The Research of Environment Perception based on the Cooperation of Multi-robot

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Abstract: The environment perception is the basis to the decision and planning of multi-robot system. It analyzed the latest progress of information fusion, the simultaneous localization and mapping (SLAM) which are the two key techniques. And it discussed the methods of information fusion and SLAM, and then concluded the advantages and disadvantages of these methods for the cooperative SLAM of multi-robot. Finally, the further research for CSLAM is raised.

Key Words: Environment Perception, Cooperative SLAM, SLAM, Information Fusion, Multiple Mobile Robots

1 Introduction

Multiple Mobile Robots system is group of the robot through the multi-agent organization structure, and to accomplish a common task[1]. Through the cooperation, robots system can complete to complete complex operation, can improve the robot system in process of efficiency, increase of the robot system capacity of adaptation, still can make the robot system solve more practical problems, to broaden the application way, but single robot difficult to do. Multi-robot system becomes the development trend of robot technology, and the cooperation of multiple mobile robots also becomes a hot topic[2-4]. Since the 1980s, the first multi-robot system based on the multi-intelligent (cellular robotic system, CEBOT) [5] set up in the world, Many significant progress has made on in theory and application of the multi-robot research[6].

Making a good decision and getting a good coordination controlling for Robots system, must rely on accurate and reliable environment perception. Localization is one of the most essential capabilities of multiple mobile robots[7]. In the localization problem of single robot, the location of the robot is inferred based on motion controls and measurements of relative information between the robot and a given map. In recent years, with the continuous development of various advanced sensing equipment, how to make full use of multiple robot sensing resources, and improve the precision and cooperative perceive ability, gradually become more and more attention for the researchers. But so far, the research of the cooperation perception of the robots system is not fully mature, especially for the dynamic and complex environment, the research is limited[8].

This paper will review the existing algorithms of SLAM firstly. Based on the review, the methods of environment perception of multi-robot are discussed in detail. Finally, the further research for CSLAM of the multiple mobile robots is raised.

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2 Environment Perception

During the working of the mobile robots, the general process of environment perception is depicted as in Fig.1.

Fig. 1: The general process of environment perception

The robots are not only to sense its own position, attitude, speed and internal state of monitoring system, at the same time, but must be able to sense their environment. It need to accurately describe everything in their environment, such as the pose information of the landmarks, obstacle. The making decision of the robot relies on the environment perception information, so the ability of the environment perception is the most key technology for the whole system. To get the environment information accurately and timely, it mainly depends on all kinds of sensor data on the robots and the processing of the data. With the development of various advanced sensing equipment and the necessary application software, robots have greatly expand the spatial awareness ability. But how to make full use of the sensor resource of the multiple robots, to improve the capacity of cooperative perceive precision, mainly involves the technologies including the information fusion and the Simultaneous Localization and Mapping (SLAM).

2.1 Information Fusion

Through the coordination perception to improve the ability of the environment perception has been the focus of the robot research. The single robot can load different kinds of sensing equipment, or each robot in the Multi-robot system can load different sensor, so as to obtain more rich information. Using the effective algorithm of information fusion, it can get relative complete environment perception
information from the incomplete, local, insure information obtained from the different sources of sensory equipment, so it can improve the abilities of information access and perception for the system. Information fusion includes different sensors information fusion of the single robot and the fusion of information from the different robot. For example the Aldebaran NAO robots in RoboCup Standard Platform League (SPL) competitions can get the local map of the single robot through the fusion the information form the onboard cameras and the odometer of the robot. And then each robot of the multi-robot system can get the global map through fusion the local maps from each robot. Therefore, the information fusion of multi-robot system include the technology of multi-sensor information fusion and image fusion, involving the difficulties of information representation, information matching, relevance and how to improve the processing speed.

Currently, there is some information fusion methods used for the same type sensors in multi-robot system, but there are few realized methods for the heterogeneity sensors information fusion. In [9] combined with visual sensor information and laser radar data modeling of multi-robot cooperation, achieving the heterogeneity multi-sensor fusion. In fact, there are different kinds of internal and external sensors on the mobile robots. Internal sensors are that is used to percept the position, pose of itself, mainly including measurement unit, the gyroscope, direction sensors, etc. The internal sensors are used to achieve the estimate of the robot. External sensor is used to get the information from external environment relative to the external object, such as the parameter of the robots distance and direction data, mainly including scanning laser sensors, ultrasonic sensors, compass and visual sensors. Sonar and laser sensor get the distance and confirm the feature points using the principle of the object reflection. When we need to identify the color of the object or the object is flat, sonar and laser sensors can’t get the feature point recognition and confirmation because there is no wave reflection. But the visual sensor has the advantages of bigger measurement range, collecting large amount of visual information and the low price, it can identify the characteristics of the target. Each sensor has its unique advantages, so it is necessary to have further research how to fuse the information which are from the different kinds of sensors.

2.2 Simultaneous Localization and Mapping

The achieving of environmental perception information for robot mainly includes building environment map, and at the same time using environment map to get its localization. Simultaneous Localization and Mapping (SLAM), is an extremely challenging open problem. SLAM involves a mobile robot building a spatial map of its environment and finding the self-localization in the partially built map. The problem is analogous to the chicken-egg situation; since, an accurate map cannot be built without knowing the ego-position, while, the position of self cannot be determined until it has a very accurate map [10]. SLAM involves the SLAM of underwater robots, the SLAM of air robots and the SLAM of surface robots. SLAM can be divided into the single robot system and the multi-robot system according to the number of ontology [11].

In recent years, with the environments are more complicated and unstructured of the robots, SLAM problem has already become the foundation of the mobile robot. In essence, SLAM should belong to the category of multiple source information fusion [12], but because of its importance, SLAM got more research. Through multiple robot co-location operation, the robots system can sign each other in unknown environment, and it can get more information and more accurate location than a single robot.

3 Methods for Implementation of Environment Perception

This part reviews the methods of the key technologies, information fusion and SLAM.

3.1 The Methods of Fusing Inertial and Visual Sensors

This area of research is quite useful as cameras and inertial sensors are inexpensive ways of extending current dead reckoning and simultaneously tracking the environment. There is an inherent problem with using any one sensor, and that is the accumulation of error. Inertial measurement, which includes the use of accelerometers and gyroscopes, is a prime example. Positioning using accelerometers requires the integration of sensor information twice after filtering, and the orientation requires a single integration. The noise from these sensors accumulates over time and results in incorrect position and orientation. Inertial measurement is very susceptible to drift, especially when stationary [13]. Vision sensors pose an almost opposite concern. When motion is slow and controlled, visual odometry is very accurate and does not introduce errors nearly as much as inertial systems do. However, visual sensors are limited when there are no visual features to track, or when the motion is too fast to track features. Similar to dead reckoning, visual odometry accumulates error over time. Nevertheless, it has been shown that visual odometry provides more accurate results than most sensor combinations when compared to dead reckoning [14]. Fusing the two systems is a natural solution for improving a positioning system.

Fusion of visual and inertial sensors has been performed by a few researchers. One of the earliest and most noteworthy approaches was done in [15]. The authors describe how stereo vision was fused with inertial information in order to recover 3D segments. This initial system as limited in the sense that it only used accelerometer data and only used vertical line segments for stereo features. However, this paper did not yield superb results, but it introduced the novel concept of fusing visual odometry and inertial navigation. After [15], other researchers attempted to fuse visual odometry and inertial measurement. Another, yet ineffectual, the approach used the information from a single camera to derive the odometry in the plane and fuse it with roll and pitch information derived from an on-board inertial measurement unit (IMU) to extend to 3D [16]. This approach used OpenCV’s implementation of Harris Corners with pyramidal Lukas-Kanade optical flow calculation of the concrete and asphalt surfaces. However, the technique proved to be very poor. Other researchers [17] used a modified linear Kalman filter to perform the data fusion, because it reduced drift over time. The state vector contained only inertial sensor errors related to position but...
no landmark information was tracked, thus no SLAM algorithms were performed. Biological systems naturally combine internally sensed motion with vision. Understanding the effect vision has on inertial perception in biological systems can give insights on how sensor fusion is done. In paper [18], the authors test and summarize various orientation experiments involving humans in moving rooms. Fusion of visual and inertial systems in robots would mimic this key biological technique. Understanding more about how accurate these internal sensors are may give some insight to what is possible.

3.2 The Methods of SLAM

Since Smith, Self and Cheeseman proposed SLAM problem [19], it has attracted more and more researcher to study SLAM, and there has been some methods of SLAM. In general, there are a large number of probability-based solutions to SLAM, including based on Kalman Filter (KF-based) approach, based on Particle Filter (PF-based) approach, and based on Maximized Likelihood Estimation (MLE-based) approach, all of which are derivations of Bayes rule. In addition, only a few based on non-probabilistic techniques, there are based set membership (SM-based) approach and the qualitative approach.

- KF-based approach

The most common approach to solving SLAM is based on Kalman Filter, which is the estimation-theoretic approach. From the point of view of Statistics, SLAM is a filter problem. It is to estimate the current state of the system according to the initial condition, the observation information and control information with the change of time from $0$ to $t$. In SLAM, the state of the system is expressed with the robot pose and the map information. Hypothesized the movement model and observation model is linear system with Gaussian noise and the state of the system obeyed the Gaussian distribution. SLAM can be use Kalman filter to achieve. The methods are including two steps: (1) predicting the state of the system; (2) updating the state; Of course, it also need to manage the map information, such as the sign of new features and delete the old features, etc.

This method provides a recursive solution to the navigation problem. In addition, it provides a means of computing estimates for the uncertainty in vehicle and map landmark locations based on statistical models for vehicle. This method provides a recursive solution to the navigation problem. In addition, it provides a means of computing estimates for the uncertainty in vehicle and map landmark locations based on statistical models for vehicle motion and relative landmark observations, which are all consistent with one another. Kalman Filter is used to linear system, but the movement model and observation model are non-linear in practice. Therefore, Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are proposed [20-21].

- PF-based approach

The approach involves the use of iconic landmark matching, global map registration, bounded regions, and other measures to describe uncertainty. Typically, this method uses a Bayesian approach to map building that does not assume Gaussian probability distributions, which are required by the Kalman filter. Examples of this style would be the Particle Filter, which uses brute force random combinations to determine probabilities. Particle filters provide another model estimation technique based on simulation. They are typically used to estimate Bayesian models and are much like an on-line version of a Markov chain Monte Carlo batch method [22]. Particle filters are often used as an alternative to the EKF or UKF. With sufficient samples, particle filters have the advantage of approaching the Bayesian optimal estimate and therefore can be more accurate than either the EKF or UKF [23]. The approaches can also be combined by using a version of the Kalman Filter as a proposal distribution for the particle filter. This approach uses a particle filter in which each particle carries an individual map of the environment [22]. This technique, while very effective for localization with respect to maps, does not lend itself to incremental SLAM solutions wherein a map is gradually built as information is received from sensors, instead several brute force possibilities exist.

- MLE-based approach

Like KF and PF, MLE is a general-purpose algorithm for estimation which has received the attention of the SLAM research community. In the light of MLE, this technique exploits the incomplete-data problem and offers an optimal solution, which makes it an ideal candidate for map building. However, this technique needs to process the same data repeatedly to obtain the most likely map. In other words, it does not perform efficiently and incrementally. Consequently, it is not a real-time algorithm and is unsuitable for online SLAM [24]. Practical applications employed an incremental MLE approach, one part of EM, to construct the map when the robot’s path is given by other techniques [25].

- SM-based approach

Apart from probabilistic approaches that are used to formulate SLAM uncertainty, SM estimation theory also tackles such uncertainty. In contrast to statistical assumption on uncertainty, e.g., correlation modeling in KF, SM imposes an assumption that uncertainty is bounded in norm by some quantity. Estimates of robot and landmark positions are defined by those regions where the robot and landmarks are guaranteed to lie, according to given information. These estimates of regions are termed feasible uncertainty sets [26].

- The qualitative approach

The qualitative approach filters observations using heuristics, and corrects the map and location using non-mathematical means. Using this method for navigation and the general SLAM problem has advantages over the probabilistic approaches, because it limits the need for accurate models. It requires less computation, and it uses an approach similar to that used by biological systems. For example, in buildings, a qualitative approach is to snap to hallways, or when driving, a qualitative approach is to ensure the car is on the road. Observations can be filtered by using facts about building size or robot size, and can help build the map.

Regarding the use of the Kalman filter approach, one research group [27] proved a few important points relevant to this discussion. Firstly, they proved that the determinant of any sub-matrix of the map covariance matrix decreases monotonically as observations are successively made. Secondly, they proved that, as the limit as the number of observations increases, the landmark estimates become fully correlated. The proofs in their paper indicate that the SLAM
problem’s entire structure hinges on maintaining complete knowledge of the cross-correlation between landmark estimates. As the vehicle progresses through the environment, errors in the estimates of any pair of landmarks always become more correlated. Eventually, the errors in the estimates of any pair of landmarks become fully correlated. Therefore, given the exact location of any one landmark, the location of any other landmark in the map can also be determined with absolute certainty. As the vehicle moves through the environment, taking observations of individual landmarks, the error in relative location estimates between different landmarks reduces monotonically until the map of relative locations is known with absolute precision.

Regardless of the aforementioned SLAM technique, SLAM can use any distinctive-environment feature that is specific to a particular area for location-based navigation [28]. Such features can be as simple as a table or a sound, or as complex as a magnetic abnormality or a painting on the wall. The key pitfall to SLAM is that, as the number of landmarks increases, the computation required at each step increases as a square of the number of landmarks. Required map storage increases as a square of the number of landmarks as well. The computational complexity associated with SLAM can be reduced by a piecewise approach of subdividing the landmarks and associations into smaller maps, as well as by reducing the observability and covariance matrix of the problem by making it more sparse [29]. Comparisons of these methods are tabulated in Table 1. From it, the inherent properties and natural advantages or disadvantages can be understood.

<table>
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<th>Title</th>
<th>Probabilistic</th>
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<th>Successful application</th>
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<td>Yes</td>
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</table>

### 3.3 The Methods of Cooperative SLAM

In recent years, cooperative SLAM has been a particularly popular topic within robotics because of the potential application of the multi-robot system. Co-operating robots can percept environment through sharing and exchanging the information each other, and it can improve the efficiency and accuracy.

For improving self-localization, Fox et al. [31] proposed a collaborative localization algorithm based on the histogram filter and the Particle Filter (PF) to utilize the measurements of relative information between team robots. Based on EKF, Roumeliotis and Bekey [32] proposed augmenting poses of team robots into one state vector and localize all robots simultaneously. Howard et al. [33] formulated the multiple robot localization problems as an optimization problem based on MLE. These works extended the localization problem from a single robot to multiple robots. In [34] proposed an observability-based methodology for designing consistent estimators in which the linearization points are selected to ensure a linearized system model with observable subspace of correct dimension. In particular, it propose two novel observability constrained (OC)-EKF estimators that are instances of this paradigm. SM-based SLAM can be extended reasonably well to multi-robot systems. The extensions are from more formulated measurement sets. These include measurements of inter-robots, and measurements between the robot and the landmark; uncertainty affecting the measurements between the robot and the landmark, and affecting the measurements of inter-robots and similar measurement sets for orientation. Di Marco et al. [35] reported an omnidirectional stereo system was equipped on the multi-robots, which SLAM using SM-based approach.

In the multi-robot SLAM problem, the single robot SLAM problem is reformulated in which the states of the team robots and the map are estimated concurrently. A number of algorithms based on different filtering techniques have been proposed to solve this problem [36-38]. In [39-40], the multi-robot SLAM problem was treated as a map merging problem. However, the environments are assumed to be static in these approaches which could fail in dynamic environments. Given correct moving object detection, the proposed cooperative localization and tracking approach directly deals with the non-static environment by explicitly considering the dynamics of robots and moving objects.

In [41], the relative information between a moving object and a static landmark in one captured image is utilized to track this moving object using a particle filter. Although this approach can theoretically separate localization and tracking as all measurements are related to the map directly, the coexistence of the map features and the moving objects in one image is needed. In [42], a moving object is used to localize and calibrate a sensor network. However, the sensor nodes are stationary. In [43], an approach let all robots operate individually and then tried to merge the different local grid map into a single global map. In [44] presents a practical point of multiple robot HAR-SLAM, where theoretical algorithms are rephrased into implementable versions. Cooperative SLAM with Landmark Promotion (LP-SLAM) consists of HAR-SLAM using Forgetful SLAM as a low-level sensor fusion, and incorporating visual features using LK-SURF.

### 4 Conclusion and Future Work

One of the advantages of SLAM is being able to map larger areas in parallel, making exploration more efficient if done correctly (such as trying to limit the time that robots spend exploring areas that other robots have already explored). For many years the research of environment perception Multi-robot has been much achievement, but cooperative perception poses specific challenges in the areas, such as each robot’s role, optimal cooperative coverage, control construction and communication methods all need to be addressed.

- Optimized the structure of multi-robot system
- More reasonable control construction and cooperative mechanism need to be developed for the efficiency of the system.
- Reasonable communication mechanism
How sing the limited bandwidth meet the system’s mutual information exchanging and sharing in real-time.

- Fusion of heterogeneous sensors
- Understanding the effect vision has on inertial perception in biological systems can give insights on how sensor fusion is done.
- Complex environmental perception
- For large-scale and complex environments, especially those requiring full 3D mapping, the cooperative SLAM problem is still an open research issue
- Strengthen the physical research

Most methods are only in simulation stage, and it must transplant the theory in practice. And how to design low cost multi-robot system is a challenge for the designer.

References


