Fuzzy-RRT for Obstacle Avoidance in a 2-DOF Semi-Autonomous Surgical Robotic Arm

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Background

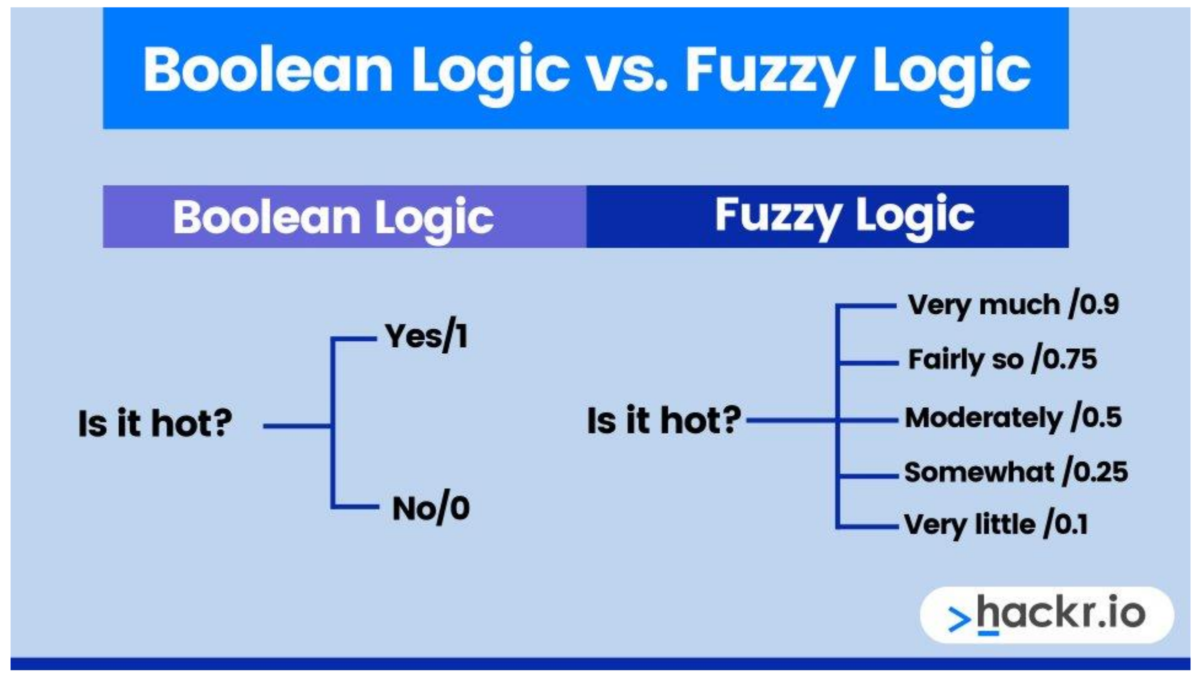
Long-duration space missions present unique medical challenges, where surgical interventions must occur despite communication delays and limited medical staff. Traditional robotic surgery systems rely on full surgeon control, unsuitable for space applications. Therefore, AI-driven semi-autonomous systems are needed to allow robotic arms to operate independently yet safely. The MIRA Surgical System provides a compact robotic platform ideal for these missions, but effective obstacle avoidance and efficient path planning remain critical challenges.

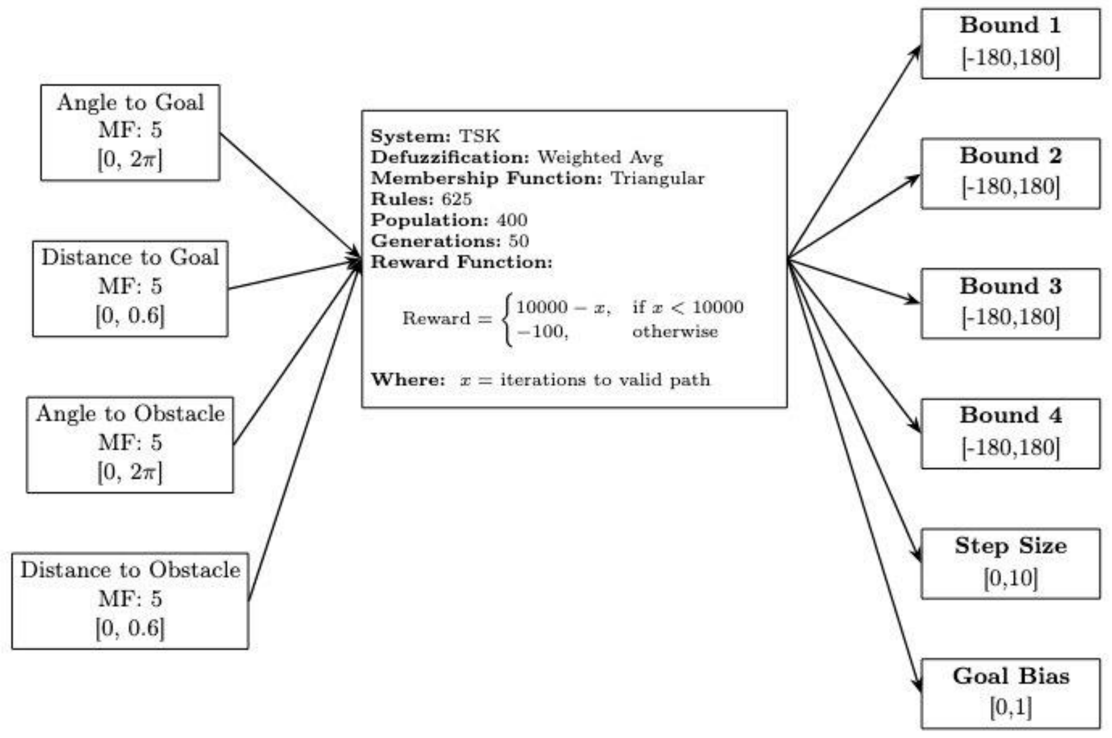
Objectives

- Develop a semi-autonomous, AI-driven surgical robotic system capable of operating with minimal human intervention.
- Improve path planning and obstacle avoidance in constrained and dynamic environments.
- Create an explainable and efficient control algorithm using Fuzzy Logic integrated with Rapidly-exploring Random Trees (RRT).
- Benchmark the system for performance gains over traditional RRT methods.

Methodologies

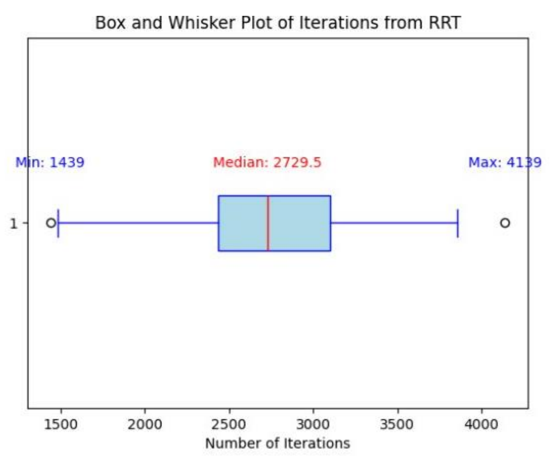
We propose a hybrid path planning approach that combines Rapidly-exploring Random Trees (RRT) with a Fuzzy Inference System (FIS) to enable fast, adaptive, and explainable motion control for a 2-DOF surgical robotic arm.
Traditional RRT algorithms explore the robot's joint space to find a collision-free path but often suffer from high computation times. To address this, we incorporate Fuzzy Logic to dynamically tune key parameters—step size, goal bias, and search bounds—based on real-time information such as the angle and distance to both the goal and the nearest obstacle.
The FIS is trained using Thales True AI to find the optimal parameters for the Fuzzy Inference system using Genetic Algorithms.



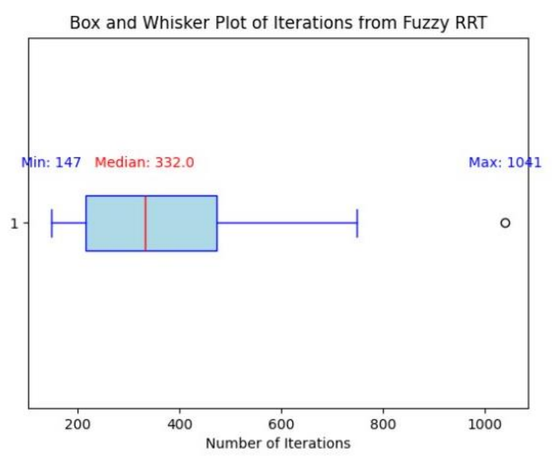


Results

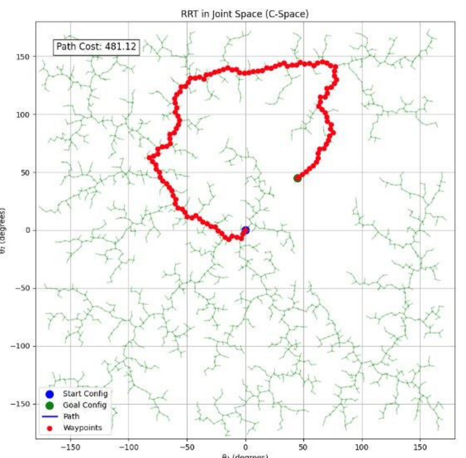
- 743% faster path search time compared to standard RRT
- 43% lower path cost, leading to smoother, safer movements
- Fitness target (9750) achieved within just 10 generations of Genetic Algorithm training
- Outperforms prior improvements by Wang et al. (2024) (46.5% faster, 10% lower cost)



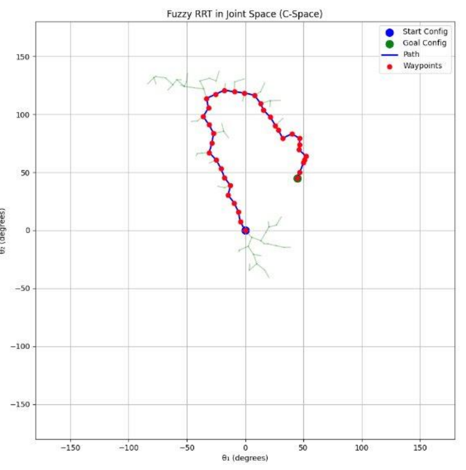
(a) Performance metrics of RRT.



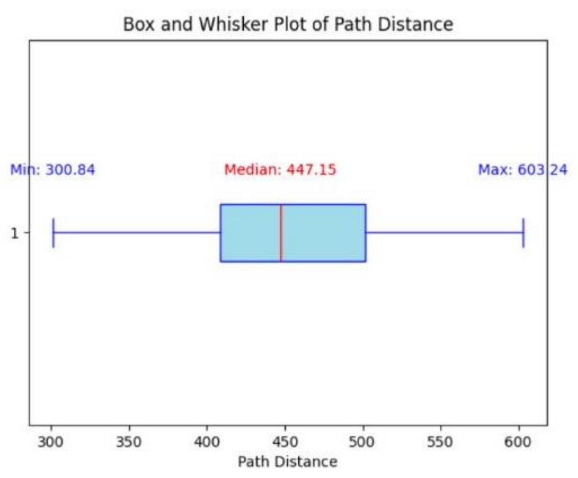
(b) Performance metrics of Fuzzy RRT



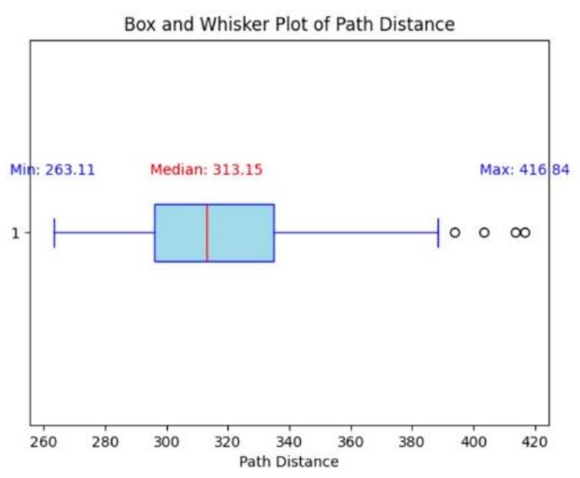
(a) Path generated using RRT.



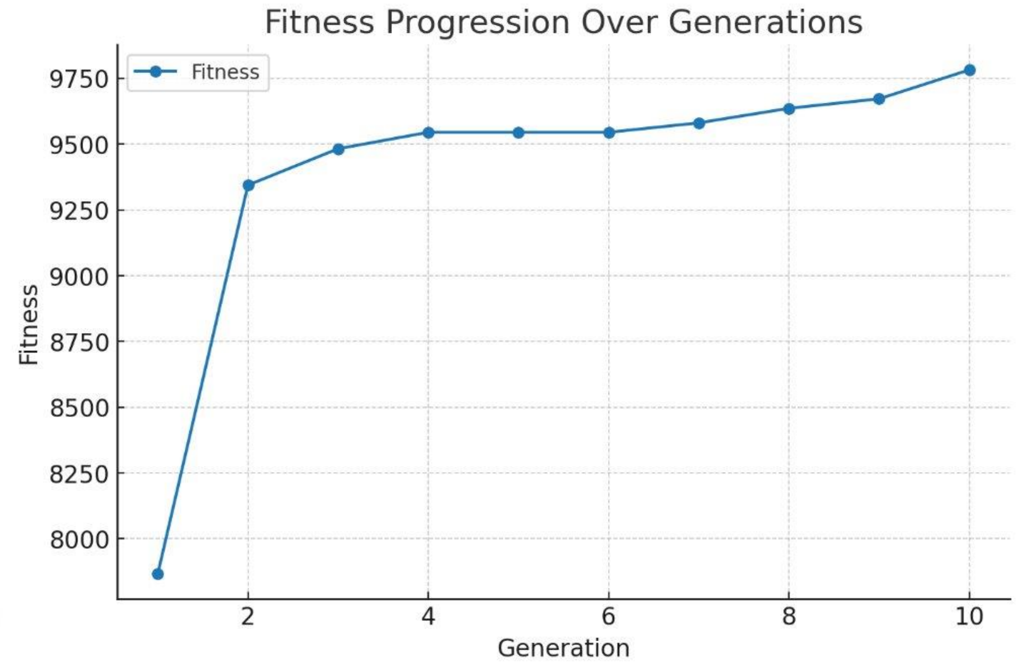
(b) Path generated using Fuzzy RRT.



(a) Performance metrics of RRT.



(b) Performance metrics of Fuzzy RRT.



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