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Robust Navigation and Obstacle Avoidance Control of Inspection Robots in Complex Confined Environments

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Abstract. Abstract Inspection robots are usually used in challenging and narrow environments like mines, underground pipe galleries and closed industrial workshops. These areas pose practical difficulties, such as poor lighting, small corridors, and crowded barriers, and the absence of existing maps. To accomplish tasks of inspection safely, robots need to have good obstacle avoidance and powerful navigation. Nevertheless, in constrained spaces, sensors are prone to interference and positioning drift and perception failures can have a direct impact on operational safety. This paper provides a systematic review of the recent technologies in the perception, localization, obstacle avoidance and navigation of inspection robots in confined spaces. It gives a summary of the key technical issues and control strategies to achieve strong navigation and obstacle avoidance control with focus on local mapping by light detection and ranging (LiDAR) systems, fault-tolerant multi- sensor fusion localization, real-time obstacle avoidance in dynamic conditions, and robust navigation under high interference. The paper also looks at the benefits as well as the current limitations of current methods, such as sensitivity to sensor noise, localization drift, environment variation, and computational limitations. This paper offers an ordered literature basis to the future study of robust inspection-robot navigation in complex confined environments by demystifying the connection between perception, mapping, localization, obstacle avoidance and navigation.

Keywords: Inspection robot, strong navigation, obstacle avoidance control, multi-sensor fusion

1. Introduction

Current mobile inspection robot technologies have developed out of the primitive technologies that used single sensors and simple reactive obstacle avoidance to more complex positioning frameworks, which use multiple sources of sensing, including light detection and ranging (LiDAR) and an inertial measurement unit (IMU). These systems with local mapping and classical path-planning algorithms like dynamic window approach (DWA) and timed elastic band (TEB) algorithms are able to complete simple real-time navigation tasks. Sensors used in a confined environment can however be interfered with due to dust, weak textures among others. The data obtained can include noise and outliers, and the drift in positioning due to a long-running process is not easy to get rid of. A lack of robustness thus is one of the bottlenecks of stable operation. A

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review of LiDAR simultaneous localization and mapping (SLAM) technologies in global positioning system (GPS)-denied areas by Jiang et al. revealed that sparse features and dynamic confined scenes might severely deteriorate the stability of localization [1]. Liu et al. suggested the closely integrated GTS-SLAM system to overcome dust interference and darkness on underground inspection systems, which provides strong localization and dense mapping [2]. Cao et al. tested the open-source LiDAR SLAM algorithms on the basis of tunnel simulation benchmarks. Their findings revealed that localization errors may quickly build up in featureless confined settings and gave technical advice on the sound advancement of navigation research in the field [3].

There are two modules in this paper. The former is perceptual and localization in complicated confined settings. It initially surveys local-environment construction, which is established on LiDAR perception, and examines how the LiDAR data are manipulated into local maps that facilitate navigation. It then discusses practical localization schemes using multi-sensor fusion with the drawbacks of single sensors, and the concept on how multi-source information can enhance the reliability of localization.

The second module is on autonomous obstacle avoidance and robust navigation of inspection robots. It proposes real-time local obstacle-avoidance and motion-control algorithms, and then optimization policies to robust navigation in sensor interference and dynamic environmental variations. This organization explains the interrelationships between perception and mapping, localization, obstacle avoidance, and navigation.

2. Perception and localization in complex confined environments

2.1. LiDAR perception and local environment construction

Perception and localization are the basis of autonomous functioning in complex constrained spaces in the research of inspection-robots. In this module, LiDAR perception and local-environment construction are fundamental elements. Being common environmental perception sensors, 2D and 3D LiDAR systems may gather spatial data about the walls, equipment and obstacles. Once the raw sensor data have been processed and the sensor data are interpreted, local maps and environmental models can be created. The local environmental model should be constantly updated during the work of the robot based on real-time observations. The resultant environmental data forms a valuable foundation to further autonomous navigation and real-time obstacle avoidance.

There is 2D LiDAR which is utilized in existing studies in path planning and obstacle avoidance and 3D LiDAR which is utilized in constructing point-cloud maps of unknown confined spaces. Preliminary studies of reactive navigation suggest that sensor data has to be used to update local maps at high frequency and with high reliability. The entire technical chain involves measurement of the environment, extraction of obstacles and real time mapping that are utilized to generate usable navigation information.

In the case of 2D LiDAR, Ran et al. considered the current advances in research, on 2D LiDAR SLAM. They categorized the existing algorithms as filter-based, matching-based, graph-optimization-based, and deep-learning-based algorithms and compared the pros, cons, and situations when each type of algorithm could be used. The experiment showed that 2D LiDAR SLAM map could be used in path planning and avoiding obstacles, thus making it possible to use autonomous navigation in indoor settings. It also determined two key research directions: dynamic-object processing and LiDAR-vision fusion, and addressed the future development trends. This work is applicable to local-environment construction since it encompasses technical chain of environment measurement and obstacle extraction to real-time mapping and output of navigation-information [4].

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In the case of 3D LiDAR, Zhao et al. suggested a method that integrates the early fusion with the offset correction to overcome the perception error due to the poor spatiotemporal synchronization between cameras and LiDAR in inspection conditions. The paper generated a coarse-to-fine LIF-Seg network to LiDAR semantic segmentation. The method does not depend on the one-to-one correspondence between point clouds and image information, instead, it employs early fusion to take advantage of the image-context information and propose an offset-correction algorithm to align features across images and point clouds. The role of each module was confirmed by simulation experiments on the public nuScenes data, along with ablation studies. The technique alleviated the performance loss due to the sensor spatiotemporal synchronization bias and enhanced the semantic-segmentation accuracy of 3D LiDAR. It thus offers a practical implementation plan in multi-sensor fusion in the perception of the environment as well as LiDAR mapping on complex confined settings [5].

2.2. Multi-sensor fusion and reliable localization

In the case where robot localization is done with a single sensor, the system is susceptible to inherent sensor noise, measurement drift due to long operating period, and short term sensor failure due to interference with the environment. All these effects can render localization to be unstable and unreliable. The researchers thus combine the data of various sensing systems, such as an IMU, LiDAR, ultra-wideband systems and odometry to combine their distinct advantages and enhance localization performances. To illustrate, an IMU can deliver high frequency data on attitudes, however, over the long-term operation there is cumulative drift and therefore the external environmental measurements are needed to correct the errors.

Welch and Bishop described in some detail the mathematical algorithm of discrete Kalman filter and extended Kalman filter and provided a recursive least-squares estimation scheme. Their algorithms were demonstrated with the help of numerical simulations, which gave classical theoretical instruments of multi-sensor localization with the help of IMU, LiDAR, and other sensors. Kalman filtering is able to reduce cumulative IMU drift, combine multi-source measurements and make better robot position and attitude estimates. Fusion based on machine learning has also been actively researched and the two technical routes have varied benefits. The sensor system should also have a strong multi-sensor to ensure that abnormal sensor outputs are detected when there is an environmental interference and their impact on the final localization outcome is minimized [6]. Wei et al. introduced ground-constrained LiDAR odometry, an indoor ground-plane-based odometry that takes advantage of the indoor ground-plane features to stabilize pose estimation and remove vertical drift in GPS-denied constrained settings. This technique can be used along with an IMU to perform multi-source information fusion and enhance long-term localization accuracy [7]. Nevertheless, most of the current fusion schemes are proven in open indoor or outdoor flat-ground configurations and continue to be practically limited in confined inspection applications. LiDAR can experience missing returns in small areas with many obstacles and the cumulative IMU drift cannot be corrected entirely in long-term operation. Even one filtering framework can have difficulties in trade-offs between localization accuracy and real-time computational performance. Sensors can enhance robustness, but may add cost and computational expense, and may be hard to implement on small and medium-sized inspection robots with limited computing capabilities. Enhancing fusion algorithms with constraints on the scene and tradeoffs between localization accuracy and computations given finite hardware resources is hence a practical issue of concern.

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3. Autonomous obstacle avoidance and robust control of inspection robots

3.1. Local obstacle avoidance and real-time motion control

In autonomous navigation, the direction of motion of the inspection robots is determined by local obstacle avoidance in real time after the perception of environmental information. Safe operation in the dynamic and unknown conditions is thus important. DWA, TEB and artificial potential field methods are mainstream local obstacle-avoidance algorithms. These algorithms vary greatly in terms of their mechanism of operation and performance. The features of representative methods are discussed below.

Hu et al. suggested a better DWA algorithm with a new evaluation function to include the speed of movement, the direction of motion, and the distribution of pedestrians in space in the weights of the decision. The algorithm was tested using a simulation in an 18m x 18m scenario. The enhanced approach compared to traditional DWA reduced the robot trajectory and running time, enhanced the balance of local obstacle-avoidance decisions in dynamic and complex environments, and was more adaptable to dynamic obstacles. This research deals with the shortcoming of the single dimensional evaluation of the traditional DWA, and the quantitative comparisons show that it can enhance path length and run-time. It is thus a valuable source of information when it comes to assessing local obstacle-avoidance algorithms [8].

Another mainstream local obstacle-avoidance technique of inspection robots is the TEB algorithm. It solves a local cost map to tackle the path as a time-trajectory elastic deformation joint optimization problem to allow obstacle avoidance in real-time in unknown environments. Li et al. suggested a motion-planning framework that includes a better A star algorithm and a better TEB. The primary innovation that it has brought to TEB is the addition of a layered obstacle-handling mechanism. It was tested and confirmed in simulations and real-world experiments on the Robot Operating System platform, and made it 5.2% less, 11.5% less, and 66.7% less path inflection points on average path length, completion time, and path inflection points respectively. These findings suggest enhanced local obstacle-avoidance performance and smoothness of the pathways of multi-robot systems in dynamic settings. It is also experimentally supported in the paper within the configuration of the parameters and performance of TEB local planners when working with confined inspection scenarios [9].

To conclude, DWA uses velocity sampling to achieve the robot motion constraints, but TEB uses a local cost map to optimize the trajectories. The two algorithms have various benefits in the response speed and path smoothness.

3.2. Robust navigation under interference and environmental changes

Even in simple confined inspection problems, a single local planning algorithm may be susceptible to noise in perception and abrupt changes in the environment, and it may be hard to generate safe and consistent plans. Strong navigation plans are thus required to enhance the reliability of the whole system. There are primarily three types of perturbation namely sensor noise or anomalies, localization bias and environmental or obstacle changes. Outlier rejection, multi-sensor redundancy, real time map updating and local replanning are commonly used to ensure continuous navigation in existing studies.

In the multi-sensor fusion level, when abnormal observations are allowed to directly partake in fusion, reliability of pose estimation can be significantly decreased. Judgment based on threshold and associated approaches are hence frequently employed to sieve outliers and unusual

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measurements and preserve believable perception inputs. Fan and Zhe suggested a neural-prior-based perception reconstruction scheme to resolve sensor failure and poor information of perception. The technique rejuvenates and recovers environmental perception data during various disruptions and alleviates the deterioration of navigation-performance due to unnatural data. The rate of performance degradation when subjected to external interference in simulation experiments decreased to 82.74% to 8.84%, which offers a possible way of robust navigation in abnormal sensor conditions [10].

In terms of path planning, more demanding on algorithmic reaction to environmental changes is imposed by complex dynamic inspection situations. One planning algorithm might not be able to work efficiently with all the complicated operating conditions. Combination of real-time map updating and local replanning should then be implemented in a manner that faster handling of the updated obstacle information can be achieved. Bai et al. developed a coherent local risk-map framework which combines the perception uncertainty and dynamic-obstacle prediction. The framework would quickly update the map when the environment is changing, creating safe paths with local replanning, thus enhancing robot adaptability in dynamic cluttered environments [11].

Overall, LiDAR mapping and multi-sensor fusion can be used to localize the robot in a constrained environment, and algorithms like DWA and TEB can be used to plan the motion to avoid local obstacles. However, the effectiveness of the current technologies could deteriorate in case of environmental interference and sensor failures, and it is hard to adjust completely to the difficult situations of confined inspection. More refinement in control logic and fusion plans are thus needed.

4. Conclusion

The paper summarizes the studies of navigation and obstacle-avoidance technologies in inspection robots in complex confined spaces in two aspects, environmental perception and localization and autonomous obstacle avoidance and robust control. LiDAR SLAM applies point-cloud data to build confined scenario maps in the environmental perception. In tunnels, enclosed equipment rooms, and other constrained conditions and incomplete information environments, however, feature loss and abnormal point-cloud reflections may be commonplace. LiDAR by itself might not thus be capable of providing sufficient long-term localization accuracy. Common sensors that are proposed in existing literature include IMUs and odometry to combine multi-source information. Kalman filtering and associated algorithms are able to mitigate localization drift and partially overcome the shortcomings of LiDAR-only perception, but cumulative error can nonetheless impact localization in long-duration continuous operation.

DWA and TEB are two popular obstacle-avoidance algorithms applicable to inspection robots in case of local motion planning. DWA is a velocity-space sampling that is constrained by robot motion and the cost of computation is relatively low with high real time performance. TEB defines obstacle avoidance as a time-dependent trajectory-optimization problem, and is more fully developed to deal with dynamic obstacles. However, the two algorithms are limited when there are environmental disturbances. Planning oscillation and obstacle-avoidance failure can be experienced when sensor outputs have noisy values or when dynamic obstacles emerge.

In solving these issues, scholars have suggested solutions based on cost-function adjustment, extra constraints, and multi-coupling of information between sensors. In the case of DWA, the weight and the evaluation terms of the cost function can be optimized to enhance the choice of a trajectory in dynamic obstacles. In the case of TEB, the kinematic and continuity-of-trajectory to eliminate oscillation of the trajectory can be introduced and enhance resistance to interference. Most

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of the better algorithms, however, are tested in rather ideal conditions. Some optimization methods in practice have significantly greater computation requirements or are poorly hardware-adaptable, and cannot be easily applied on inspection-robot platforms with limited computing capabilities in real confined inspection environments with narrow apertures, sparse features, and a high number of disturbances.

Overall, existing research has established a theoretical foundation for inspection-robot navigation in confined environments. However, the balance among localization accuracy, robustness to dynamic disturbances, and computational overhead has not been fully resolved. Further research is therefore needed on navigation and obstacle-avoidance schemes that balance localization accuracy, real-time computational performance, and interference resistance in complex confined inspection scenarios. This provides a basis for subsequent algorithm design and simulation experiments.

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