REALIZATION AND VALIDATION OF SWARM ROBOTS FOR MAPPING, SEARCH AND APPREHEND APPLICATION

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Introduction:

Swarm control as the name states involves controlling multiple robots or devices in a way which allows the devices to communicate with each other and form a hive like communication structure. This control system was inspired by bee and ant colonies where they act together and separate tasks accordingly which helps them achieve the task in an efficient manner. This involves designing small-scale robots, their control systems as well as the required algorithms to map the maze as well as to apprehend the robber robot.

Objectives:

1. To develop a fleet of police bots capable of navigating an unknown environment to apprehend a robber bot.
2. To implement camera feedback and encoder odometry for precise movement and localization.
3. To analyse the effectiveness of varying the police to robber bot ratio in enhancing apprehension strategies.

Methodology:

We begin with the robots' physical design, followed by kinematic modelling to establish a mathematical foundation for their movement and interaction. Control algorithms, including PID controllers and feedback mechanisms, are then introduced to enable precise maneuvering and responsiveness. Image processing techniques, such as camera calibration and perspective transformation, support localization and coordination. Lastly, we discuss software simulations in ROS2 and Gazebo, which are critical for testing and refining algorithms before real-world deployment.

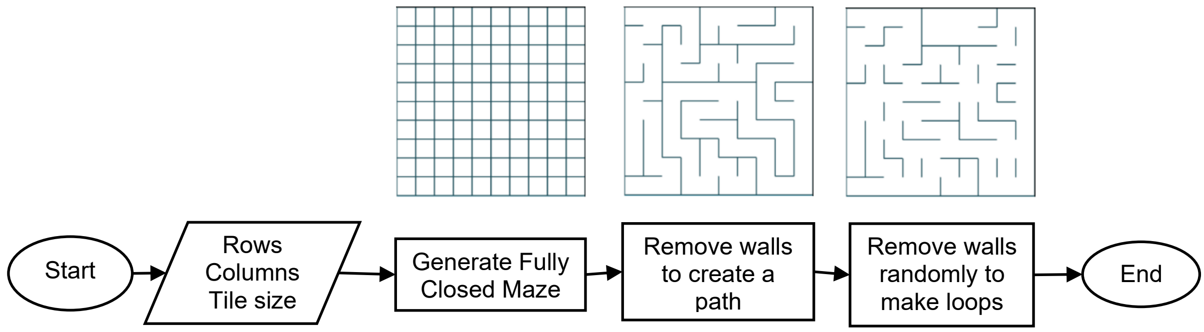

Figure 1: Maze Generation Flowchart

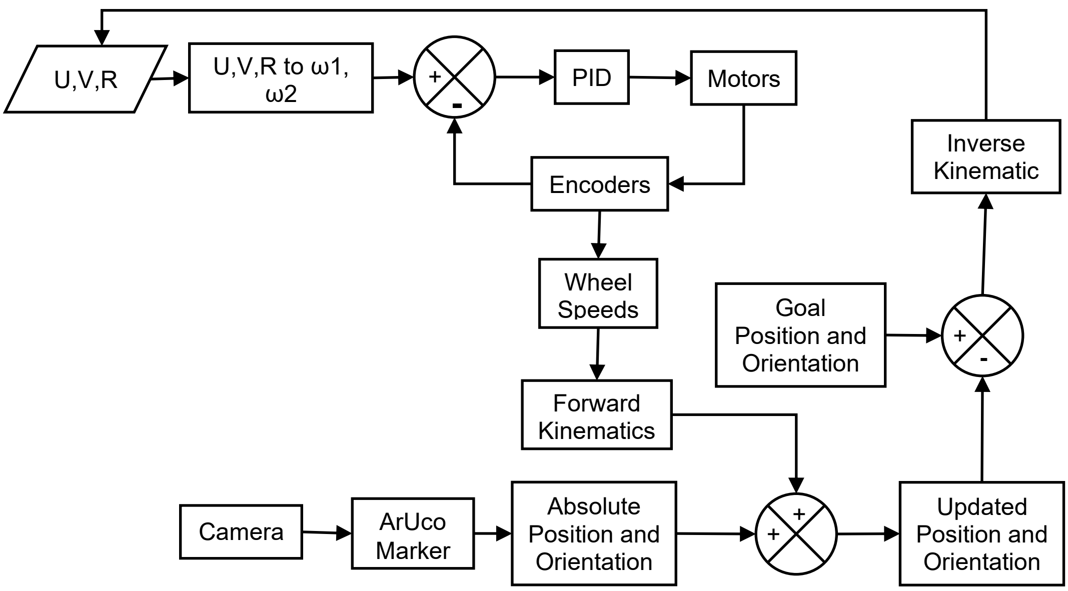

Figure 2: Control Logic Flowchart

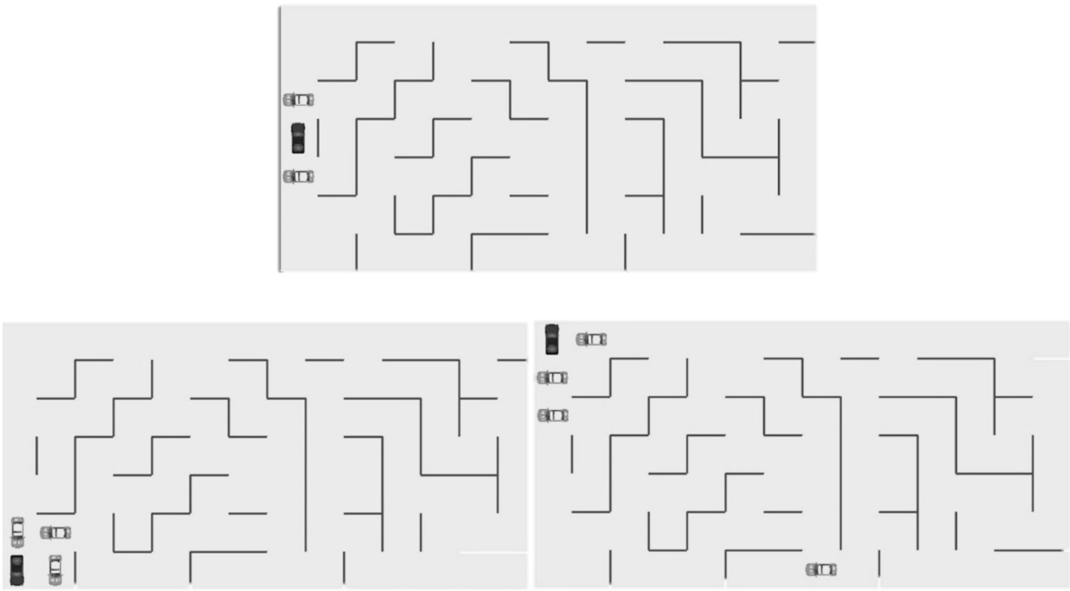

Figure 3: Python Simulation with varying bot numbers

In this simulation, the blue bots represent police units, while the black bot represents the robber. Green lines mark impassable walls, and the maze boundaries act as additional walls, confining the bots within a closed environment. The simulation accounts for the orientation of the bots, requiring them to face the correct direction before making a move, which adds complexity to their navigation strategies.

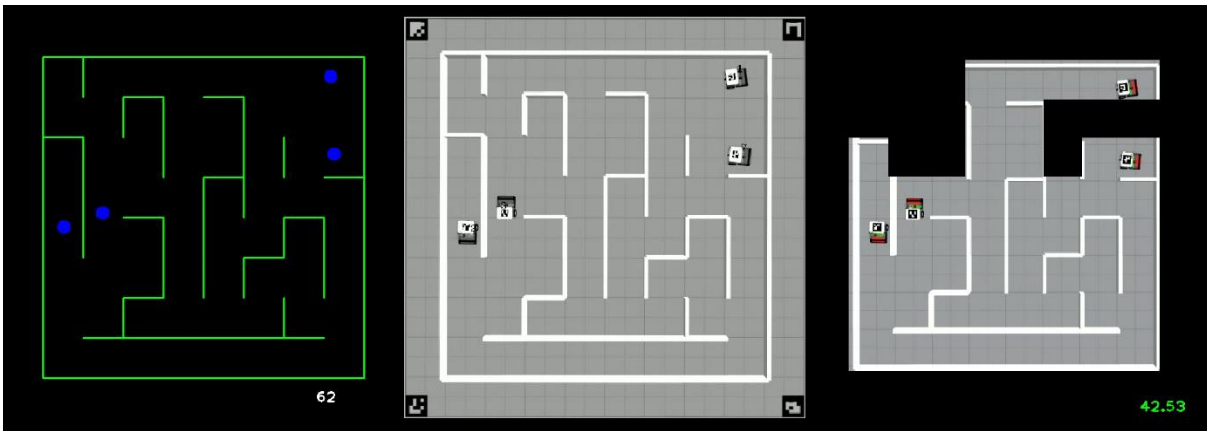

Figure 4: Gazebo Simulation with varying bot numbers

The Gazebo simulation was used to test various mapping algorithms, aiming to determine their efficiency in exploring the entire map within minimal time. Gazebo provides a realistic simulation environment, incorporating physical forces and environmental constraints that approximate real-life conditions.

Result and Conclusion:

The mapping process evaluates the ability of swarm robots to navigate and map a maze-like environment. The performance of each algorithm is assessed through simulation and physical implementation, with a focus on the time taken to complete mapping as the primary metric.

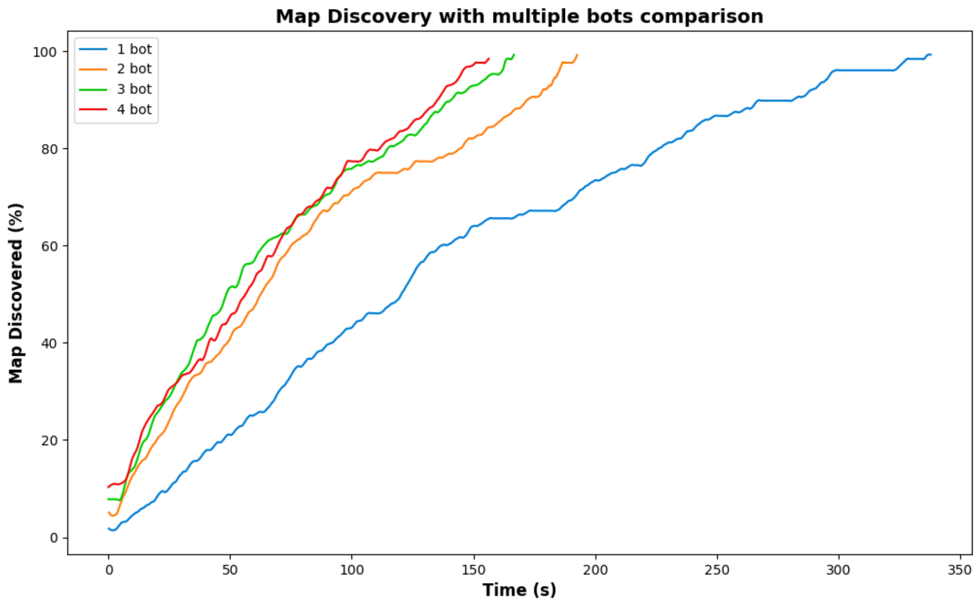

Figure 5: Map Discovery Gazebo Comparison

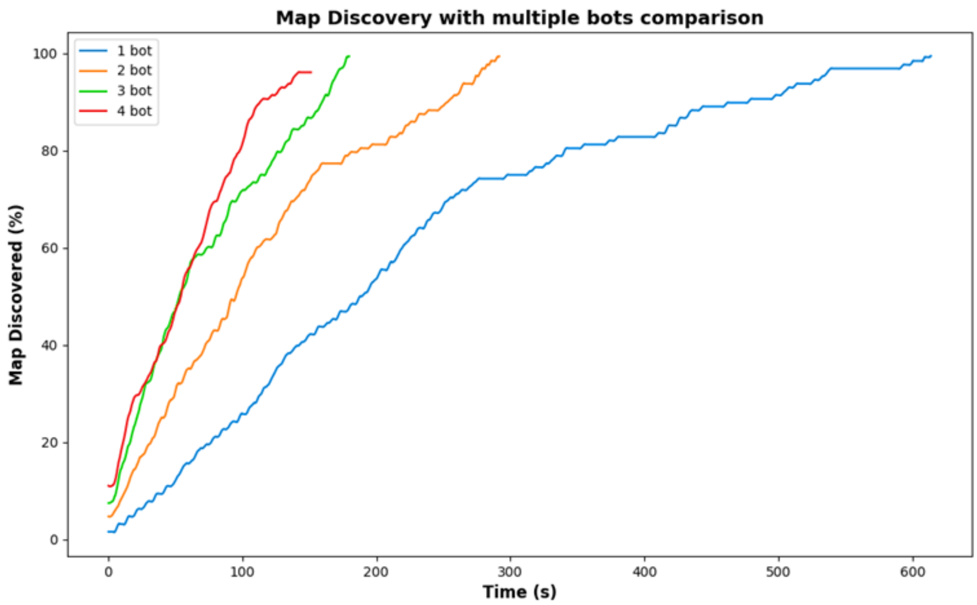

Figure 6: Map Discovery Physical Implementation Comparison

The apprehension task involves detecting and capturing a target robot (the "robber") within a controlled environment. The performance of search and apprehend algorithms is evaluated in terms of capture time, using both Gazebo simulations and physical implementations.

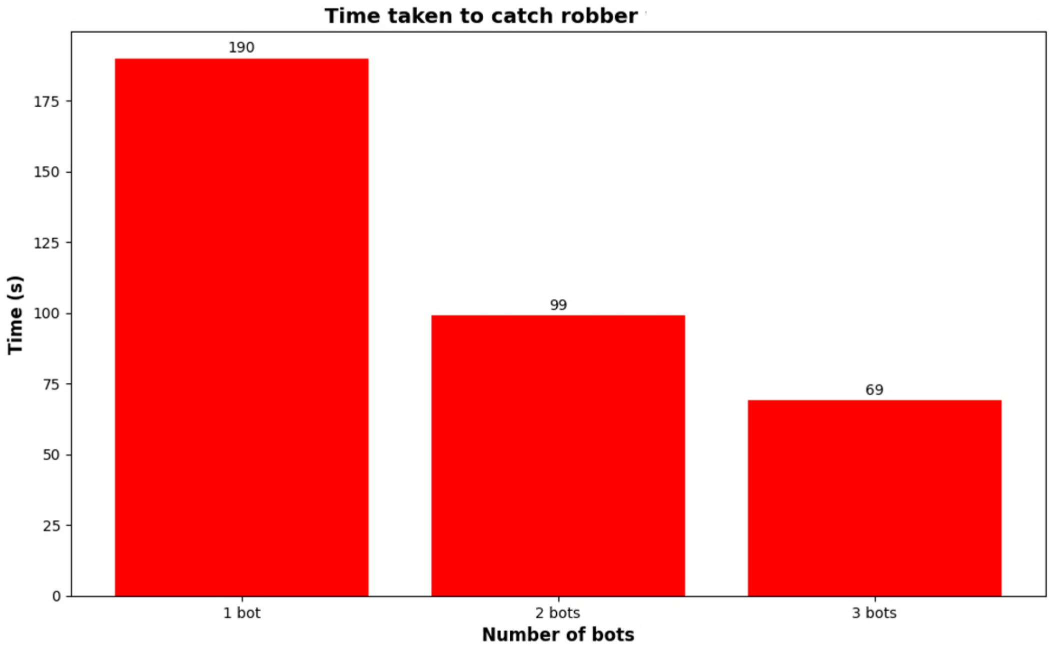

Figure 7: Search and Apprehend Gazebo Simulation Comparison

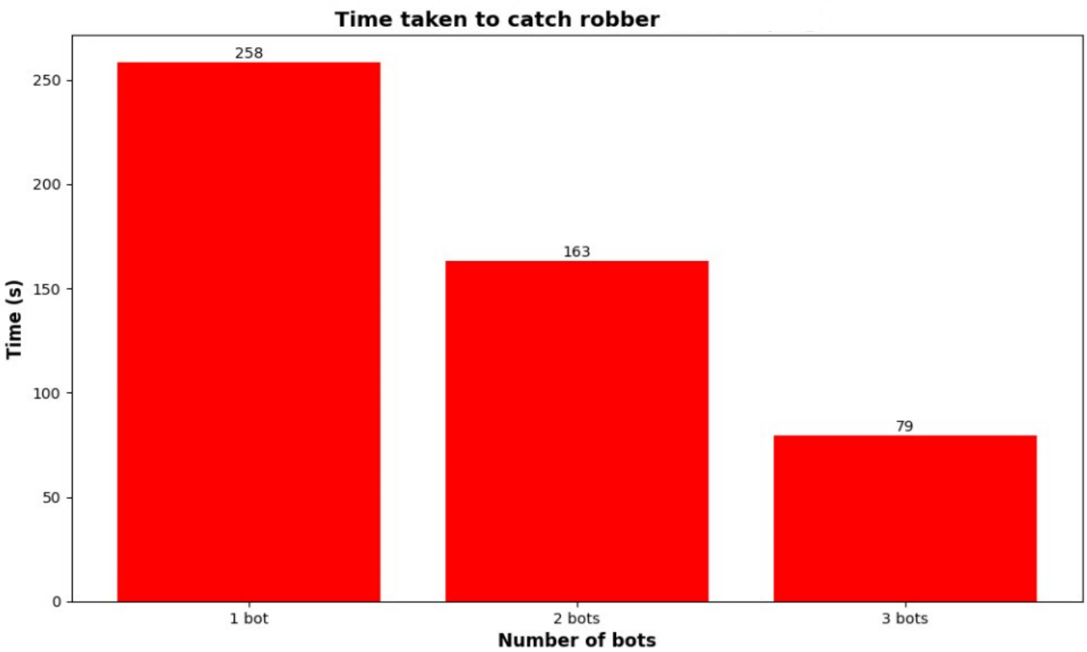

Figure 8: Search and Apprehend Physical Implementation Comparison

In conclusion, this project demonstrates the efficiency of swarm robots working together to achieve a common goal by effectively dividing tasks and illustrates how cost-effective hardware solutions can provide robust localization without the need for more advanced, expensive sensors such as GPS or IMUs. The multi-bot system showed effective swarm coordination, with police bots successfully collaborating to trap the robber bot, showcasing the potential for applications in surveillance, rescue missions, and autonomous navigation within unstructured environments. This lays a foundation for the development of swarm robotics in real-world scenarios, emphasizing the advantages of collaborative agent systems.

Project Outcome & Industry Relevance:

The project successfully demonstrates the implementation of a swarm robotics system in a unpredictable environment. Multiple autonomous police bots collaboratively navigate a randomly generated maze to pursue and capture a single robber bot using decentralized decision-making and coordinated strategies. The bots communicate and share positional data, optimize their paths. The system highlights efficient real-time multi-agent coordination, path planning, and pursuit-evasion dynamics in a constrained environment.

Key outcomes include:

1. Real-time multi-bot communication and coordination.
2. Autonomous pathfinding in complex and unknown environments.
3. Robotic implementation of pursuit-evasion algorithms.
4. Scalability and robustness of swarm behaviour in dynamically changing conditions.

Swarm robotics is a growing field with applications across multiple industries, and this project models real-world scenarios with high impact potential:

1. **Surveillance & Security:** The system reflects intelligent, automated patrolling in restricted or dangerous zones (e.g., military bases, border control), where multiple autonomous units collaborate to intercept intruders.

2. **Search and Rescue Operations:** Similar swarm coordination can be applied to search operations in collapsed buildings or disaster zones where centralized control is difficult or impossible.
3. **Warehouse Automation & Logistics:** The principles of decentralized coordination and navigation through constrained spaces translate well into optimizing the movement of autonomous warehouse robots.
4. **Autonomous Vehicle Fleets:** The pursuit-evasion concept is relevant for defense against rogue autonomous agents or in traffic monitoring and control systems.
5. **Gaming & Simulation:** This project also has potential in game AI development and simulation training for law enforcement strategies.

Working Model vs. Simulation/Study:

The project followed a structured development pipeline, beginning with simulations and culminating in a fully functional physical implementation:

1. **Initial Simulation (Python & Pygame):** The core algorithms for maze generation, bot navigation, and pursuit-evasion were first developed and validated in a lightweight 2D environment using Pygame. This stage enabled rapid prototyping and testing of pathfinding strategies and swarm coordination logic without the overhead of physics or real-world constraints.
2. **Physics-Based Simulation (Gazebo):** After validating the logic in 2D, the system was ported to a 3D physics-based environment using Gazebo and ROS. This allowed testing under realistic conditions, including robot dynamics, sensor noise, and collision handling. It provided a critical bridge between abstract algorithmic design and real-world implementation.
3. **Hardware Implementation:** The final stage involved deploying the system on physical robots. Each bot was equipped with onboard control, communication capabilities. The successful hardware integration confirmed the robustness of the algorithms in real-world scenarios, completing the transition from simulation to a working model.

This layered approach ensured both theoretical soundness and practical viability, allowing for iterative refinement at each stage of development.

Project Outcomes and Learnings:

This project provided a deep, hands-on understanding of swarm robotics, from theoretical foundations to real-world implementation. Key learnings include:

1. **Algorithm Design & Optimization:** Gained practical experience in developing and optimizing pathfinding algorithms (A*, BFS) for real-time navigation and pursuit-evasion scenarios.
2. **Swarm Coordination:** Understood the principles of decentralized communication and collective decision-making, and how simple rules at the individual level can lead to complex and effective group behavior.
3. **Simulation to Reality Gap:** Learned the challenges involved in transitioning from ideal simulations to physical robots, including dealing with hardware limitations, sensor inaccuracies, and real-world uncertainties.
4. **ROS & Gazebo Integration:** Acquired hands-on experience with Robot Operating System (ROS) and Gazebo for simulating realistic robotic behavior in complex environments.
5. **Hardware Prototyping:** Gained exposure to building, programming, and testing autonomous robots, including sensor integration, wireless communication, and embedded control systems.
6. **Problem-Solving & Debugging:** Developed strong debugging and problem-solving skills through iterative testing across multiple platforms (Python, Gazebo, hardware).

This project not only enhanced technical skills across multiple domains but also strengthened collaborative thinking, system design, and adaptability—core competencies for real-world robotics and automation roles.

Future Scope:

The future scope of this project includes:

1. **Advanced Pursuit and Evasion Strategies**: Future work could integrate machine learning algorithms to predict movement patterns and adapt paths in real time. Machine learning-based path prediction models, for example, could

allow police bots to anticipate the robber's movements, while adaptive path planning algorithms would enable bots to adjust their routes based on new data.

2. **Scaling for Larger Swarms**: Extending the system to support larger groups of bots would allow for greater versatility and improved swarm coordination. As the swarm size increases, the system would be better equipped to cover expansive or complex environments, such as search-and-rescue operations in disaster zones. Future iterations could explore optimized communication and control strategies to maintain seamless coordination and prevent interference as the number of agents grows.
3. **Obstacle Detection and Dynamic Adaptability**: Incorporating additional sensors, such as LiDAR or ultrasonic sensors, would enable real-time obstacle detection and avoidance. This addition would make the bots more adaptable to dynamic or unstructured environments, allowing them to operate in settings where obstacles appear or shift unexpectedly. Dynamic adaptability would be crucial in situations where navigation is required within crowded or changing environments.
4. **Hardware and Battery Optimization**: Improving power efficiency through energy-efficient components and optimized circuit design could enhance the bots' operational lifespan. Exploring wireless charging solutions or modular battery packs would provide longer mission durations, which would be especially beneficial for applications where continuous operation is needed.
5. **Enhanced Communication Protocols**: The use of advanced communication protocols, such as Zigbee or LoRa, would improve data transfer across larger distances, making the system more resilient and adaptable in larger, real-world environments. These protocols offer low-power, long-range communication, allowing bots to maintain reliable connections over broader areas without extensive infrastructure.