Chapter 7

Conclusions and Future Perspective

Each chapter discussed earlier has concluded the work without consolidating the aims and objectives of the thesis. This chapter summarizes the important contributions of the thesis.

Summary of Contributions

The research contribution of the thesis in the area navigation and tracking of mobile robots are addressed in Section 7.1, the limitations of the thesis is discussed in Section 7.2 and finally outlines of future work are presented in Section 7.3.

7.1 Conclusions

In Chapter 2, the available literature is reviewed thoroughly in the areas of vision sensor based navigation and tracking of mobile robot. A summary of research gap was identified in the navigation and tracking related literature and observed that the challenges lie in real time navigation in structured/unstructured outdoor terrain, existence of moving obstacles, visual perception and incorporation of mobile robot tracking information in the control loop.

The research work in Chapter 3, implemented vision based object detection and tracking method for mobile robot perception. The proposed method has practical importance when the mobile robot is tracked while moving on a predetermined or specified path as the size of the image of the mobile robot is small relative to the captured image of the environment. The mobile robot movement tracking was carried out with the help of KLT algorithm while Viola-Jones algorithm was used for detection. In order to carry out this tracking process, a ROI window has been created in each frame of the mobile robot image position with homography constraints. The entire tracking process was automated and the system would restore its desired task itself when the tracking information gets lost. Because of the locomotion constraints, mobile robot does not follow the specified path giving rise to tracking error which was rectified by using Kalman filter. Firstly, the Kalman filter motion model has been established using the KLT algorithm to choose centroid and tracking window as the features. The proposed approach accurately detects and tracks the mobile robot with error percentage ranging from 0.5% to 10% in different parts of the specified path.

In Chapter 4, a mobile manipulation-based path planner is presented that focuses on multi-target object clean-up operations using vision sensor. A vision-based path planning approach has been implemented using A* algorithm in order to avoid the obstacles and reach the goal location using the shortest path. The algorithm was developed to classify objects in the workspace as handleable/non-handleable from real-time measurements. For priority generation in case of multi-objet clean-up operations, a weighted cost function approach was used. A series of experiments were conducted to get the effectiveness of various parts of the algorithm. The error of the measurement process was found out to be in a range of ± 4cm in height and ± 2cm in width. Secondly, the entire workflow of the mobile manipulation-based path planner was demonstrated using a various scenario. Thirdly, the process of priority generation was tested by changing the weights of the algorithm and analyzing the performance of the path planner. In this case, the path planner with weights of 0.8 for d_{tg}; 0.1 for d_{st} and 0.1 for A_n resulted in optimum performance. This combination of weights required a total of 147 nodes from the search space to be explored and had a total path cost of 50.6274 for the process of multi-target path planning, which was lowest among all the other combination of weights.

The Chapter 5, discussed an approach for path planning and tracking of shape aware mobile robot in structured environment using vision sensor. Obstacle detected was analyzed within structured real-world environments using vision-based refinement like thresholding, erosion and clustering. Feature point based object detection and tracking method was implemented for mobile robot. An open source vision library (OpenCV) was incorporated in ROS framework to convert real-time images to ROS formats. The detection and tracking algorithms was written in python which has been deployed using the OpenCV library for 2D mobile robot navigation. This research investigates the shape aware based mapping and navigation algorithm for mobile robot that has been established to be free of collisions in real time. The error percentage between the obtained modified shape aware path with KLT tracking and Kalman filtering were computed to test the efficacy of the proposed algorithm. The tracking algorithm generated 30-40% of error due to unsteady velocity and change in the direction of mobile robot. With the implementation of Kalman filter based de-noising method generated 6-10% results with respect to KLT tracking. Safe movement on a planned path was accomplished by avoiding narrow paths and maintaining a minimum distance when travelling along a wall or line of objects. The proposed modified shape aware path planning algorithm provided a collision-free path. The above results confirmed that the obstacle avoidance task was carried out while considering shape and kinematics of the mobile robot.

Finally, Chapter 6, investigated the use of safe path tracking in an unknown environment among static and dynamic obstacles in order to determine the shortest path possible from any start position to its destination. D* lite path planning algorithm for robot navigation in unknown workspace was implemented and vision sensor is used to capture the movement of the mobile robot. The captured video is analyzed to track the mobile robot using TLD algorithm. The path planning algorithm was implemented in real-time as a global planner plugin with the ROS Navigation Stack along with Dynamic Window Approach as the local planner. D* lite path planning algorithm included a rapid re-plan in an unstructured, unknown environment with experimental and analytical data. The tracking error in terms of positional error is observed in the range 8-10 % in test path (1 & 2) when TLD algorithm is implemented. This could be attributed to the variations in the direction of the mobile robot and non-uniform speed. Similarly, Kalman filter based denoising is applied to output from TLD algorithm which produced tracking error in a range of 4-7% in test path 1 &2. Despite the good performance of path planning and path tracking navigation algorithms, the approach has a few limitations related to motion control (angular speed), obstacle boundary segmentation, from which the minimum distance path is computed. In future these limitations will be addressed by selecting suitable strategies for path planning algorithm, sensing and decision making.

The next subsection describes some of the limitations of the present thesis and discusses future scope. In this sub-section, potential research areas will be defined that can enhance vision based navigation activities and advance progress towards a robust solution.

The key accomplishments of this thesis can be summarized as follows:

- After thorough literature review, summary of research gaps were identified in the navigation and tracking related area and observed that the challenges lie in real time navigation in structured/unstructured outdoor terrain, existence of moving obstacles, visual perception and incorporation of image information in the control loop.
- The research focused on object detection and tracking method using vision sensor for mobile robot perception. Mobile robot movement tracking was performed by the KLT algorithm while detection was performed using the Viola-Jones algorithm. The proposed method is of practical importance when the mobile robot is tracked while moving on a predetermined or specified path as the size of the image of the mobile robot is small relative to the captured image of the environment.
- Because of the locomotion constraints, mobile robot could not follow the specified path giving rise to tracking error which was rectified by using Kalman filter. Firstly, the Kalman filter motion model is established using the KLT algorithm to choose centroid and tracking window as the features. The proposed approach accurately detected and tracked the mobile robot with error percentage ranging from 0.5% to 10% in different parts of the specified path.
- A mobile manipulation-based path planning approach using vision sensor has been implemented using A* algorithm in order to avoid the obstacles and reach the goal location using the shortest path. The algorithm was developed to classify objects in the workspace as handleable/non-handleable from dimensions of captured images.
- The process of object measurement was done by keeping the same object in various views in order to understand the variation in the error. The error of the measurement process was found out to be in a range of ± 4cm in height and ± 2cm in width. The entire workflow of the mobile manipulation-based path

planner was demonstrated using a single handleable object and two non-handleable object scenarios.

- The shape-aware based path planning and tracking algorithm of mobile robot in structured environment using vision sensor has been implemented to determine collisions free path in real time. The error percentage between the obtained modified shape aware path with KLT tracking and Kalman filtering were computed to test the efficacy of the proposed algorithm.
- The tracking algorithm generated 30-40% of error due to unsteady velocity and sudden change in the direction of the mobile robot. With the implementation of Kalman filter based de-noising method, the tracking result improved to 6-10% as compared to KLT tracking. Safe and viable movement on a planned path was accomplished by avoiding narrow paths and maintaining a minimum distance while travelling along a wall or line of objects.
- Algorithms to determine the shortest path for navigation of a mobile robot in an uncertain environment with static and dynamic obstacles from any current location to its destination is investigated.
- D* lite path planning algorithm for robot navigation using stereo camera is implemented and the mobile robot was tracked using vision sensor. D* lite path planning algorithm included a rapid re-plan in an unstructured, unknown environment with experimental and analytical data. For tracking, the captured image/vedio is analyzed using TLD algorithm. Kalman filter based denoising.

7.2 Limitations of the Proposed Research

- The mobile robot has several mechanical constraint such as (i) the maximum turning angle should be less than 60°, (ii) approximate speed is required for proper rolling without longitudinal or lateral slipping of the wheels, and (iii) two motorized wheel should be synchronized properly at starting position, otherwise the mobile robot fail to travel in straight line and error increase over time.

- Commonly available low cost USB based web camera (iball-roboK20) has been used for capturing image, then Viola-Jones algorithm integrated KLT algorithm for mobile robot tracking have limitations in terms of response based on (i) sensor resolution: 300K pixels, (ii) maximum video resolution: 1600×1200 pixels, (iii) maximum frame rates: 30 fps. Camera with better parameters would have improved the performance even when mobile robot moves at a higher speed than 0.6 m/s.
- The KLT algorithm cannot track objects properly (i) when the moving objects are large for real time implementation (ii) due to poor illumination, shadows and parallax effect. The main condition of the KLT algorithm is that the camera should be stationary.
- The method to locate the trackable features in the detected bounding box region at a speed 0.6m/s is quite risky while using low level vision sensor. In the Viola- Jones training process, approximately 200 images were used to reduce false positive rate to 0.2 which indicate a high detection of ROI.
- A* algorithm works well in known environment where the obstacles are static and generates a shortest path that a mobile robot without considering the shape and size of the mobile robot. In this case, the shortest path to reach the destination is always replanned from the start location only. While D* Lite algorithm replans from its current location once the information regarding environment is known from the first search.
- Kalman filter based denoising technique cannot achieve zero tracking error and it achieves lower the tracking error values. In addition to unknown non-Gussian noise, the output of Kalman filter is decreased by truncation, system modeling, linearization and cumulative rounding errors. If the initial parameter values of the Kalman filter such as process noise with covariance matrix Q, white noise with covariance matrix R, are not chosen properly then the denoising error cannot be reduced. In most cases it requires several experimentation steps.

7.3 Future Perspective

For the research work covered in this thesis, there are several potential areas of further research, in particular with regard to the vision based navigation and tracking of mobile robot. Some perspectives are:

- Current work deals with a mobile robot which has constant speed during exploration. Thus work should focus on navigation of mobile robot in the structured environment with variable speed during exploration in same direction or in opposite direction and tracking of the same.
- The thesis focuses on real time tracking of mobile robot, however real time tracking based control strategies for the mobile robot should be explored and associated techniques should help real time exploration.
- Present work discusses vision based navigation where image processing is an important step. The time taken for processing and interpretation plays an important role in decision making. Thus, faster image processing methods and sensor fusion methods such as scale invariant feature transform (SIFT), speeded-up robust features (SURF), simultaneous localization and map building (SLAM) could have been integrated for navigation of mobile robot and tracking.
- Present work has implemented Kalman filter for denoising of tracked path and trajectory. Other advanced and faster de-noising approaches such as extended Kalman filter (EKF), unscented Kalman filter (UKF) can be implemented for reduction of tracking errors.
- Similarly, the thesis has implemented A* and D* lite path planning algorithm. Comparison of probabilistic approaches like Random Rapidly- Exploring Trees (RRTs) and Probabilistic Cell Decomposition (PCD) with the A* algorithm could have been implemented to show enhancement in path planning process. Enhancement and test of implemented approaches can be part of surveillance system.
- For navigation of mobile robot in a unstructured environment with dynamic obstacles D*Lite algorithm has been implemented. In this thesis only one dynamic obstacle with more than one static obstacle were considered for the tracking and denoising. In future, experimental implementations will be carried out for navigation of same mobile robot with more than one moving obstacles in the unstructured environment. This would require dead lock negotiations as well.