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Article

Human-Robot Collaborative Path Planning with Predictive Obstacle Avoidance

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Abstract: Jointly planning paths for robots and humans in dynamic environments is considered an immensely complex task with regard to uncertainties in human motion patterns, thereby requiring real-time collision avoidance systems. Keeping in mind these challenges, there comes into existence in this publication an efficient, new model combining predictive systems for obstacle avoidance, along with hierarchical path planning to facilitate improved safety functions with optimized efficiency for collaborative robots. Utilizing the new model, there is the use of Gaussian Processes for Regression with biomechanical constraints to predict patterns in human motion with different predictive horizons in generating dynamic spatial risk maps for planning strategies for robot paths. A dual-level model, in particular, facilitates optimal trajectory planning for improved algorithms in RRT* algorithms, together with optimized Dynamic Window Approach modifications, to provide proactive collision avoidance with efficient computational processing in real-time with not more than 42.3ms planning latency in experimental analysis for UR5 in real-life collaborations for optimized safety improvements with overall success rates reaching 94.3% with optimized path-length reduction of 12.4% compared to traditional algorithms, Drawable.

Keywords: human-robot collaboration; predictive obstacle avoidance; path planning; Gaussian process regression; dynamic environments

1. Introduction

1.1. Background and Motivation

With their increasing applications in work environments, there is a growing need for efficient ways in which these robots are able to navigate their environment in optimal ways while safeguarding their counterparts from any harm. It is especially necessary in shared work spaces for these robots to have the capability to predict routes for humans while successfully changing their route to steer away from any possibility of collision (Smith et al., 2023).

Path planning in human-robot collaborations is an extension to general problems in path planning, taking into consideration the dynamic nature implied by human movement. For an autonomous robot to navigate its environment successfully, there is a need for efficient algorithms to be employed in collision avoidance, especially in environments with human labor in proximity to robots (Katona et al., 2024). It is crucial to note that interaction between robots and humans through trajectory planning is rigorously constrained from the computational standpoint in relation to changes in environment.

Obstacle avoidance predictive models have become an essential component in collaborative robotic technology, filling a gap in reactive obstacle avoidance models in robotics. Traditional models based on sensor technology mainly make predictions based on environment conditions at any given point in time, while predictive models forecast what the environment conditions might be in the next instant, hence enhancing safety and optimal route performance (Li et al., 2020). Anticipation in predictive models gains importance in an industry whose productivity relies on the continuous interaction between human operators and automated systems.

Integration of algorithms for path planning on a global scale with algorithms for avoidance of obstacles in close proximity could provide an encouraging paradigm for overcoming challenges related to collaborative path planning. Hybrid algorithms have proved to be efficient in handling uncertainties in motion patterns for humans, as well as dynamic changes in environments, according to Liu et al. (2023). Hybrid algorithms make use of various properties, such as trajectory planning in algorithms for global path planning, to produce efficient algorithms for collaboration.

1.2. Main Contributions

Moreover, there is an overall model for cooperative planning between human and robot for path planning, which considers predictive obstacle avoidance during real-time trajectory planning to increase safety and efficiency in shared environments (Tung et al., 2024). It combines dual-level planning, whereby overall goals are achieved by strategic planning, aided by global path planning, while dynamic safety is achieved by predictive systems.

Its innovation lies in its fusion with predictive models for motion behavior, such as kinematic constraints, to optimally plan trajectories, further outperforming those based on planning in reactive systems, comprehensively studied in experiments (He et al., 2025). It not only preserves safety margins for interactions with cooperative humans, but it also optimizes route planning concerning its performance goals.

2. Related Work

2.1. Human-Robot Collaborative Path Planning

Collaborative path planning studies in HRI have identified substantial improvements enabled by advanced algorithms for addressing multiple agents planning problems. More contemporary studies have explored the feasibility of algorithms with social reward functions, such as those based on Monte Carlo Tree Search, to foster cooperative planning approaches for robots in consideration for human comfort and preference (Dalmasso et al., 2021). These algorithms monitor probability distributions for joint action spaces to enable replanning based on different patterns of human behavior.

These modern kinematic frameworks for collaborative robots have propelled studies on customized path planning algorithms, which employ such unusual joint properties. Using infinite rotation joints, there is promising maneuverability in constrained environments, albeit with new mathematical frameworks, such as high-dimensional torus configuration spaces, to manage their properties concerning bounded and unbounded dimensions (Yang et al., 2023). Another example of such algorithms from traditional sampling-based motion planning for collaborative robots is IR-RRT*.

Decentralized planning architectures have developed scalable methods for groups of robots to operate in collaborative environments with shared computational needs in cooperative goal functions. These planning architectures utilize trained models for human motion to enable socially informed trajectory planning with minimal disruption to ongoing human activity. By incorporating behavioral models for human activity, robots are able to predict patterns for occupancy in shared workspaces while taking into consideration social rules for trajectory planning to perform tasks.

2.2. Predictive Obstacle Avoidance Technologies

Obstacle avoidance systems based on predictive technology have greatly improved safety in interaction between humans and robots, especially regarding the detection of motion intentions in good time. Currently, new sensors such as wearable interfaces, which rely on not only IMU information but also EMG information, have enabled accurate classification with an accuracy rate exceeding 94% in only 160 ms after motion initiation (Tortora et al., 2019). These predictive properties grant robots enough time to initiate changes in their motion path to evade any collision situation, improving safety during interaction with humans.

Probabilistic models for anticipating human motion have evolved to incorporate biomechanical constraints, resulting in more realistic predictions for motion trajectory. These models use Gaussian Process Regression, with biomechanical constraints for joint limits, in addition to environment geometry, to provide predictions with accuracy, even in situations with uncertainties in measurement (Kothari et al., 2025). By having the capability to provide information about accuracy levels for predictions, algorithms for risk-informed planning have the capacity to adjust robotic motion based on accuracy levels for predictions about human motion.

Obstacle avoidance, from being reactive to predictive, is indeed a paradigm shift in cooperative robotics. Presently, there are obstacle avoidance algorithms for robots that utilize observed information coupled with predictive models based on observed human motion patterns to make predictions in sync with what humans expect. Adaptive predictive horizons have optimal computational complexity for accuracy, such that they can be used on embedded systems with appropriate response times for safety during HRI. These innovations have further bridged any gap between what humans and robots are able to do in shared workspaces.

3. Methodology

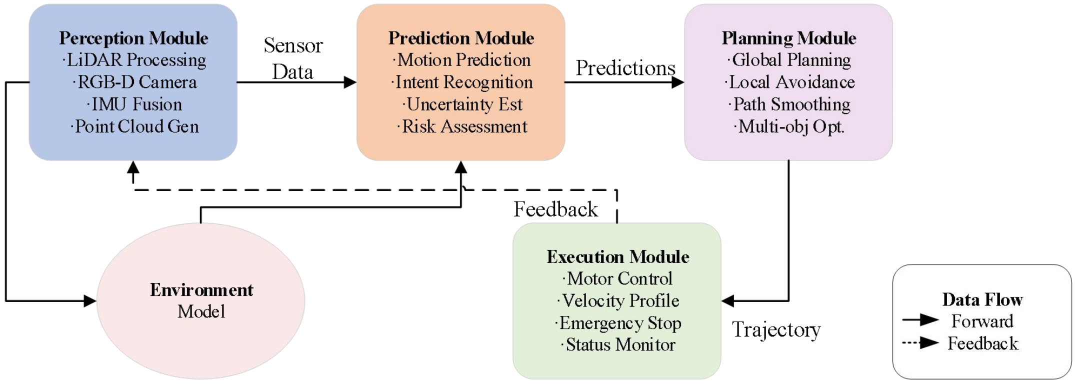
3.1. Problem Definition and System Framework

It is necessary to establish HRPP from a constrained optimization problem, incorporating trajectory optimality constraints, coupled with safety constraints in dynamic environments with static obstacles, as well as other dynamic entities such as human agents. Mathematically, for each robot with configuration space C in environment working space $W \subseteq \mathbb{R}^3$, there are obstacles O_s, in addition to dynamic agents $H = \{h_1, h_2, \ldots, h_n\}$ with each individual person h_i having stochastic trajectory patterns $p_i(t)$ for which there is a need to have probabilistic predictions based on their partially observable behavior. Overall performance metric is computed by incorporating multiple objectives with their respective weights in $J = \alpha \cdot L(\tau) + \beta \cdot S(\tau) + \gamma \cdot T(\tau)$.

Figure 1 below shows the proposed hierarchical system architectural platform, which incorporates collaborative robot-human navigation with highly interrelated modules for sensory information, predictive modeling for human behavior, trajectory planning for collision avoidance, and real-time action implementation in a closed-loop fashion. A perception interface is utilized to enable multiple heterogeneous sensors such as LiDAR point clouds, RGB-D images, and inertial sensors to provide a platform to depict environment constraints in synergy with semantic descriptions for patterns of human activity, thereby facilitating decision-making in trajectory planning. Additionally, to provide predictions on probabilistic trajectories for interacting with humans, there is also a predictive model for motion patterns in the planning model, with feasible trajectory planning for robots in collision avoidance to be realized in real-time action implementation.

Figure 1

System Architecture for Human-Robot Collaborative Path Planning



3.2. Predictive Obstacle Avoidance Algorithm

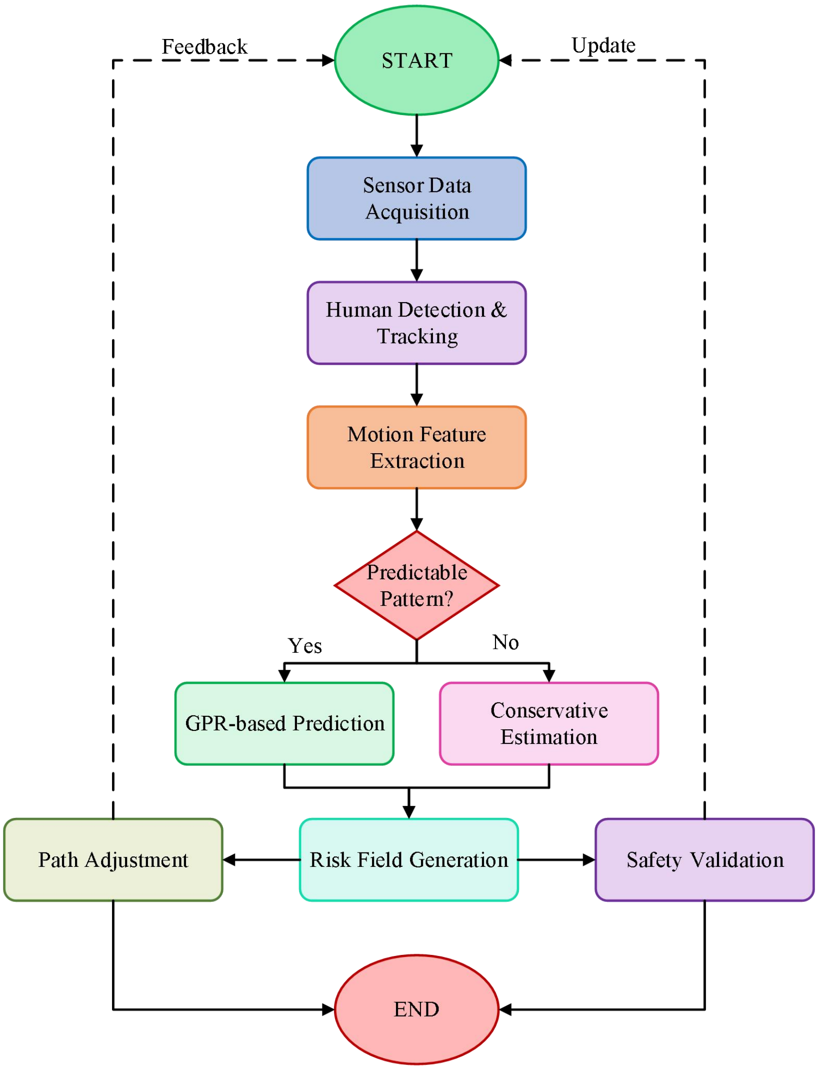
The predictive obstacle avoidance algorithm integrates the complicated probabilistic model through combining Gaussian Processes with anthropocentric motion models for efficient trajectory predictions on dynamic predictive horizons, based on the algorithmic flow in **Figure 2**. To start with, there is the process for addressing multi-modal sensor readings for pose trajectory extraction, from which kinematic features such as trajectory location, velocity, and acceleration features are determined through Kalman Filtering, to effectively capture state transitions, which are tolerant to noisy sensor readings with intermittent occlusion, typical in shared working environments. These features are utilized for generating predictions based on an optimized motion model, optimized based on large data samples for motion patterns in an industry setting, taking into consideration task-specific motion actions such as reaching motion, trajectory motion, and collaborative motion, in particular for human-robot interaction tasks.

“The predictive model, based on Monte Carlo simulation, gives, in probability, a set of candidate futures, represented by sample trajectories, each with a probability weighting based on their likelihood, inferred from statistics, to represent multimodal intentions in human motion. Calculation for collision probability involves estimating the region of overlap between candidate paths for the human motion, computed with those for robot motion trajectory planning, to produce a space-time risk map in which danger levels are associated with spatial coordinates in operational space. It changes its predictive horizon dynamically, based on motion regularity index, to extend into the ‘future’ in regular, in-line motion, while shortening to ‘conservative bounds’ in the face of perceived changes in direction.”

Computationally efficient optimization algorithms employ selective sampling methods like those for high-risk areas to concentrate computational resources on areas likely to contain space-time intersections for paths from humans to robots, thereby avoiding unnecessary computation in areas with low probability of collision. Modularity further facilitates easy interaction with different planning architectures through common interfaces for risk queries, validation, and dynamic updates to maintain consistency with different robotic systems.

Figure 2

Predictive Obstacle Avoidance Algorithm Flow



3.3. Collaborative Path Planning Strategy

The cooperative method for path planning relies on using a hierarchical platform for optimization, which proves to be efficient in incorporating global trajectory planning with local reactive planning, thereby ensuring optimality in planning on one side, while on the other side, it ensures safety in dynamic environments with the presence of humans. For its global planning method, it relies on an optimized version of the algorithm for RRT* with real-time corridors for the expected motion of humans, such that initially, routes for planning will be explored, anticipating their avoidance from the occupancy of their workplace, while also moving on for goal satisfaction. On the other side, for its method regarding planning, it relies on an optimized version for its Dynamic Window Algorithm, with options for its velocity checked for optimality based on real-time risk maps, with decision-making optimized for multiple objectives like goal achievement, collision avoidance, while taking into consideration comfort for passing humans, based on studies in proxemics.

4. Experiments and Results

4.1. Experimental Setup

Experimental validation was carried out on the UR5 collaborative robot in a shared working environment with dimensions 4m x 4m x 2.5m, equipped with a Velodyne VLP-16 LiDAR sensor for environment perception, in addition to an Intel RealSense D435i camera for human detection. Industrial collaboration environments such as assembly, handling, and inspection scenarios with human participants following predetermined trajectory patterns, some of which included predictable trajectories with sudden direction changes, common in most collaborative industrial environments, were used for validation. Benchmarking for comparison included common Dynamic Window Approaches, regular RRT*, in addition to reactive potential functions together, in an environment with common settings to enable fairness for comparison based on differences in algorithm.

4.2. Results Analysis

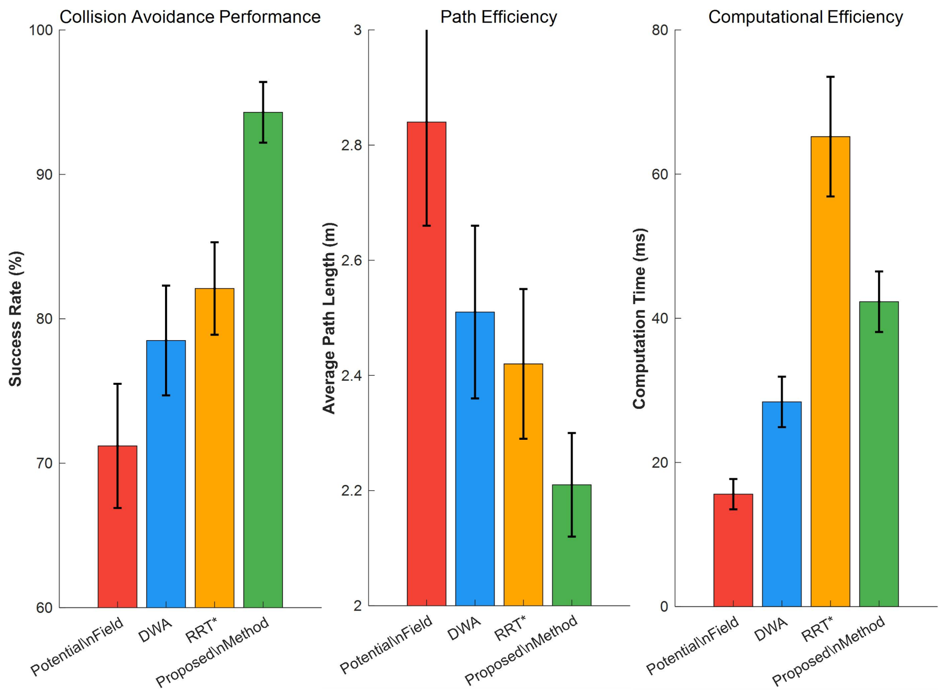
As observed in **Figure 3**, from the quantitative analysis, there are marked improvements in performance for different parameters in testing the proposed predictive obstacle avoidance algorithm in comparison to some widely accepted competing algorithms. The algorithm achieved an average success rate of 94.3% after

500 trials, with significantly better success rates than other algorithms, 78.5% success rate for DWA, 82.1% success rate for RRT*, and 71.2% success rate for the Potential Field algorithm, especially in environments with complex human motion patterns, thereby accenting the role of predictive functions in decision-making for path changes. For analysis related to path efficiency, there have been substantial decreases in path length for the predictive algorithm, with averages being 12.4% less than DWA, 8.7% less than RRT* with safety margins above 0.8m in 96.2% of trials, thereby emphasizing algorithm aptness for dual objectives such as path efficiency and safety with predictive planning.

The computational performance analysis reveals that the algorithm remains in real-time feasibility, with average planning times of 42.3ms for initial trajectory planning, and 8.7ms for dynamic replanning tasks, thereby meeting real-time constraints common for cooperative scenarios, in addition to incurring additional computational costs in probabilistic prediction and risk analysis steps. Evaluation for accuracy in predictions revealed an error in location prediction with an average value of 0.23m for 1-second predictions, with an improvement to 0.51m in predictions with a 3-second horizon, indicating the success in uncertainty quantification to contain 95% of real human locations in their respective prediction regions, thereby validating the accuracy of the adopted GP Regression model for predictions on human motion.

Figure 3

Performance Comparison of Path Planning Methods

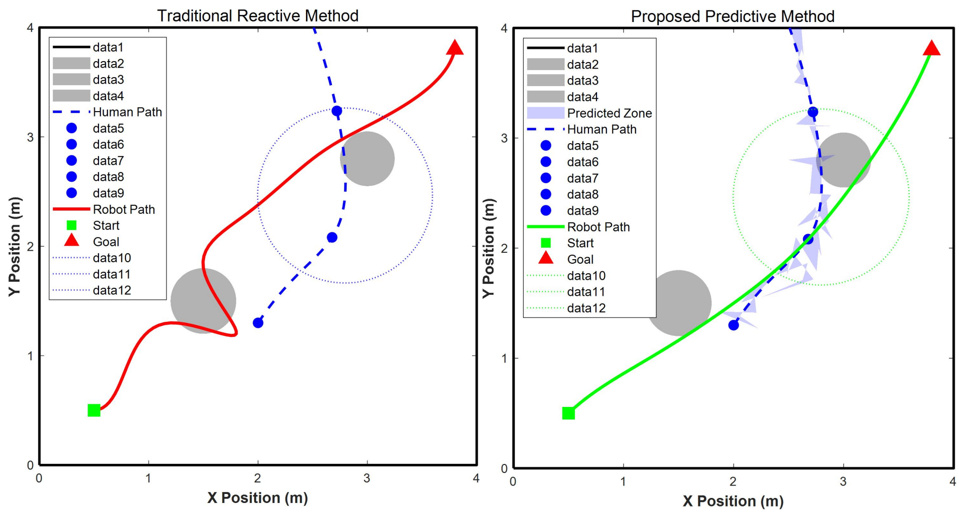


4.3. Case Study

Figure 4 below shows an example collaborative situation involving joint human-robot manipulation, which practically demonstrates the efficacy of the new method. Here, the transport of parts by the robot had to be done while navigating around an assembly process being carried out by a human in the shared environment in reaching motions in some irregular patterns. It can be observed that the new predictive model accurately forecasted occurrences of extending the human arms, proactively adjusting for appropriate robot trajectory offsets to create safe distances. Conventional reaction-based methods, in comparison, showed near-collisions requiring emergency stop interventions, halting work flow, while analysis of trajectory planning indicated fewer sharp corners for less mechanical loading, with more predictable patterns for human observation.

Figure 4

Trajectory Comparison in Human-Robot Collaborative Scenario



5. Discussion

Experiments have confirmed that predictive obstacle avoidance improves joint-human-robot collaboration performance in planning trajectory routes while maintaining safety and optimizing efficiency. On the other hand, the rates of improved collision avoidance made possible through the proposed method are based on its capacity to forecast human intention, in addition to its capacity to adjust its route trajectory in advance, in contrast to response-based collision avoidance strategies. Smooth trajectory routes, on the other hand, provide optimized robot motion with less wear and tear on mechanisms, in addition to its effect on improved predictability, which reduces concern on the side of human participants.

6. Conclusion

It provides an overall paradigm for addressing human-robot cooperative path planning with predictive obstacle avoidance, realized in real-time trajectory optimization. Simulations have indicated overall success in collision avoidance with respect to traditional reactive approaches with 94.3% success rate, with optimized path planning, yielding overall path shortening rates of 12.4% on average. It is assured through an optimal computational complexity paradigm for necessary safety, with predictive horizon interventions based on principles for risk management. Experiments have confirmed its applicability in an industry-based cooperative environment for its overall paradigm. Future works shall majorly concentrate on its respective applications in multiple-robot setups, with overall adaptations to guarantee safety protocols for certification in an industry setting.

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Conflict of interest: The authors declare no conflict of interest.

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