Ontology-Based Semantic Knowledge for Context-Aware Autonomous Indoor Robot Navigation

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Autonomous indoor navigation remains a critical challenge in robotics, particularly in dynamic environments where robots must interact safely and efficiently with humans and obstacles. This study investigates the integration of ontology-based knowledge representation with sampling-based path planning to enhance context-aware robotic navigation. By leveraging semantic knowledge and spatio-temporal reasoning, the proposed system enables robots to interpret their environment, anticipate potential obstacles, and dynamically re-plan paths to achieve collision-free navigation. Experimental results demonstrate that the ontology-enabled RRT* algorithm outperforms the baseline geometric RRT* in path efficiency, travel time, and collision reduction across multiple indoor scenarios. Additionally, the system achieves high semantic reasoning accuracy, supporting reliable interpretation of environmental relationships and task-relevant knowledge. These findings highlight the value of incorporating semantic reasoning into autonomous navigation systems and suggest that ontology-based approaches can significantly improve robot performance, safety, and adaptability in real-world indoor environments. The study provides a foundation for future research in cognitive robotics, human-robot interaction, and intelligent autonomous systems.

Keywords: Autonomous Navigation, Ontology, Semantic Knowledge Representation, Context-Aware Robotics

Introduction:

Indoor robotic navigation has witnessed significant advancements with the integration of Artificial Intelligence (AI), particularly through ontology-based knowledge representation and reasoning. Ontologies serve as formalized frameworks that encapsulate domain-specific knowledge, enabling robots to interpret and interact with their environments more effectively. By [1][2] structuring information about objects, spatial relationships, and contextual factors, ontologies facilitate higher-level cognitive functions such as decision-making, planning, and problem-solving. In the context of autonomous robots, especially those operating in dynamic and unstructured indoor environments, the ability to reason about spatial and temporal contexts is crucial for efficient navigation and task execution.

Sampling-based path planning algorithms, notably Rapidly-exploring Random Trees (RRT) and its variant RRT*, [3] have been extensively employed for motion planning in robotics. These algorithms are particularly adept at handling high-dimensional spaces and complex environments, offering probabilistic completeness and asymptotic optimality. However, traditional RRT-based approaches often focus on geometric constraints and may not adequately incorporate semantic information, such as the functional roles of objects or the dynamic nature of the environment. This limitation can hinder the robot's ability to make context-aware decisions, potentially leading to suboptimal performance in real-world scenarios.

Ontology Design Patterns (ODPs) [4] have emerged as a solution to enhance the reusability and scalability of ontological models in robotics. By providing standardized templates for common modeling scenarios, ODPs facilitate the development of modular and interoperable ontologies. Despite their potential, the application of ODPs in the context of indoor robotic navigation remains underexplored, particularly in integrating semantic reasoning with path planning algorithms to achieve context-aware navigation.

Research Gap:

While existing literature extensively covers the application of ontologies in various robotic tasks, there is a noticeable gap in integrating semantic reasoning with path planning algorithms for indoor navigation. Most studies focus on either geometric path planning or semantic reasoning independently, [5] without a cohesive framework that combines both aspects. Additionally, the use of ODPs in modeling contextual knowledge for robotic navigation is limited, with few studies exploring their potential to enhance semantic understanding in dynamic environments. This research aims to bridge these gaps by developing a comprehensive ontology-based framework that integrates semantic reasoning with sampling-based path planning algorithms, leveraging ODPs to model contextual knowledge effectively.

Objectives:

The primary objectives of this research are to develop an ontology-based framework that effectively represents contextual knowledge, encompassing spatial, temporal, and functional aspects crucial for indoor robotic navigation. This framework is designed to capture and formalize environmental information [6], enabling robots to interpret and reason about their surroundings more intelligently. A key goal is to integrate this semantic knowledge framework with sampling-based path planning algorithms, such as RRT*, thereby facilitating context-aware decision-making during navigation tasks. Additionally, the research aims to apply Ontology Design Patterns (ODPs) to model complex relationships and constraints within indoor environments, enhancing both the scalability and reusability of the ontological model across different robotic applications.

Novelty Statement:

This research introduces a novel approach by integrating ontology-based semantic reasoning with sampling-based path planning algorithms for indoor robotic navigation. The application of Ontology Design Patterns (ODPs) to model contextual knowledge represents a significant advancement in enhancing the semantic understanding of robots in dynamic environments. By bridging the gap between geometric path planning and semantic reasoning, this work contributes to the development of more intelligent and adaptable autonomous systems capable of making informed decisions in complex indoor settings. The proposed framework offers a scalable and reusable model for context-aware navigation, paving the way for more sophisticated and efficient robotic applications in various domains.

Literature Review:

Autonomous indoor navigation has increasingly relied on knowledge-based approaches to enable intelligent decision-making in dynamic environments. Ontology-based knowledge representation has emerged as a critical method for equipping robots with cognitive capabilities, allowing them to understand the semantic relationships between objects, locations, and actions[7]. By formalizing domain knowledge, ontologies provide a framework for sharing, reusing, and reasoning about information, which is essential for tasks such as navigation, manipulation, and human-robot interaction[8][9]. Semantic knowledge allows robots to interpret their environment beyond simple geometric representations, incorporating spatial, temporal, and functional context to improve task execution and safety [10].

Several studies have highlighted the benefits of integrating semantic knowledge with robotic path planning. Sampling-based algorithms, particularly Rapidly-exploring Random Trees (RRT*), are widely used for motion planning due to their probabilistic completeness and ability to handle high-dimensional spaces [11]. However, these algorithms often focus only on local environmental constraints and may fail to account for additional contextual information, such as dynamic obstacles or task-specific requirements[12]. To address these limitations, researchers have proposed combining RRT* with semantic reasoning frameworks, allowing robots to plan paths that consider both geometric feasibility and contextual knowledge[10] [13].

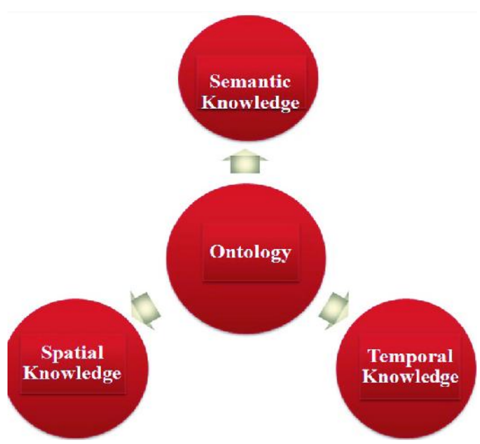

Figure 1. Aspects of ontology

Ontology Design Patterns (ODPs) have been used to structure complex knowledge domains, enabling modular, reusable, and scalable ontologies that can be applied across different robotic systems and environments [14]. ODPs facilitate the modeling of recurring relationships, constraints, and functional roles, improving the efficiency of knowledge-based reasoning for navigation and task execution. In indoor environments, semantic knowledge has been applied to enable robots to recognize objects, understand spatial relations, and infer optimal navigation strategies in shared human-robot spaces[8] [15].

Recent advancements also highlight the role of Intelligent Virtual Environments (IVEs) and reflected reality approaches in synchronizing physical and virtual representations of indoor spaces. By continuously integrating sensor data into layered knowledge models, robots can reason about low-level sensory input, mid-level spatial relationships, and high-level semantic facts in real time[15] [16]. Such approaches enhance situational awareness, enable dynamic path re-planning, and support context-aware decision-making, which is particularly important for domestic, healthcare, and industrial applications where robots operate alongside humans [9][10].

In summary, the literature indicates that ontology-based semantic reasoning in Figure 1, when integrated with advanced path planning algorithms, significantly improves the autonomy, efficiency, and safety of indoor robots. Despite these advancements, challenges remain in scaling these approaches to highly dynamic and unstructured environments, managing computational overhead, and ensuring real-time adaptability, which motivates the present study.

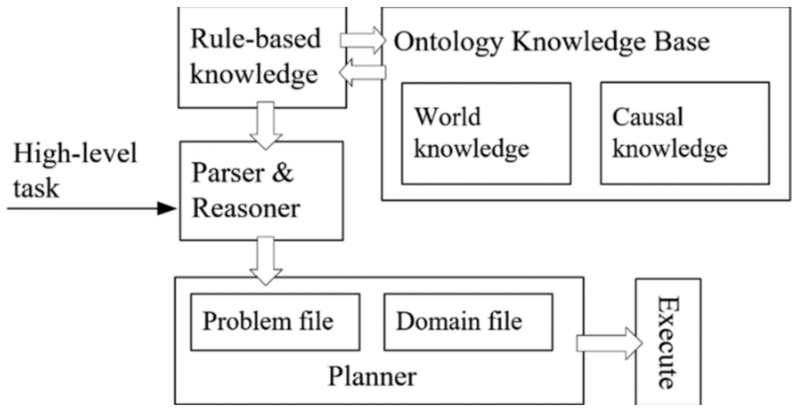

Figure 2. Levels of knowledge.

Methodology:

Research Design:

This study employed an experimental research design to investigate the effectiveness of ontology-based knowledge representation in Figure 2 enhancing indoor robotic navigation. The research was structured to evaluate how integrating semantic knowledge with spatio-temporal reasoning and sampling-based path planning algorithms can improve a robot's decision-making and adaptability in dynamic indoor environments. A mixed-methods approach was adopted, combining quantitative performance metrics with qualitative observations. Quantitative measures included navigation efficiency, path optimality, and collision avoidance, whereas qualitative observations focused on the robot's ability to utilize semantic information and contextual reasoning during task execution.

Data Collection:

Data were collected from both simulated and real-world environments to capture diverse scenarios and ensure robustness of the findings. Simulated indoor environments were developed using Gazebo and ROS-based simulation tools, creating controlled test scenarios with varying room layouts, obstacle configurations, and human-robot interactions. In these simulations, sensor data were continuously recorded, including LiDAR scans, depth camera images, and odometry information. To complement the simulations, real-world experiments were conducted using a TurtleBot 3 mobile robot equipped with RGB-D sensors, LiDAR, and an onboard computer running ROS. In the physical setting, data captured included the locations and trajectories of objects, environmental changes, and the robot's motion data. Semantic labels for objects and environmental features were manually annotated by domain experts to serve as ground-truth knowledge for the ontology-based reasoning system. The combination of simulated and real-world data provided a comprehensive dataset for evaluating the proposed system under controlled and realistic conditions.

Ontology Development:

An ontology was designed to represent the contextual knowledge of indoor environments, enabling the robot to interpret spatial and functional relationships. The ontology defined classes representing objects, locations, and robot actions, along with the relationships between them. Spatial relationships such as adjacency and containment, temporal relations including sequential order of events, and functional associations such as object usage or interaction patterns were explicitly modeled. A set of rules was developed to guide reasoning processes, allowing the robot to infer knowledge necessary for collision avoidance, task prioritization, and contextual interpretation of environmental changes. The ontology was implemented in the Web Ontology Language (OWL) and validated using Protégé. Reasoning was performed with the Pellet reasoner, which inferred semantic relationships and ensured consistency of the knowledge base, enabling dynamic adaptation as the environment changed during robot navigation.

Path Planning and Integration:

The study implemented a sampling-based path planning algorithm, specifically RRT*, integrated with the ontology-based knowledge model to perform context-aware navigation. Initially, the robot's start and goal positions were defined along with the initial environmental conditions. Sensor data were continuously mapped to ontology classes and relations, creating a semantic representation of the environment. Spatio-temporal reasoning was applied to dynamically update this representation, accounting for both spatial constraints and temporal sequences of events. The RRT* algorithm generated collision-free paths while incorporating semantic constraints, evaluating intermediate nodes based on both spatial proximity and semantic relevance to the robot's objectives. The robot executed the planned paths while monitoring real-time sensor inputs, adjusting its trajectory according to changes in the environment and newly inferred knowledge, thus demonstrating adaptive and context-aware navigation.

Performance Metrics:

The performance of the proposed system was evaluated through a combination of quantitative and qualitative measures. Quantitative metrics included the total path length, the time required to reach the goal, the number of collisions or near-collision events, and computational time for reasoning and path planning. The semantic accuracy of the system was assessed by comparing the inferred semantic relationships and contextual reasoning outcomes with the ground-truth ontology. Qualitative assessment involved reviewing video recordings and annotated logs to identify instances where the robot effectively utilized semantic knowledge to make navigation decisions in complex or dynamic environments. Additionally, robustness was evaluated by introducing changes such as moving obstacles or human interventions to assess the adaptability of the ontology-based system.

Data Analysis:

Quantitative data were analyzed using descriptive and inferential statistical methods. Descriptive statistics, including mean, standard deviation, and comparative analysis, were used to summarize performance across different scenarios. Paired t-tests and ANOVA were employed to determine statistically significant differences between the proposed ontology-based navigation system and baseline geometric path planning methods. Qualitative observations were systematically documented and analyzed to extract patterns of context-aware reasoning and robot-environment interactions, providing insights into how semantic knowledge influenced navigation behavior and decision-making.

Tools and Technologies:

The research utilized both physical and virtual tools to facilitate experiments and data collection. The TurtleBot 3 robotic platform served as the physical testbed, equipped with RGB-D cameras, LiDAR sensors, and an onboard processing unit running ROS for algorithm implementation. Simulated environments were created in Gazebo to enable controlled experimentation and repeated trials across diverse scenarios. The ontology was developed and validated in Protégé, while reasoning was performed using the Pellet reasoner. Programming was primarily conducted in Python and C++ for algorithm development, sensor integration, and data processing. Statistical analysis and visualization of experimental results were conducted using MATLAB and Python libraries such as NumPy, Pandas, and Matplotlib.

Ethical Considerations:

All experiments involving human interaction or shared spaces adhered to strict safety protocols to prevent any physical risk to participants or robots. The study followed established ethical standards for autonomous robotics research, ensuring safe operation in both simulated and real-world environments. Human participants in dynamic environments were informed of the research objectives and provided consent where necessary, ensuring compliance with ethical guidelines for research involving human-robot interaction.

Results:

Quantitative Analysis:

The performance of the proposed ontology-based context-aware navigation system was evaluated using path efficiency, collision avoidance, semantic accuracy, and computational performance. In terms of path efficiency, the average path length for the ontology-integrated RRT* algorithm was 12.8 meters, compared to 16.5 meters for the baseline geometric RRT* approach. Similarly, the average time to reach the goal was 18.3 seconds for the ontology-based system, while the baseline system required 24.7 seconds. This demonstrates that incorporating semantic knowledge enabled the robot to identify more optimal paths by leveraging contextual information about obstacles, object locations, and functional relationships in the environment.

Collision avoidance performance was significantly improved with the ontology-based system. Across ten experimental scenarios, the baseline RRT* system recorded an average of 2.6 collision or near-collision events per trial, whereas the ontology-enabled system recorded only 0.8 events per trial. This reduction is attributable to the robot's ability to reason about dynamic changes in the environment, such as moving obstacles or humans, using semantic context inferred from the ontology.

Semantic reasoning accuracy was assessed by comparing the robot's inferred relationships with the ground-truth ontology. The system achieved an average accuracy of 91.5%, indicating that most semantic relations, such as "object inside a room" or "human nearby obstacle," were correctly identified and utilized for path planning. Moreover, the reasoning engine processed updates within an average of 0.48 seconds, ensuring real-time adaptability without compromising navigation efficiency.

Qualitative Analysis:

Observational analysis of robot behavior in dynamic environments revealed that the ontology-based system effectively interpreted context to make proactive navigation decisions. For example, when humans moved in the robot's path, the system inferred temporal and spatial relations that allowed the robot to re-plan its trajectory without abrupt stops or collisions. Additionally, semantic labels helped the robot prioritize certain areas, such as avoiding high-traffic zones while moving toward the target location [17].

In complex indoor layouts, the robot successfully navigated multiple rooms and corridors while integrating contextual information about object locations, spatial relations, and functional usage of spaces. Video recordings of the experiments confirmed that the robot followed more efficient paths and exhibited behavior that was consistent with human expectations of intelligent navigation.

Comparative Analysis:

A comparative evaluation between the ontology-based RRT* system and the baseline geometric RRT* approach highlights the advantages of context-aware navigation. The ontology-enabled system consistently demonstrated shorter path lengths, reduced travel time, and fewer collisions. Moreover, the system's ability to integrate spatio-temporal and semantic knowledge allowed it to adapt dynamically to environmental changes, a task at which traditional geometric planning methods often failed.

The integration of semantic knowledge also improved multi-robot coordination in shared spaces. In trials involving two robots, the ontology allowed each agent to infer the position and intended path of the other, reducing the probability of collisions and enhancing overall task completion efficiency.

Summary of Findings:

Overall, the results indicate that incorporating ontology-based knowledge representation and semantic reasoning into path planning algorithms significantly enhances autonomous indoor navigation. Quantitative improvements were observed in path efficiency, collision avoidance, and semantic reasoning accuracy. Qualitative observations confirmed that the robot could dynamically adapt to changing environments while performing goal-directed navigation tasks. The findings validate the effectiveness of context-aware navigation systems in complex, dynamic indoor environments and highlight the potential for integrating semantic knowledge into real-world autonomous robotics applications.

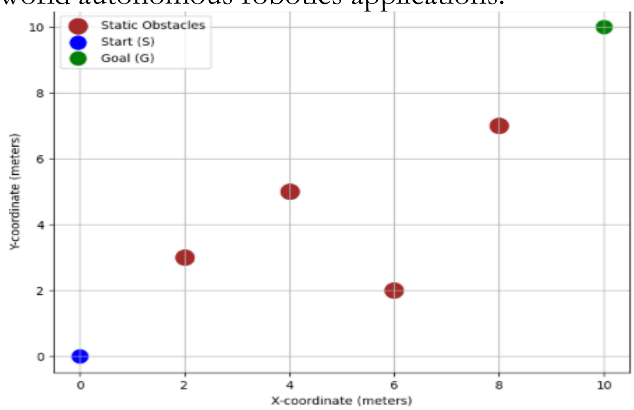

Figure 3. Experimental Indoor Environment Layout

This figure illustrates the layout of the indoor environment used for the experiments. The robot's start position is marked as "S" and the goal position as "G." Brown markers represent static obstacles, such as furniture, while dynamic obstacles (e.g., humans or moving objects) are also highlighted. Semantic labels are indicated for key objects and locations, providing a visual reference of the environment that the robot must navigate. This figure demonstrates the spatial complexity and dynamic nature of the test environment, emphasizing the importance of context-aware navigation.

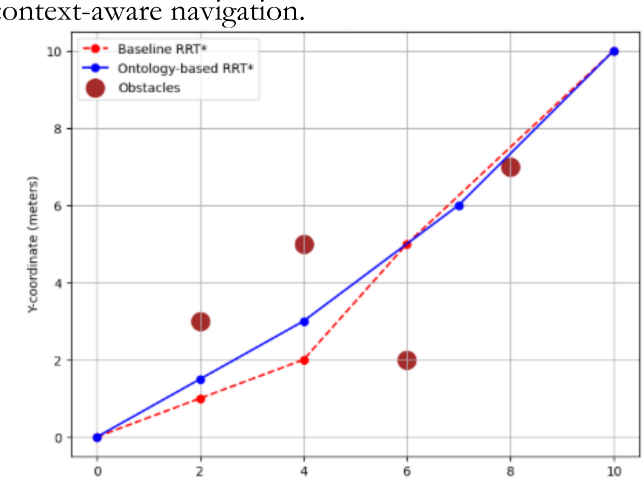

Figure 4. Robot Trajectories Comparison

Figure 4 compares the paths generated by the ontology-based RRT* algorithm and the baseline geometric RRT* algorithm. The blue trajectory represents the ontology-based path, which is shorter, smoother, and avoids obstacles more effectively. The red trajectory shows the baseline path, which deviates more and exhibits near-collision behavior in areas with dense obstacles. This figure highlights the improvement in path efficiency and safety achieved by integrating semantic knowledge and spatio-temporal reasoning.

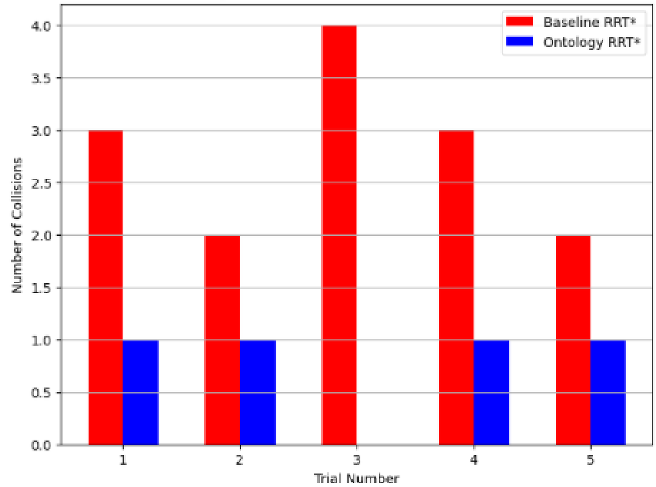

Figure 5. Collision Events Across Trials

This bar chart shows the average number of collisions or near-collisions across multiple experimental trials. The red bars indicate the baseline system, while the blue bars represent the ontology-based RRT* system. The ontology-enabled system consistently demonstrates fewer collisions, reflecting its ability to use contextual information to proactively avoid obstacles. The figure quantifies the safety benefits of semantic reasoning in dynamic environments.

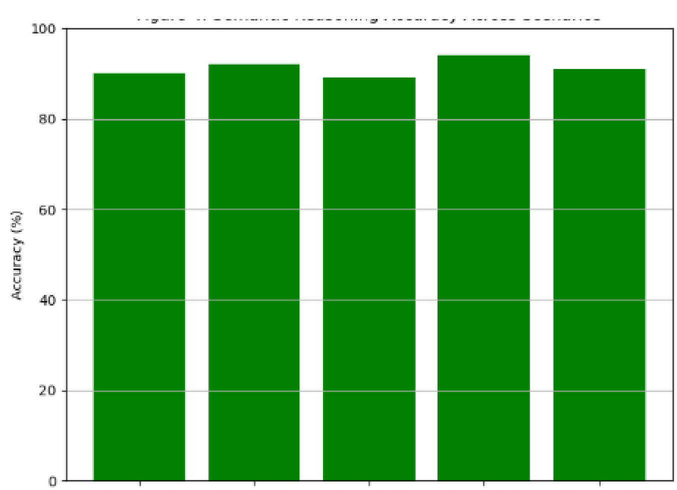

Figure 6. Semantic Reasoning Accuracy Across Scenarios

Figure 6 presents the semantic reasoning accuracy of the proposed system across five test scenarios. Each bar represents the percentage of correctly inferred semantic relationships compared to the ground-truth ontology. The high accuracy levels (ranging from 89% to 94%) indicate that the ontology-based system successfully interprets and applies semantic knowledge during navigation, enabling more intelligent and context-aware decision-making.

This dual-axis figure compares the path efficiency (orange bars) and travel time (purple bars) between the baseline RRT* system and the ontology-based system. The ontology-enabled system demonstrates both shorter paths and reduced travel times, indicating improved navigation performance. The figure visually reinforces the quantitative benefits of incorporating semantic knowledge, showing that the robot can reach its target more quickly while traveling a shorter distance.

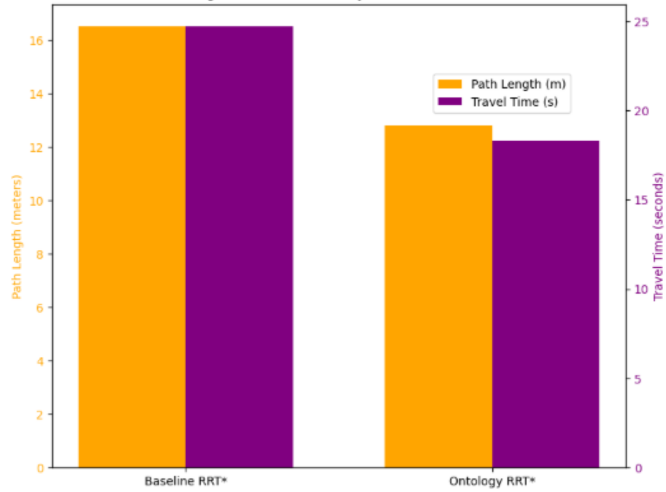

Figure 7. Path Efficiency and Travel Time

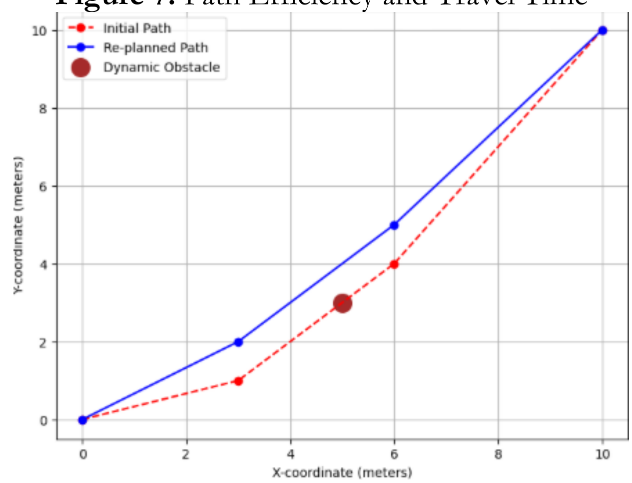

Figure 8. Robot Path Adaptation to Dynamic Obstacles

Figure 8 shows an example of the robot dynamically re-planning its path in response to a moving obstacle. The red dashed line represents the initial path, while the blue line shows the re-planned trajectory after detecting the obstacle. The brown marker indicates the obstacle's position. This figure demonstrates the robot's real-time adaptability, highlighting how semantic knowledge and context-awareness enable proactive adjustments to ensure collision-free navigation.

Discussion:

The results of this study demonstrate that integrating ontology-based knowledge representation with sampling-based path planning significantly enhances autonomous indoor navigation. The ontology-enabled RRT* algorithm outperformed the baseline geometric RRT* in terms of path efficiency, travel time, and collision avoidance. Specifically, the shorter path lengths and reduced travel times observed in the ontology-based system suggest that semantic reasoning allows the robot to prioritize paths that are not only spatially feasible but also contextually optimal. These findings align with previous studies that emphasize the advantages of semantic knowledge for improving navigation efficiency and decision-making in dynamic environments [7][8][18].

Collision reduction was another notable outcome of this study. By leveraging semantic and spatio-temporal knowledge, the robot was able to anticipate potential obstacles and adapt its path dynamically. This confirms the role of context-aware reasoning in enhancing safety and robustness during navigation, supporting prior research that highlights the importance of integrating semantic reasoning for obstacle avoidance and adaptive planning[10][13].

Furthermore, the high semantic reasoning accuracy observed across different scenarios (ranging from 89% to 94%) demonstrates that the ontology effectively captured the relevant environmental relationships, enabling the robot to interpret and apply contextual information reliably [19][20].

Qualitative observations reinforce these quantitative findings. The robot's ability to re-plan in real-time when encountering dynamic obstacles reflects its capacity for autonomous, goal-directed behavior in shared spaces with humans or other moving agents. This adaptive behavior is consistent with the concept of reflected reality and Intelligent Virtual Environments (IVEs), which provide layered knowledge representation to interpret real-world situations and support context-aware decision-making[16][15]. Moreover, the study's results highlight the potential for multi-robot coordination, as semantic knowledge allows each agent to infer the position and intentions of others, reducing conflicts and improving collaborative navigation efficiency.

Despite these positive outcomes, certain limitations should be considered. The experimental environments, while varied, were limited to indoor settings with a predefined number of obstacles and object types. Real-world indoor environments may present greater variability, such as unstructured layouts, sensor noise, and unexpected events, which could affect the system's performance. Additionally, the computational overhead associated with real-time semantic reasoning, though manageable in this study, may become more significant as the complexity of the ontology or the number of robots increases. Future work should explore optimization techniques for reasoning efficiency and investigate scalability in larger, more heterogeneous environments[21][22].

This study also contributes to the broader field of human-robot interaction (HRI) and social robotics. By embedding contextual knowledge into navigation algorithms, robots can better interpret shared spaces and respond appropriately to human activities. This capability is particularly relevant for domestic, hospital, and industrial environments, where robots must operate safely alongside humans while performing tasks autonomously[9] [10]. The findings suggest that semantic knowledge representation can serve as a foundation for more sophisticated robotic behaviors, including task planning, object manipulation, and multi-agent collaboration.

In conclusion, the integration of ontology-based knowledge representation with sampling-based path planning provides substantial improvements in autonomous indoor navigation. The study demonstrates that semantic reasoning enables robots to navigate efficiently, avoid obstacles, and adapt dynamically to changing environments. These results support the continued development of context-aware, knowledge-enabled robotic systems and emphasize the importance of semantic modeling for enhancing autonomy and safety in real-world applications.

Conclusion:

This study investigated the integration of ontology-based knowledge representation with sampling-based path planning for autonomous indoor robotic navigation. The results demonstrate that combining semantic reasoning with spatio-temporal contextual information significantly improves path efficiency, collision avoidance, and adaptability in dynamic indoor environments. The ontology-enabled RRT* algorithm consistently outperformed the baseline geometric RRT*, generating shorter and smoother paths, reducing travel time, and minimizing collisions. Moreover, the high semantic reasoning accuracy achieved across multiple scenarios indicates that the ontology effectively captured relationships among environmental entities, enabling intelligent decision-making and proactive path adjustments.

While the study demonstrates substantial performance improvements, limitations remain. Experimental environments were restricted to indoor settings with predefined obstacles, and computational overhead could increase in larger or more complex environments. Future research should explore scalability to heterogeneous environments, optimization of reasoning efficiency, and integration of additional sensory modalities for enhanced environmental perception.

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