN and talks about the issues that arise. In Section IV, various experiments to evaluate the proposed approach are presented, followed by the real-world experiments in Section V. The discussion on the limitations is presented in Section VI, and the conclusions in Section VII.

II. Locating the Invisible Humans

The locations of the invisible humans are estimated using an emulated laser scan on a 2D map. A custom laser scan is attached to the robot's base and it is continuously updated as the robot moves on a given map. The entire system is implemented in ROS [16] and requires the map that is published by the ROS Navigation stack. In order to avoid too many detections, we limit the invisible humans detection to a radius of $5\,\mathrm{m}$ in front of the robot. The process to locate invisible humans is briefly explained below.

A. Building the contour

The custom laser scan sensor that is attached to the robot's base, scans the given 2D map to get the visible contour of the map. An example laser contour built using this is shown in Fig. 1 (a). Different parts of these contour lines are shown in different colors for ease of explanation. The red and the blue lines together constitute the regions on the real map where the laser has hit a wall or an obstacle. The black lines represent the laser data that did not hit anything and reached the end of their range (in our case, range of the laser is $7\,\mathrm{m}$). Finally, the yellow lines are interpolated rays joining large separations between consecutive laser values and play a major role in our algorithm. The red circle and the arrow represent the robot's position and its direction.

B. Estimating Invisible Humans' locations

The first part of the estimation is the detection of corners of interest from the contour. To do this, all the pairs of consecutive laser values (ranges) that are separated by more than $0.5\,\mathrm{m}$ are determined. The threshold of $0.5\,\mathrm{m}$ is chosen

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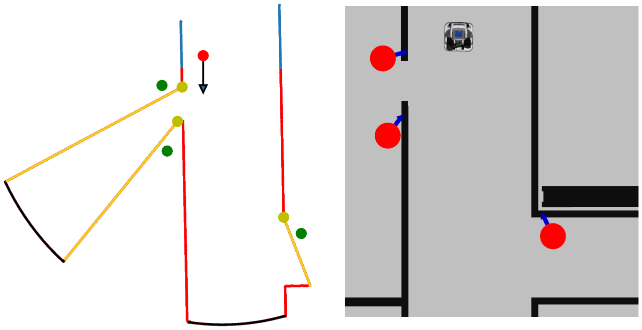


(a) Contour

(b) Invisible Humans

Fig. 1: (a) Laser contour built by the custom laser sensor. The red and blue lines are the actual walls or obstacles in the front and back of the robot respectively. The black lines are the laser range boundaries and the yellow lines are interpolated lines between two gaps of laser data. The robot is shown as a red dot with an arrow. The detected corners are shown in yellow, while the detected invisible humans are shown in green. (b) The detected invisible humans on the map for the situation shown in the contour. The red circles shows the location and the blue arrow shows the assumed orientation, which is always oriented towards the robot.

to filter out small gaps from where a human will not emerge. Since the laser is attached to the base of the robot, the lower value in each of the above laser value pairs corresponds to a corner of interest, and the location where it hits the map is determined to be the corner of interest. These are shown as yellow circles in Fig. 1 (a).

Once these corners are detected, these are used as the reference points to determine possible locations for invisible humans. The built contour can be seen as an approximate non-convex polygon, and the invisible humans can be seen as circles that lie outside this polygon and near the corners of interest. The initial guess for the centers of these circles is determined by using the properties of the polygons and the laser scan data from the custom laser. Finally, the locations of the centers that avoid overlap with obstacles are estimated using ray tracing. These centers are shown as green circles in Fig. 1 (a). Finally, the corresponding locations of the invisible humans are as shown in Fig. 1 (b).

III. Integration with a Human-Aware Planner

In the previous version of CoHAN, we address different types of visible humans by introducing new modalities and human-aware constraints [15]. In this work, we extend it further to address the invisible humans. The locations of the invisible humans are published on a ROS topic. CoHAN subscribes to this topic and adds a new constraint to its optimization, specifically designed to address invisible humans.

A. Invisible Humans Constraint

The invisible humans constraint takes into account the human reaction time, walking speed, and deceleration and aims to make the robot cautious about the sudden human emergence. The cost added by this constraint for the n$^{\text{th}}$ pose of the robot's trajectory is given as:

$$\begin{aligned} cost_{inv\_human} &= max\left(\frac{V - a\Delta t_n}{d}\right) \quad if \quad \Delta t_n > 0.5s \\ &= \frac{V}{d} \quad otherwise \end{aligned} \tag{1}$$

where d is the distance between the invisible human and the robot, V is the average human walking speed, $1.3\,\mathrm{m/s}$ [17], a is the deceleration of the human and Δt_n is the time difference between the n$^{\text{th}}$ pose and the starting pose of the planned trajectory of the robot. The value of the deceleration, a, can vary and can be up to a maximum of $2.94\,\mathrm{m/s^2}$ ($0.3\,\mathrm{g}$) [18]. In this work we take a reaction time of $0.5\,\mathrm{s}$ as discussed in [18], [19]. Hence the constraint adds the maximum possible cost until $0.5\,\mathrm{s}$. Then we assume that the human will continuously decelerate to avoid collision with the robot over time and eventually stops, which is reflected in the upper part of Eq. (1). The time (Δt) and human detections are reset after every control cycle.

1) Issue with the constraint: The main objective of the constraint is to push the robot away from openings, anticipating the emergence of invisible humans. However, when the robot needs to pass through this opening and if the passage is narrow (door or narrow corridor), the constraint pushes the robot back and makes it impossible to enter the passage. To mitigate this, whenever such scenarios are detected, CoHAN switches to a new modality called *Passing Through*, which turns off the invisible humans constraint and reduces the maximum robot's velocity until it passes through. Based on the location of the invisible humans and the laser scan data, we detect three kinds of scenarios in this work which are shown in Fig. 2.

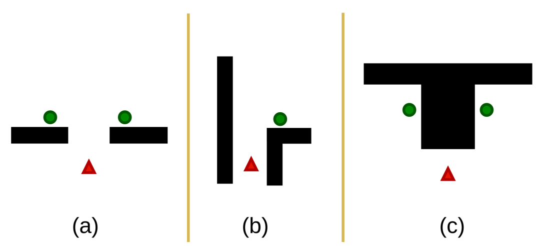


Fig. 2: Different types of passages that are detected using invisible humans. (a) Doorways, or openings and endings of the corridors (b) a narrow passage with opening on one side and a wall on the other side (c) a large pillar or obstacle where the robot cannot see on either side. The green circles are the possible locations of the invisible humans and the red triangle shows the robot pointed towards the direction of its motion.

IV. Experiments

The proposed idea, after being completely integrated with CoHAN, is tested in several settings, and this section shows some interesting scenarios and presents a detailed analysis. We use ROS-melodic with Ubuntu 18.04, and all the scenarios are simulated using MORSE [20] simulator. The simulated human agents used in the experiments are controlled using InHuS [21], an intelligent human simulator developed in our lab. The PR2 robot in our lab is used for real-world tests.

A. The effect of the Invisible Humans constraint

To show the effect of introducing the invisible humans constraint into CoHAN, we present the robot with a door crossing scenario as shown in Fig. 3. We test this scenario without and with the invisible humans constraint and the corresponding paths of the robot are presented in Fig. 4 (a) and Fig. 4 (b) respectively. The paths are colored, and the color moves from blue to red as the robot moves from start to goal. It can be clearly seen from these paths that the inclusion of the constraint made the robot more cautious as it takes a larger turn and aligns its path earlier to pass through the doorway. The corresponding speed plots are shown in Fig. 4 (c) and (d). From the plot in Fig. 4 (d), we can see that

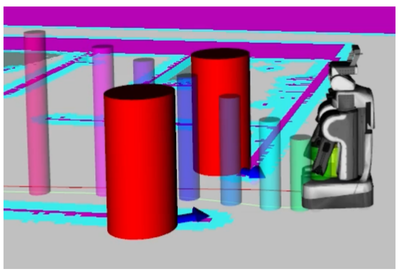
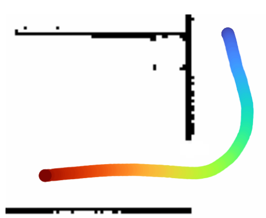
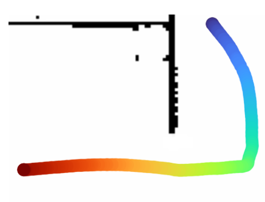


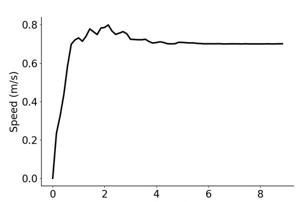
Fig. 3: The robot passing through the door under the presence of invisible humans. The translucent colored cylinders represent the planned poses of the robot and different colors correspond to different time instances. The height of each cylinder is proportional to the speed at the planned pose of the trajectory. The red cylinders are the estimated invisible humans.



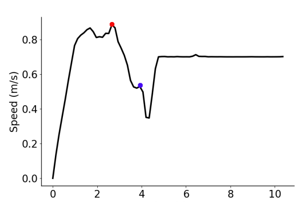
(a) Path without constraint



(b) Path with constraint



(c) Speed without constraint



(d) Speed with constraint

Fig. 4: Paths and speed profiles of the robot passing the door without ((a), (c)) and with ((b), (d)) the Invisible Humans constraint. The color of the paths indicates the time and progress of the robot, from blue to red (start to goal).

the robot slows down twice, once when the robot turns and aligns with the door around $2.5\,\mathrm{s}$ (red dot) and then again before passing through the passage around $4\,\mathrm{s}$ (blue dot). The cautious behavior of the robot is reflected again in these speed profiles.

B. Navigation in the presence of visible humans

The inclusion of the invisible humans into human-aware navigation planning should not cause discomfort to the visible humans that are moving around the robot. To show that CoHAN finds a fine balance between the invisible and visible humans, we present a corridor scenario with many doors, as shown in Fig. 5. In this scenario, the robot

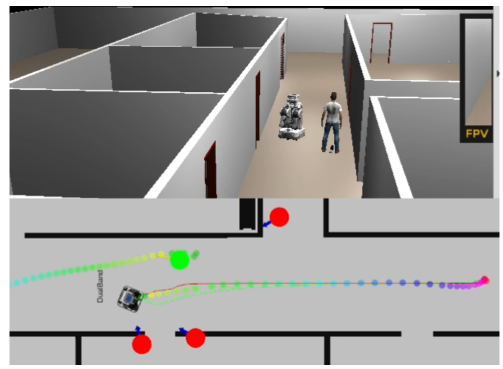
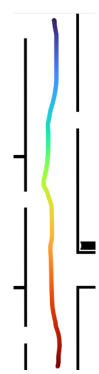
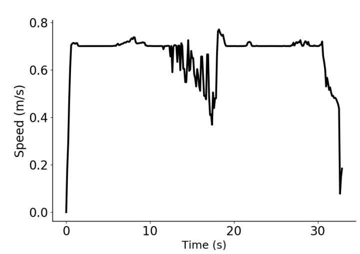


Fig. 5: Corridor with many openings where the robot continuously anticipates the emergence of humans. The robot tries to find a balance between visible and invisible humans. The green circle is the visible human interacting with the robot, while the red circles are estimated invisible humans. The colored path with circles is the planned trajectory of the robot.



(a) Path



(b) Speed Profile

Fig. 6: Path and speed profile of the robot in the corridor scenario. The color of the path indicates the time and progress of the robot, from blue to red (start to goal).

anticipates that an invisible human might emerge at any time and tries to move away from the openings. However, when it sees a human passing through the corridor, it tries to provide more space for the human by moving to one side. At the same time, it faces the forces from the invisible humans and tries to find a balance between these and the visible human. By observing the path and speed profile of this scenario from Fig. 6 (a) and (b), we can see that the robot moves away and reduces its speed rapidly to accommodate the visible human. Nonetheless, it does not move very close to the wall as it anticipates a human emergence. We can, therefore, infer that

CoHAN tries to find a balance between visible and invisible humans to mitigate such complex situations.

C. Sudden emergence of a human

This final scenario shows a situation where a human emerges suddenly from an occluded region from where the robot is already anticipating an invisible human. The snapshots of this scenario before and after the emergence are shown in Fig. 7. Before a human actually emerges from the

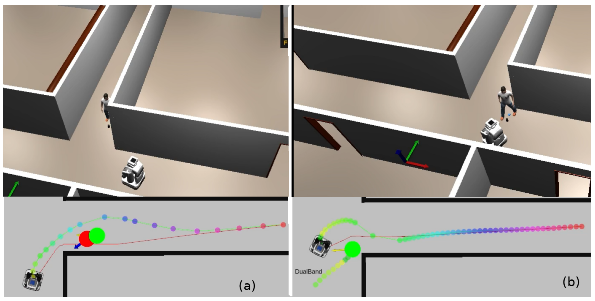
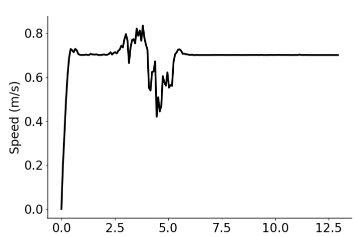


Fig. 7: Sudden emergence scenario. (a) Shows the anticipated invisible human in red and the real human in green. The robot has not yet seen the human but due to the invisible human it starts moving away from the corner. (b) The robot has seen the human and adjusted its trajectory to provide more space to the human. It moves away further and takes a larger turn. The colored path with circles is the planned trajectory of the robot.

corridor, a possible position of the invisible human is already estimated. As shown in Fig. 7 (a), it approximately overlaps with the real human. The robot starts moving away slowly because of this anticipation, and suddenly a real human appears in front of it. The robot quickly adapts its trajectory by moving away from the human and slowing down a little, before continuing to its goal. From Fig. 8 (a), we can see the discontinuity in the path when the human emerges. However, the total change in path is not very drastic as the robot was already anticipating a human. The speed profile in Fig. 8 (b) shows an oscillation that occurred when the robot moved back suddenly and then slowed down until the human passed.

(a) Path



(b) Speed Profile

Fig. 8: Path and speed profiles of the sudden emergence scenario. The color of the path indicates the time and progress of the robot, from blue to red (start to goal).

V. Real-world Implementation

The new CoHAN system is installed on the PR2 robot in our lab and then tested in the doorway scenario discussed

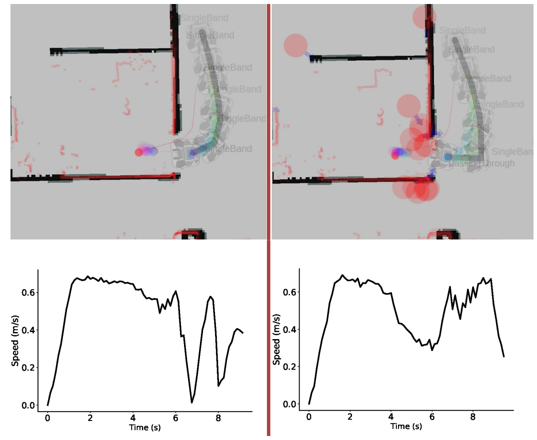


Fig. 9: Real world testing of the constraint

above. The real-world results match the results of the simulation approximately both in the paths and the speed profiles. These real-world results are shown in Fig. 9. The video showing some more experiments and the tested scenarios can be found at `https://youtu.be/f8JS0dg_Luw`.

VI. Discussion and Limitations

The introduction of invisible humans (the unseen humans who can emerge any time into the scene) into human-aware navigation planning is relatively new and requires further research. We present one possible approach to address this issue. What is particularly interesting here is that our approach is modeled as a situation assessment and prediction ability to integrate into a mobile robot human-aware navigation. Having this, we will have a robot that can interact, using several modalities, with humans present in its field of view while making provisions to adapt to humans that are not yet seen. One difficulty we faced was integrating all these features without being "too conservative" and avoiding another case of the "freezing" robot. However, there are still some limitations to this approach. Since the approach is based on a 2D map, we can have false detections in the regions visible through the head of the robot but not through the base. It can be mitigated by augmenting the current approach with new sensor data and filtering further. The second limitation is the imperfect detection of the invisible humans, where sometimes, the detected human overlaps with an obstacle. The presented algorithm needs to be refined further, and the current work is just a preliminary step.

VII. Conclusion

We have introduced the idea of invisible humans into human-aware navigation and presented a methodology to estimate the locations of the invisible humans. The idea was then integrated into our human-aware navigation planner by defining a new constraint using these estimations. We addressed the limitations of this constraint by defining a new modality in our planning system. Finally, through a series of simulated and real-world experiments, we have shown the advantages of the proposed approach.

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