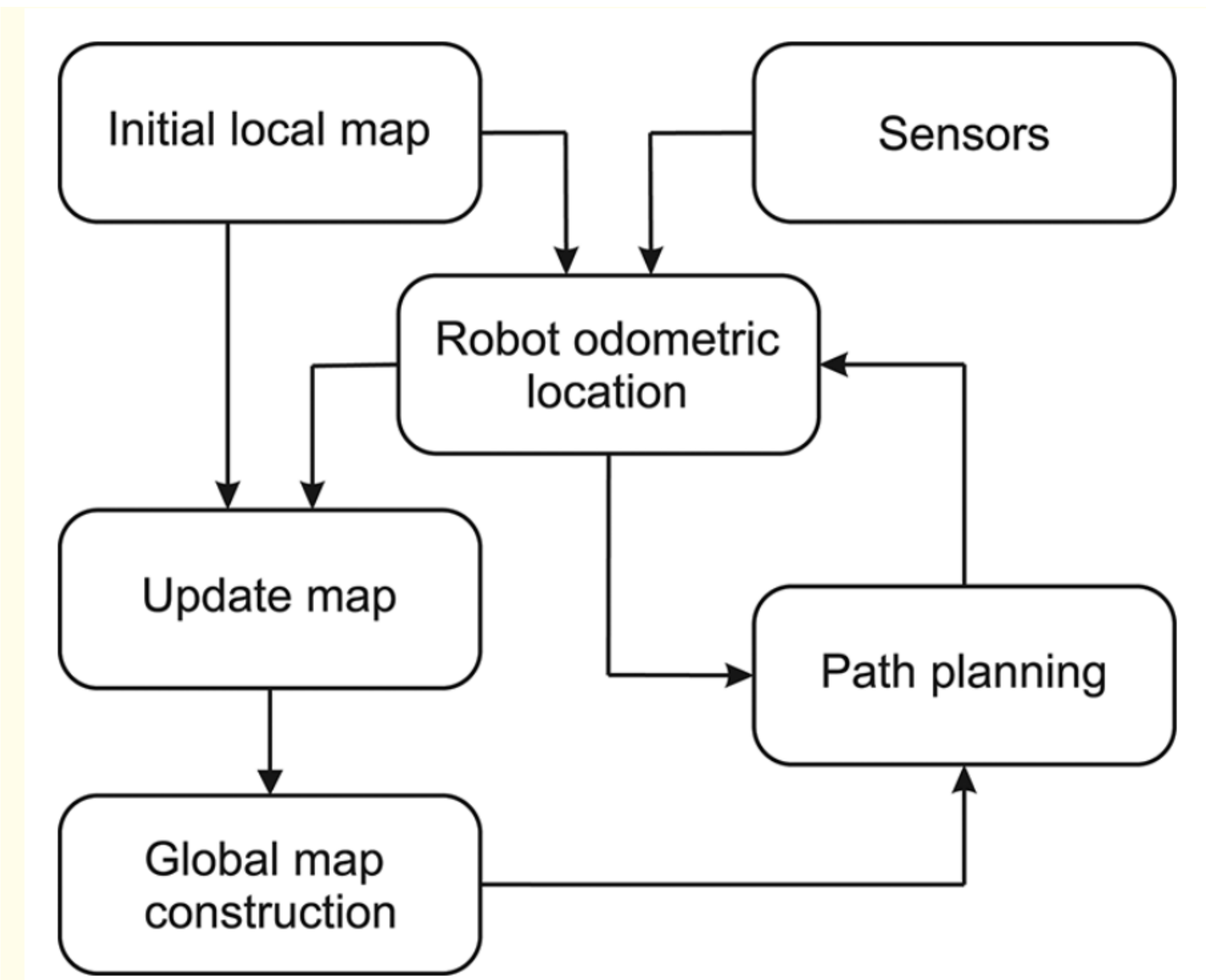
Develop a 2D Occupancy Grid Map of a Room using Overhead Cameras

1. Problem Definition

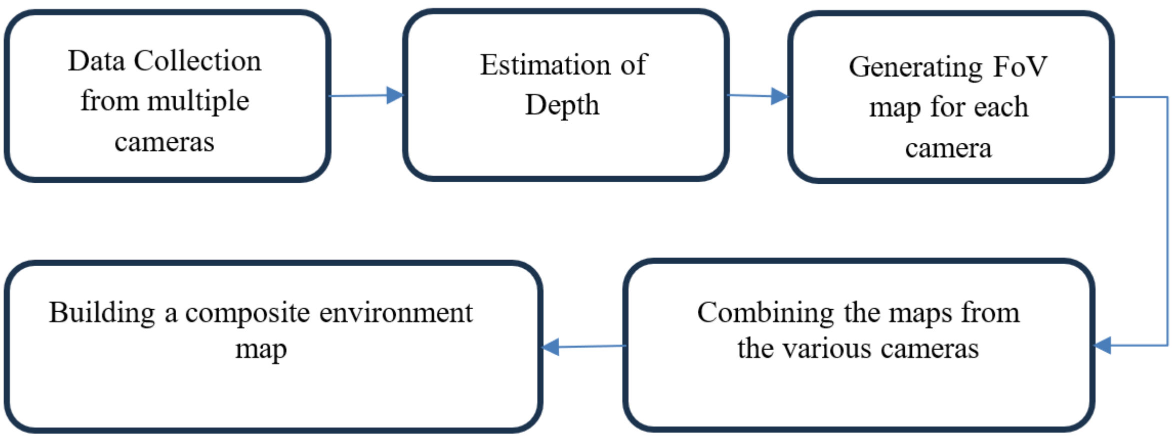
The project aims to create a detailed and accurate 2D occupancy grid map of a room using overhead cameras. This map will facilitate better navigation and spatial awareness for autonomous systems, like those used in AMRs with ROS2-based SLAM algorithms.

2. Solution Approach

1st Approach: -



2^{nd} Approach: -



3. Novelty of the approach

Comparison to Prior Art Solutions and Novelty: -

Prior Art Solutions: -

1. LiDAR-based SLAM:

   - Utilizes LiDAR sensors to map environments by measuring distances to objects.

   - Widely used in autonomous mobile robots (AMRs) for indoor and outdoor navigation.

2. Laser Range Finder SLAM:

   - Employs laser range finders to detect obstacles and build maps.

   - Effective but limited by sensor range and resolution.

3. Monocular or Stereo Camera SLAM:

   - Uses single or dual cameras for SLAM by tracking and identifying features.

   - Involves complex algorithms for depth estimation and feature matching.

4. RGB-D Camera SLAM:

   - Combines RGB images with depth data to create maps.

   - Offers rich data but can be expensive and computationally demanding.

Novelty and New Ideas in Our Solution: -

1. Use of Overhead Cameras:

   - Innovative use of multiple overhead cameras to capture the entire room from above.

   - Provides a top-down view, minimizing occlusions and offering a comprehensive perspective.

2. Advanced Camera Synchronization and Calibration:

   - Techniques for synchronizing and calibrating multiple cameras to ensure accurate data capture and stitching.

   - Enhances consistency and mapping accuracy compared to single-camera or unsynchronized multi-camera setups.

3. Image Stitching for a Unified View:

   - Unique approach to combine images from multiple cameras into a single, comprehensive view of the room.

   - Increases detail and coverage compared to single-viewpoint methods.

4. Sophisticated Feature Extraction and Landmark Detection:

   - Algorithms for extracting features and detecting landmarks within the room.

   - Provides robust reference points for creating an accurate occupancy grid map.

5. Efficient Occupancy Grid Mapping:

   - Method to construct a 2D occupancy grid map from overhead images, distinguishing between occupied and free spaces.

   - More efficient and cost-effective than LiDAR and RGB-D solutions.

6. Scalability and Flexibility:

   - Scalable for different room sizes and configurations by adjusting the number and placement of cameras.

   - Can be integrated into existing infrastructure with minimal modifications.

4. Methodology

Creating the Solution: -

1. Overhead Camera Installation:

   - Installed multiple overhead cameras at strategic locations to ensure complete coverage of the room.
   - Ensured cameras were positioned to minimize occlusions and provide overlapping fields of view.

2. Camera Calibration:

   - Calibrated each camera individually to correct for lens distortion and alignment issues.
   - Used a checkerboard pattern and calibration software to achieve precise calibration parameters.
   - Synchronized the cameras to ensure they capture images simultaneously, reducing discrepancies.

3. Image Capture and Pre-processing:

   - Captured images from all cameras simultaneously.
   - Pre-processed the images to enhance quality, including noise reduction, brightness adjustment, and contrast enhancement.

4. Image Stitching:

   - Used image stitching algorithms to combine the images from different cameras into a single panoramic view.
   - Implemented feature-based stitching techniques to align and merge the images accurately.

5. Feature Extraction:

   - Applied feature extraction algorithms to identify key points, edges, and textures within the stitched image.
   - Used these features to detect landmarks and reference points crucial for mapping.

6. Landmark Detection:

   - Employed machine learning algorithms to classify and identify landmarks within the room.
   - Used these landmarks to enhance the accuracy of the occupancy grid map.

7. Occupancy Grid Mapping:

   - Developed algorithms to convert the stitched and processed images into a 2D occupancy grid map.
   - Distinguished between occupied and free spaces based on detected features and landmarks.
   - Created a dynamic map that updates in real-time as new images are captured and processed.

Validation: -

1.Ground Truth Comparison:

   - Compared the generated occupancy grid map with a manually created ground truth map of the room.
   - Assessed the accuracy by measuring the alignment and overlap between the two maps.

2. Real-time Updates:

- Tested the system's ability to update the map in real-time as objects were added, removed, or moved within the room.
- Verified that the occupancy grid map accurately reflected these changes without significant delay.

3. Error Analysis:

- Analyzed errors and discrepancies between the generated map and the ground truth.
- Identified sources of errors, such as camera misalignment, calibration inaccuracies, or stitching artifacts.

4. Performance Metrics:

- Measured key performance metrics, including processing time, accuracy, and robustness.
- Ensured that the system met the required performance standards for real-time operation and accurate mapping.

5. Describe advantages and limitations of the approach

Pros/Advantages: -

1. Accuracy:

- Uses multiple overhead cameras for detailed mapping, reducing occlusions and improving accuracy.
- Advanced calibration and synchronization techniques enhance mapping precision compared to single-sensor solutions.

2. Scalability:

- Easily scalable for different room sizes and configurations by adjusting camera placement.
- Integration into existing environments is straightforward, requiring minimal modifications.

3. Computational Complexity:

- Efficient image processing and feature extraction algorithms support real-time or near real-time updates of the occupancy grid map.
- Less computationally demanding compared to solutions relying on RGB-D cameras or LiDAR, leading to lower hardware costs.

4. Cost-Effectiveness:

- Overhead cameras are generally more affordable than specialized sensors like LiDAR or RGB-D cameras.
- Reduced initial setup and maintenance costs contribute to overall affordability.

5. Flexibility:

- Provides flexibility in deployment due to straightforward installation of overhead cameras \ and minimal disruption to existing spaces.

Cons/Limitations: -

1. Dependency on Camera Placement:

- Accuracy heavily relies on optimal placement and precise calibration of overhead cameras.
- Effectiveness may be limited in complex environments with obstacles hindering camera coverage.

2. Environmental Conditions:

-Performance may degrade in challenging lighting conditions or environments with highly reflective surfaces, affecting image quality and feature detection.

3. Processing Overhead:

- While less computationally intensive than some alternatives, real-time processing may still require significant computing power, depending on the number of cameras and complexity of algorithms used.

4. Mapping Limitations:

-Dynamic environments with frequent object movements may pose challenges, necessitating continuous updates and recalibration of the system.

5. Initial Setup Complexity:

- Requires initial efforts for camera calibration, synchronization, and image stitching, which can be time-consuming and require expertise in image processing and computer vision.

6. Results

Method Validation and Testing

To ensure the robustness and accuracy of our method for creating a 2D occupancy grid map using overhead cameras, rigorous testing and validation procedures were conducted:

1. Data Collection:

- Collected images from multiple overhead cameras installed in various indoor environments with diverse layouts and lighting conditions.

2. Camera Calibration and Synchronization:

- Precisely calibrated and synchronized the cameras to minimize distortion and ensure consistent data capture.

3. Image Processing and Stitching:

- Employed advanced image processing techniques to improve image quality, reduce noise, and adapt to different lighting conditions.
- Implemented stitching algorithms to seamlessly merge images from multiple cameras into a unified panoramic view.

4. Feature Extraction and Landmark Detection:

- Developed algorithms to extract robust features such as edges, corners, and textures from the stitched images.
- Applied machine learning algorithms to detect and classify landmarks within the environment, essential for accurate mapping.

5. Occupancy Grid Mapping:

- Utilized extracted features and landmarks to construct a detailed 2D occupancy grid map.
- Differentiated between occupied and free spaces based on feature density and the presence of landmarks.

Map Accuracy Evaluation: -

1. Ground Truth Comparison:

- Compared the generated occupancy grid map with manually created ground truth maps of the environment
- Evaluated accuracy metrics such as overlap, alignment, and feature recognition rates.

2. Error Analysis:

- Conducted comprehensive error analysis to identify discrepancies between the generated map and ground truth.
- Investigated potential sources of errors, including camera misalignment, calibration

inaccuracies, and limitations in feature detection.

3. Performance Metrics:

- Measured key performance indicators, including mapping accuracy, processing time per frame, and system robustness under varying environmental conditions.
- Validated the system's capability to update the map effectively in real-time or near real-time as environmental dynamics changed

4. User Feedback and Iterative Improvement:

- Solicited feedback from users and stakeholders to assess usability and effectiveness in practical applications.
- Incorporated feedback into iterative improvements aimed at enhancing mapping accuracy and system reliability.

6.1 Fused map of the environment and detailed dimensions

1. Infra-cam Fusion Algorithm:

- Overview: Utilizes overhead cameras and possibly infrared sensors to construct a detailed 2D occupancy grid map.

-Features: Integrates multiple camera views through stitching and employs advanced image processing for precise feature extraction and landmark detection.

- Accuracy: Focuses on achieving high mapping accuracy by meticulously calibrating and synchronizing cameras.

2. Ground Truth Map from Gazebo:

- Overview: A simulated or manually crafted map that represents the true layout and occupancy status of the environment.

- Features: Used as a reference standard to validate mapping algorithms, assessing metrics like overlap, alignment, and feature recognition.

- Accuracy: Assumes high precision as it reflects an ideal or simulated environment without real-world sensor limitations.

Evaluation Criteria: -

- Overlap and Alignment: Measures how closely the generated occupancy grid map matches the ground truth map. Higher overlap and alignment indicate greater accuracy.

- Feature Recognition Rates: Evaluates the algorithm's capability to accurately detect and classify landmarks and features throughout the map.

7. Learnings

1.Skill Development in Technology:

- Image Processing: Advanced techniques for enhancing images, reducing noise, and extracting. features.

-Sensor Fusion: Integrating data from multiple sensors, like cameras and potentially infrared sensors, to improve mapping accuracy.

-Algorithm Development: Creating algorithms for camera calibration, synchronization, image stitching, and generating occupancy grid maps.

2. Problem-Solving and Optimization: *

- Addressing challenges such as sensor calibration, variability in environmental conditions, and real-time processing demands.

- Optimizing algorithms and workflows to achieve higher mapping accuracy and efficiency.

3. Validation and Evaluation:

- Learning methods to validate mapping results against ground truth data or simulations (e.g., using Gazebo).

- Understanding metrics like overlap, alignment, and feature recognition rates to evaluate mapping accuracy.

4. Integration of Interdisciplinary Knowledge:

- Applying knowledge across fields such as computer vision, robotics, and spatial mapping to develop practical solutions.

- Translating theoretical concepts into real-world applications within autonomous systems and robotics.

5. Collaboration and Communication Skills:

- Working effectively with team members from diverse technical backgrounds to achieve project objectives.

- Communicating technical concepts, challenges, and solutions clearly to stakeholders and team members.

6. Continuous Learning and Adaptation:

- Embracing new technologies, methodologies, and feedback to iteratively improve solutions.
- Fostering a mindset of ongoing learning and development within the realm of autonomous navigation and spatial awareness.

8. Conclusion

In summary, this project has significantly enhanced our skills and understanding in the realm of autonomous systems and robotics. It has equipped us with some proficiency in image processing techniques, sensor fusion, and algorithm development necessary for creating precise 2D occupancy grid maps using overhead cameras and other sensors. Throughout this endeavour, we've honed our problem-solving abilities, particularly in optimizing algorithms for real-time processing and overcoming challenges such as sensor calibration and environmental variability.

The experience of validating and evaluating our mapping solutions against ground truth data has provided invaluable insights into measuring accuracy and refining system performance.

Moving forward, the lessons learned from this project will continue to guide our pursuit of innovation in robotics and autonomous navigation.