Subgoal Estimation for Enhanced Decision Making in Human-Guided Robotic Followers

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***Abstract*—Conventional human-guided robot followers employ velocity-based prediction to forecast the future position of their leader. While functional in structured environments, this method is prone to suboptimal behavior due to difficulty in handling human variability and the inability to formulate a deeper understanding of the human's intentions. To mitigate the robot's insensitivity to task contexts, unintended collisions, and erratic movements, it must leverage advanced generalization and hierarchical task decomposition. This paper accordingly proposes and demonstrates the employment of subgoal estimation to remediate the decision making flaws of velocity-based prediction in human-guided robotic followers.**

***Index Terms*—Human-Robot Interaction, Autonomous Navigation, Subgoal Estimation, Velocity-Based Prediction**

I. Introduction

The capability for a robot to move in harmony with a human, as natural as it may seem, requires sophisticated perception, planning, and control strategies. Such capabilities stretch beyond the conventional navigation problem of reaching a destination via an optimal path. It calls for a robot to interpret human intentions, predict movements, and adjust its path proactively—not reactively—in environments that are neither static nor predictable.

Standard human-guided robotic followers leverage velocity-based prediction whereby a robot predicts the partner's position and then tries to simply move to be at the "side" of the predicted position of the partner [4]. For instance, researchers developed a wheel-chair robot that moves alongside a care-giver, basically modeling the situation where it needs to avoid obstacles while trying to move at the "side" of the partner [4]. The limitations of velocity-based prediction become apparent, however, in various aspects of human-robot interaction. Challenges primarily arise from the difficulty in accommodating the diverse range of human movements and the limited capacity to delve into the deeper layers of human intentionality. In structured environments, these human-guided robotic followers may perform adequately, but their utility diminishes when faced with the complexities of unscripted scenarios, unintended collisions, and erratic human motions. Robots employing velocity-based prediction are further hindered by tasks that require hierarchical planning such as navigation through crowded environments. The insensitivity of velocity-based approaches to the specific context of a task can undermine adaptability and context-aware behavior. This limitation poses a risk of less effective performance, particularly in dynamic environments, where there is an increased likelihood of unintended collisions. Human variability in movement patterns and styles poses another challenge for velocity-based prediction, as it may struggle to adapt to individual differences. As highlighted in [4], robotic followers that employ velocity-based predictions were found to be sensitive to erratic movements and left a dangerous impression to participants because the robot did not move straight down a path but rather in a zigzag way.

This paper subsequently demonstrates the utilization of subgoal estimation to rectify the decision-making flaws inherent in velocity-based prediction for human-guided robotic followers. Through the employment of subgoal estimation, the robotic follower gains the ability to discern and anticipate the underlying objectives of its leader, thereby mitigating the insensitivity to task contexts and reducing the likelihood of unintended collisions.

Our research draws inspiration from studies in social robotics and human-robot collaboration, which suggest that people prefer robots that can behave in a human-like manner, especially when sharing space and tasks. Yet, existing systems often fall short in dynamic and unstructured settings, where precision and adaptability are crucial.

In the subsequent sections, we will delve into the theoretical underpinnings of subgoal estimation, detailing its implementation and showcasing experimental results that highlight the efficacy of this approach. By doing so, we aim to contribute to the evolving landscape of human-robot collaboration, providing a viable solution to enhance the adaptability and decision-making capabilities of robotic followers, particularly in scenarios characterized by human variability and unpredictable environmental dynamics.

II. Related Work

The exploration of human-robot interaction (HRI) has been multifaceted, encompassing the development of robots capable of assisting, collaborating, and cohabiting with humans. The study of side-by-side navigation has emerged as a crucial aspect of HRI, reflecting everyday human activities such as walking together. This section reviews the literature that informs and contextualizes our research.

A. Social Robotics and Side-by-Side Navigation

Early work in social robotics highlighted the importance of robots understanding and adhering to social norms to be accepted by human users. For example, Breazeal's work on sociable robots laid the groundwork for robots that could engage people through non-verbal communication and social interaction [1]. Side-by-side navigation can be viewed as an extension of this, requiring a robot to not only navigate a shared space but also to do so while recognizing and respecting the social cues of its human counterpart.

B. Adaptive Path Planning

The complexity of human environments necessitates adaptive path planning for robots. Researchers like Kruse et al. have addressed this by developing algorithms that allow robots to maintain a comfortable distance from humans while navigating shared spaces [2]. These algorithms serve as a foundation for our approach, which advances the concept by requiring the robot to maintain a specific formation relative to a moving human.

C. Human-Aware Robot Navigation

Human-aware robot navigation is another relevant area that has been extensively studied. Works by Sisbot and Alami have provided insights into how robots can plan paths that are not only efficient but also comfortable and safe for nearby humans [3]. Our research builds upon these principles to ensure that the Turtlebot3 navigates in a manner that is intuitive and predictable to the human partner.

D. Implicit Communication and Intent Recognition

Understanding human intent has been a critical challenge in HRI. Murakami et al.'s "Destination Unknown: Walking Side-by-Side without Knowing the Goal" is particularly relevant to our work [4]. Their robot companion was able to walk alongside a human without a predefined destination by interpreting implicit communication cues. We extend this work by integrating advanced sensors and machine learning algorithms to enhance the robot's ability to infer direction and intent in real-time, allowing for smoother and more intuitive side-by-side navigation.

E. Dynamic and Unstructured Environments

Lastly, our research is informed by studies focused on navigating dynamic and unstructured environments. Researchers have explored various sensor technologies and data fusion techniques to enable robots to operate in unpredictable settings [5]. Our system intends to employ a similar sensor suite, but with the added challenge of maintaining a side-by-side formation with a human, necessitating even more sophisticated data processing and decision-making algorithms.

Our review of related work indicates that while significant progress has been made in the field of HRI and autonomous navigation, there remains a gap in solutions that allow for seamless, adaptive, and autonomous side-by-side navigation with a human in dynamic and unstructured environments. Our research aims to bridge this gap, leveraging insights from the aforementioned studies to develop a system that advances the state-of-the-art in collaborative human-robot navigation.

III. System

In light of our revised approach to the navigation algorithm, we adapted the technical setup to support the new route learning mechanism. This mechanism involves the simulated robot analyzing its surroundings in a 3x3 grid, identifying objects such as intersections and the leader (human partner), and predicting the next motion of the leader based on their position in this grid.

To facilitate this process, we employed a combination of the robot's sensor data and a custom-developed linear regression model. The model uses the observed position and movement vector of the leader within the 3x3 grid to predict their next move. This prediction then informs the robot's own path planning, allowing it to maintain the side-by-side formation effectively.

The implementation of this model required significant adjustments to our original software stack on ROS Noetic. We integrated additional data processing nodes to analyze the sensor inputs more intricately, specifically focusing on the spatial analysis within the 3x3 grid around the robot. This analysis includes identifying the leader and calculating their movement vector, which is then input into the linear regression model.

The linear regression model, obtained during the "unknown destination" paper tests, calculates the most probable next position of the leader. The values were adjusted by trial and error on the simulation interface to find the optimal results to enable a smoother motion for subgoal estimation

Despite these advancements in our navigation system, direct deployment on the Turtlebot3 Waffle Pi was not feasible due to the sensor integration issues. Consequently, we validated our revised navigation algorithm through simulations. We used OpenCV in these simulations to replicate the robot's environment and test the efficacy of our route learning mechanism and linear regression model in various dynamic scenarios.

In summary, the subgoal is estimated by splitting the surrounding area into a 3x3 grid. For each block, the probability is computed for the subgoal being there, based on the utility function. This is akin to a reward value for each block. The value is computed by looking at how the leader moves and how far the robot is from the goal.

This simulation-based approach allowed us to refine our algorithms and ensure their robustness before any potential real-world application. It also provided valuable insights into the interaction dynamics between the robot and human in a controlled setting, informing further improvements and adjustments to our system.

IV. Demonstration

In this section, we present the results of our developed subgoal estimation algorithm deployed in an OpenCV simulation, including observations of what functioned as intended and what did not.

A. Observations and Performance

Route planning and decision making functioned as intended, whereby the robot first moved and checked the surrounding area for objects. If it did not see the intersecting point or the goal, it went directly with the leader and if there was an intersection point it followed the leader. When there is a goal that is the same direction as the leader, it went directly to the goal. Our simulation is depicted in figures 1, 2, and 3, where the leader is blue, robot is green, and yellow is the goal.

Our subgoal estimation algorithm enabled the follower to perform very smoothly and was not susceptible to erratic movements. *Performance metrics based on our observation of the algorithm are elaborated in section V, where an evaluation study was performed.*

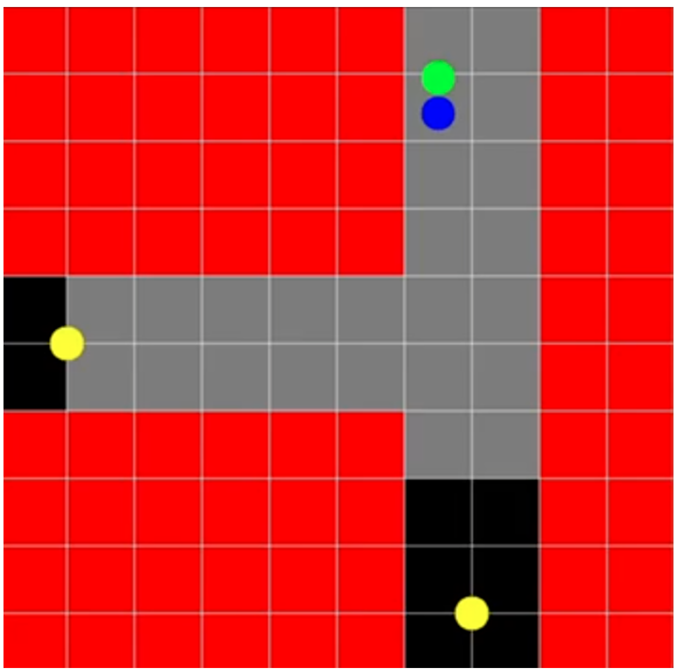

Fig. 1. We assume that the robot has information on all the grey blocks. If there are objects, intersections or goals it will factor that into the utility function accordingly to plot a course.

B. Challenges Encountered

Despite our successful implementation of the subgoal estimation algorithm, we encountered several challenges during the demonstrations. Primarily, While we were able to sufficiently demonstrate the leader-follower state, encapsulating the collaborative state was a challenge due to deficiencies in our algorithm, which require further iterations to configure. In addition, our algorithm did not handle intersections as well as intended, which is why in an intersection the robot will follow the leader. We also struggled to tailor our simulation to be as high-fidelity as possible to ensure effective translation of this algorithm in a real-world scenario.

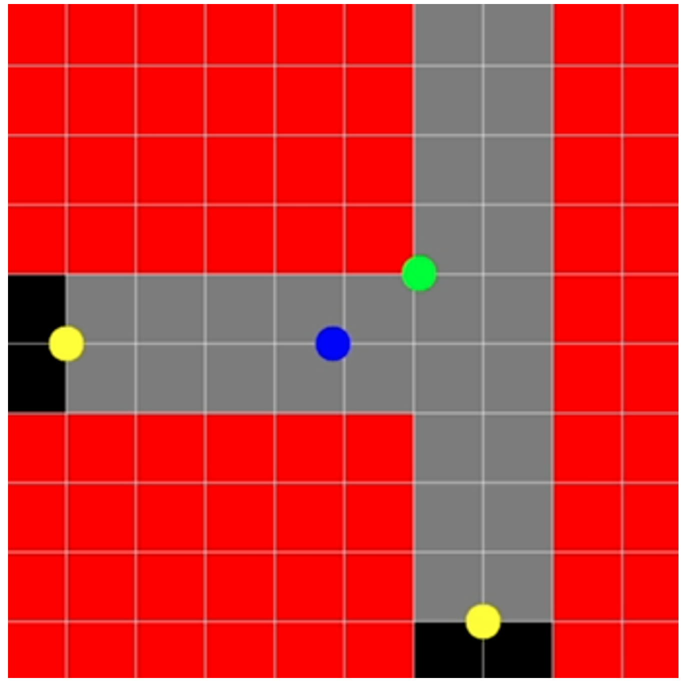

Fig. 2. Since the leader stayed very close to the follower it deviated from going to (goal 2)

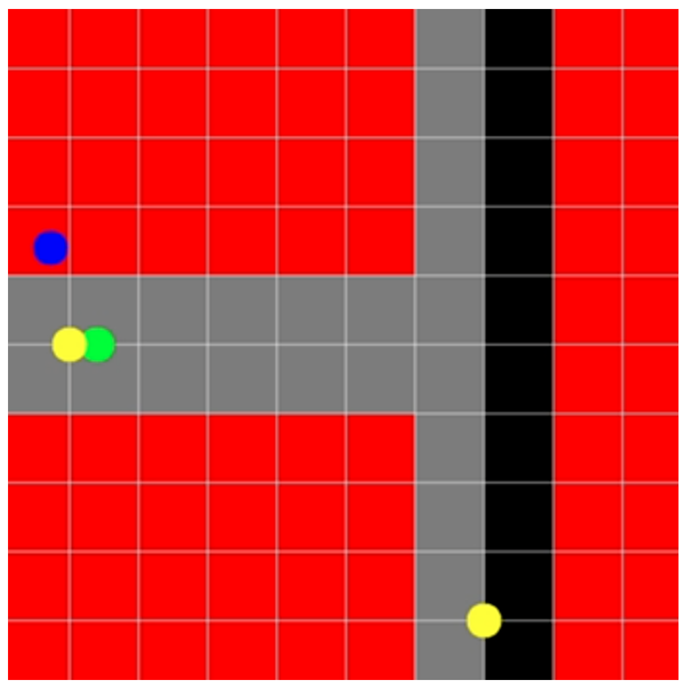

Fig. 3. Once the robot reaches a goal then it won't leave it even if the leader tried to move around the map.

V. Evaluation Study

A. Study Objective

The objective of our study was to evaluate the utility of subgoal estimation in enabling human-guided robotic followers to follow a leader in comparison to velocity-based prediction.

B. Study Design

To perform our evaluation, we leveraged the subgoal estimation algorithm highlighted in the System section and a velocity-based prediction algorithm for human-guided robotic followers. Both algorithms were subsequently assessed by 4 participants examining the simulation based on the following performance metrics:

1) Path Following Accuracy
2) Collision Avoidance
3) Smoothness of Movement
4) Perceived Safety

To simulate environmental changes, the initial scenarios for the TurtleBot3 were abstracted to our OpenCV simulation. For instance, navigating crowds was simulated by the leader performing erratic zig-zag movements.

C. Research Questions and Hypotheses

This evaluation of the study is guided by the following research questions and hypotheses:

Research Question 1: How does the performance of a human-guided robotic follower using subgoal estimation compare to that of a follower employing velocity-based prediction in terms of path-following accuracy, collision avoidance, and adaptability in dynamic and unstructured environments? **Hypothesis 1:** We hypothesize that subgoal estimation will outperform velocity-based prediction in at least the latter 2 metrics.

Research Question 2: What are the user satisfaction levels and perceived safety implications when individuals are guided by a robotic follower utilizing subgoal estimation compared to velocity-based prediction, and how do these perceptions vary across different scenarios and levels of environmental unpredictability?

Hypothesis 2: We anticipate that subgoal estimation will be perceived as safer than velocity-based prediction and this will be consistent across various levels of environmental unpredictability.

D. Study Results

In comparison to velocity-based prediction, the path-following accuracy of the robotic follower utilizing the subgoal estimation algorithm was recorded by all participants to demonstrate a notable improvement in the accuracy of the follower's trajectory. This was especially true when simulating erratic movements which the subgoal estimation algorithm was not swayed by. This enhancement in path-following accuracy was particularly evident in scenarios where we attempted to simulate dynamic and unstructured environments, where the subgoal estimation algorithm exhibited a higher level of adaptability.

The collision avoidance capabilities of the robotic follower were assessed by examining responses to encountering walls in the simulation environment. The subgoal estimation algorithm was deemed by all participants to have demonstrated effective obstacle detection and avoidance strategies. The follower effectively adjusted its path to navigate around simulated ”obstacles”, showcasing a proactive approach in contrast to the reactive nature of velocity-based prediction. The results indicated a significant reduction in the frequency and severity of collisions, reinforcing the effectiveness of subgoal estimation in enhancing the safety of human-robot interactions.

In dynamic environments characterized by variations in the leader's movements and unpredictable changes in the surroundings, the subgoal estimation algorithm showcased remarkable adaptability. The follower seamlessly adjusted its trajectory to align with the leader's intentions, even in scenarios involving sudden changes in direction or pace. This adaptability was in stark contrast to the limitations observed in velocity-based prediction, which struggled to cope with the complexities of dynamic environments, leading to less effective performance. All participants noted that this benefit was evident and could have significant impacts in real-world scenarios where lack of smoothness in movement could lead to injuries for bystanders.

Feedback from participants regarding their satisfaction and perceived safety of the subgoal estimation algorithm in contrast to the velocity-based prediction revealed positive sentiments. Users reported a higher level of comfort and confidence in the follower's behavior when guided by the subgoal estimation algorithm. The smoother movements and proactive decision-making of the robotic follower contributed to a more natural and human-like collaboration. Additionally, participants noted a reduced sense of unpredictability and a safer overall experience compared to scenarios where velocity-based prediction was employed.

VI. Discussion

The findings of our study suggest that the utilization of subgoal estimation in human-guided robotic followers significantly enhances their performance compared to velocity-based prediction across various significant metrics. The observed improvements in path-following accuracy, collision avoidance, and adaptability in dynamic environments underscore the potential of subgoal estimation to address the limitations associated with conventional velocity-based approaches. The smoother interactions and proactive decision-making observed in the subgoal estimation algorithm reflect a more nuanced understanding of human intentions, contributing to a more natural and effective human-robot collaboration. All participants of our experiment, while limited in validity due to a small sample size of evaluators, supported these assertions. Ultimately, the simulation and subsequent study performed in this research reinforce the findings in literature that adaptive learning can remediate the drawbacks posed by static/hard-coded approaches to robotics. The theoretical implications of the success of this algorithm are discussed as follows.

A. Theoretical Implications

The theoretical implications of our research fundamentally lie in the advancement of our understanding of human-robot interaction strategies. By incorporating subgoal estimation, our study suggests that robotic followers can achieve a higher level of context awareness and decision-making capabilities. This aligns with theories in social robotics and human-robot collaboration, emphasizing the importance of robots behaving in a human-like manner, especially in dynamic and unstructured settings. The subgoal estimation approach offers a theoretical framework that acknowledges the significance of discerning and anticipating the underlying objectives of a human leader for improved adaptability and performance. Of special significance, which our entire group noted, was the subgoal estimation's adoption of hierarchical structures. This presents a fundamental shift in how robotic followers interpret and respond to human guidance. Hierarchical organization introduces a layered approach that contrasts with the more linear and reactive nature of velocity-based prediction. In the case of velocity-based prediction, the follower tends to respond directly to the leader's immediate movements. This approach relies on predicting the future position of the leader based on their current velocity and moving to align with that predicted position. While effective in certain scenarios, velocity-based prediction lacks the nuanced understanding of the broader context and underlying intentions that hierarchical subgoal hierarchies provide. On the other hand, subgoal estimation with hierarchical structures allows robotic followers to perceive tasks at multiple levels of abstraction. It enables the system to break down complex objectives into manageable subgoals, each contributing to the overall task. For instance, instead of solely focusing on predicting the leader's position, a subgoal hierarchy might involve understanding the leader's broader intentions (e.g., navigating through a crowd), intermediate steps (e.g., maintaining a safe distance from obstacles), and low-level actions (e.g., adjusting speed). We ultimately felt that our study was indicative of what would be experienced when our algorithm is deployed on the Turtlebot WafflePi3 and substantiates the benefit of employing subgoal estimation in comparison to velocity-based prediction for human-guided robotic followers.

B. Practical Applications

The practical applications of our research are particularly relevant in scenarios where human-guided robotic followers need to navigate through dynamic and unpredictable environments. This extends beyond the mere robot following a human navigating a path. Potential applications include assistive technologies for caregivers, robotic companions in crowded public spaces, or collaborative robots working alongside humans in industrial settings. The implementation of subgoal estimation can enhance safety, comfort, and overall user satisfaction in real-world applications, providing a valuable contribution to the development of more effective and adaptive robotic systems.

C. Limitations

A multitude of challenges were faced in this project, much of which were attributed to hardware. While we were able to get the software functioning as intended, LIDAR and the Camera on both available TurtleBot WafflePI 3's were not functioning as intended. Our original intention was to leverage LIDAR data to perform this experiment, but were unable to visualize LIDAR data in RVIZ. We were able to draw raw LIDAR data, however, displaying it in RVIZ in addition to the map was not possible. After hours of debugging, to ensure that our algorithm could be substantiated, we subsequently architected a simulation that we attempted to abstract to the Turtlebot WafflePi3 as close as possible. Ultimately, we gained extensive experience in debugging, hardware assembly, and developing an algorithm that employs subgoal estimation in contrast to conventional velocity-based prediction. Our evaluation of various algorithms, methods, and techniques learned in class to enable the success of this study was comprehensive. Ultimately, we are confident that barring hardware issues, the algorithm would deploy as intended on hardware, which is an area for future research.

D. Future Directions

The concept of subgoal estimation in human-guided robotic followers resonates strongly with cognitive science theories. Cognitive science provides a framework for understanding how humans set, pursue, and achieve goals, which can be mirrored in robotic systems for more effective human-robot collaboration.

Cognitive models, such as the ACT-R (Adaptive Control of Thought—Rational) and SOAR (State, Operator, And Result), provide insights into how humans break down complex tasks into smaller, manageable subgoals. By incorporating elements from these cognitive models, robotic systems can better predict and align with human intentions. This integration leads to a more profound understanding of human behavior, enabling the robot to anticipate changes in the leader's strategy and adjust its actions accordingly.

VII. Conclusion

Ultimately, our paper provides compelling substantiation that the adoption of subgoal estimation for decision-making in human-guided robotic followers remediates flaws inherent in velocity-based prediction. Through the implementation of subgoal estimation, the robotic follower gains the ability to discern and anticipate the broader objectives of its human leader, resulting in heightened adaptability, cognitive flexibility, and context-aware behavior. The observed improvements in path-following accuracy, collision avoidance, and adaptability underscore the efficacy of subgoal estimation in dynamic and unstructured environments. The theoretical implications align with principles from cognitive science, emphasizing a departure from linear, reactive methodologies to embrace a more nuanced understanding of human intentions. Limitations in our study include the lack of collaborative demonstration and insufficient abstraction to the real world. Future directions may involve further refinement of subgoal hierarchies, integration with adaptive learning mechanisms, and real-world validation to solidify its role as a cornerstone in enhancing the adaptability and decision-making capabilities of robotic followers.

REFERENCES

[1] C. Breazeal, ”Sociable machines: Expressive social exchange between humans and robots,” Thesis, Massachusetts Institute of Technology, 2000.

[2] T. Kruse, A. K. Pandey, R. Alami, and A. Kirsch, ”Human-aware robot navigation: A survey,” Robotics and Autonomous Systems, vol. 61, no. 12, pp. 1726-1743, 2013.

[3] E. A. Sisbot and R. Alami, ”A human aware mobile robot motion planner,” IEEE Transactions on Robotics, vol. 23, no. 5, pp. 874-883, Oct. 2007.

[4] R. Murakami, Y. Morales, S. Satake, T. Kanda, and H. Ishiguro, ”Destination Unknown: Walking Side-by-Side without Knowing the Goal,” in Proceedings of the 2014 ACM/IEEE International Conference on Human-robot Interaction, 2014, pp. 471-472.

[5] Sebastian Thrun et al., ”Robotic mapping: A survey,” in *Exploring artificial intelligence in the new millennium*, G. Lakemeyer and B. Nebel, Eds. San Francisco, CA, USA: Morgan Kaufmann, 2003, pp. 1–35.