論 文 の 内 容 の 要 旨

論文題目　Evaluation and Quantification of Digital Map Capability for Vehicle Self-Localization

（自車位置推定のためのディジタル地図性能の評価と定量化に関する研究）

氏　　名　　ジャワンマーディ　エッサン

The autonomous vehicles (AV) have gained a focus as an essential technology within intelligent transportation systems since their introduction in the early 1950s. Since then, many attempts have been made to bring this intelligent vehicle on the roads fully or partially to benefit from its capabilities. In order to make this technology work in the real-world conditions as well as the controlled environment in laboratories, researchers have encountered many challenges. One of these challenges is accurate vehicle self-localization.

Accurate and robust self-localization is an essential task for AVs. On the other hand, high precision self-localization solution when combined with a prebuilt map can simplify the difficult concept of perception and scene-understanding into a less complex positioning problem. Conventional approaches use global navigation satellite system (GNSS) for autonomous vehicle self-localization. This technology is low cost and works very well in the open sky. However, in the urban environment, the accuracy degrades dramatically due to non-line of sight (NLOS) and multipath reception of the satellites’ signals and make it difficult for an AV application.

In recent years, use of light detection and ranging (LiDAR) for the perception of AVs become more popular due to its price down, miniaturization and density enhancement. Compared to cameras, LiDARs are more reliable because problems caused by illumination change, light conditions and shadows do not affect them. On the other hand, LiDARs can obtain more accurate distance information comparing to the stereo cameras which make them more suitable for the self-localization applications. LiDAR-based localization can be divided into two main categories. Map-based and without a map which is also known as simultaneous localization and mapping (SLAM). In the SLAM methods, there is no prebuilt map. Based on the current position, the surrounding information is stored online as a map. In next time stamp, this stored map (information) are used to calculate the displacement of the vehicle. According to this displacement, the current position of the vehicle is calculated, and again the surrounding information is stored as a map to be used of next time stamp. SLAM methods work well over a short distance; however, due to its dependent nature, they are still suffering from accumulative error in long distances.

Therefore, in recent years, map-based methods have gained more attention in most of the AV platforms. In a map-based method, a raw point cloud of the environment is collected offline using high-end mobile mapping systems (MMSs). Then, based on the map formats, the map is generated from raw point cloud data. Later, in the self-localization phase, the scan acquired from LiDAR mounted on the top of the vehicle is matched to the map to obtain the position of the vehicle within the map. In map-matching based self-localization, as each sequence are independent, there is no error accumulation.

In this dissertation, the focus is made on the map based self-localization methods and several contributions have been made.

In the map based categories, map plays a significant role in achieving high accuracy self-localization. For accurate self-localization, the global and local accuracy of the map is essential as well, and many types of research have been done to obtain such a highly accurate map. Strategic Innovation Promotion Program (SIP) has defined the required global accuracy of map for autonomous driving to be less than 25cm. This requirement comes from the satellite image resolution and vehicle’s tier width. There is a misunderstanding that if the map is accurate, then the localization within the map will be accurate as well. In fact the highly accurate map does not guarantee the accuracy of the localization. In other words, map accuracy is different than the ability of the map for localization. For example, in the case of the tunnel, no matter how much the map is locally and globally accurate, the lack of longitudinal features in the map causes localization error in the moving direction. To achieve accurate self-localization within a map, the map should satisfy some requirements. In other words, the map should meet some specific criteria which define the ability of the map for self-localization. To the best of this author’s knowledge, there is no comprehensive study of the definition and formulation of these criteria. Therefore in this dissertation, for the first time, the required criteria regarding the ability of the map for accurate self-localization are defined and formulated.

Some of these criteria highly related to the environment and as surrounding environments are different from place to place in the map, it should be evaluated by defined criteria. And some other criteria are related to the quality of representation of the environment by the map. In addition to the sensor related parameters in the mapping phase such as frequency of laser scanner, layer count, the range of the beam, setup parameters, etc., quality of representation highly related to the format and abstraction ratio (resolution) of the map. Quality of representation of the environment in each of the map formats is different. In other words, some map formats discard more details of the map comparing to the others. This information loss of the map might change the quality of some of the criteria and lead to a localization error.

However, in some part of the map, abstraction does not necessarily change the quality of the map, or rate of change is acceptable. Additionally, in some cases, other criteria might compensate the lack in one criterion. Therefore, in order to evaluate the self-localization ability of the map at a specific point, all criteria should be considered together.

In this dissertation, four general criteria for the map are defined. These criteria are feature sufficiency, layout, representation quality, and local similarity of the map. These criteria are defined regardless of the map format and can be applied to any other map formats. However, in this work, to quantify each of these criteria, the focus is made on the ND map format, and several factors are defined. For each point in the map, these factors are calculated based on the features in surroundings called local vicinity. By obtaining the correlation of the map factors with localization error, the effectiveness of the factors is investigated. Additionally, by applying principal component regression (PCR), the predictability of the self-localization error based on these factors are investigated. To evaluate the predictability of the defined factors, experiments have been conducted in Shinjuku, Tokyo, Japan. The route of experiments is around 40Km. The experimental results show the error modeled from the factors can represent the localization error of the map in 71% of cases with an error lower than 10cm. In order to increase the accuracy of prediction, the factors are fed to a simple feedforward neural network to model the error. The result is improved and around 78% of the localization error can be modeled with lower than 10cm accuracy.

The outcome of the proposed map evaluation framework can be used for evaluating the map before its use for localization. Also the results of this study can be used for evaluation of the map which is not made specifically for the self-localization purpose.

As the other contribution of this dissertation, the outcome of the map evaluation framework is used for adaptive determination of the map and localization parameters. These parameters are map resolution and range of the laser scanner. Basically lower map resolution is more desirable as it can save the computation time and memory size, but it might remove some important information for localization. In order to determine the best resolution of the map, the map is evaluated for different resolution using map evaluation factors and the optimum resolution is selected. On the other hand, the range of the laser scanner is an important parameter for reducing the matching time. This parameter can be determined adaptively based on the quality and quantity of the features in the surroundings and stored in the map beforehand. In this dissertation, the adaptive determination of the laser range is proposed which uses the map evaluation factors to define the optimum laser range for different part of the map.

In addition to the aforementioned contributions, globally accurate urban mobile mapping frameworks are proposed. One of the challenges of current Mobile Mapping Systems (MMS) is their precision, accuracy and the cost. In order to get required accuracy in the urban area, current MMSs, first converge their position system in non-urban area which takes more than 10 minutes and then traverse through the urban area. And after few kilometers the positioning system needs to be re-converged in non-urban area. This process is so much labor and time intensive. Even with this, the generated map has around a meter of error. Therefore in order to remove this error post-calibration with labor-intensive Global Control Point (GCP) is performed which collection of GCP and post-calibration task costs around 10 million yen for each square kilometers for the companies.

In order to remove this cost, in the proposed urban mapping frameworks, two laser scanner is used in addition to the Inertial measurement unit (IMU), odometer, and GPS. One laser scanner is used to perform the simultaneous localization and mapping and the other is tilted downward to capture the environments as point cloud map. The airborne image is used as a reference to correct the trajectory of the vehicle. In order to correct the trajectory of the mapping vehicle, the lane markings extracted from tilted laser scanner is registered to the lane marking extracted from the airborne image. The map which is used for this dissertation is all made by this mapping system and global accuracy of the map is very high.

In this dissertation, two self-localization methods based on abstract map format which are multilayered vector map and the probabilistic planar surface map are proposed as well. One of the huge disadvantage of the map based methods are map size. For a small area, for instance 300m to 300m, around 250 million points should be stored to the autonomous vehicle storage system. On the other hand, the matching algorithm requires high computational time to deal with this data size. In the multilayered 2D vector map, different layers of building footprints are stored as a vector in the map. By using different layers of the building, the feature for matching increases and make the matching more accurate. For each vector, the variance of the points are stored in the map to allow the localization process to rely on more certain vectors rather than an uncertain one. This can reduce the map size to several thousand times. In the probabilistic planar surface map, instead of using heavy point cloud, the planar surfaces are extracted from the point cloud map. Each planar surface contains the variance of the points which shows the uncertainty of the planes. Storing the variance for each plane help the localization process to rely more on the certain walls. In the matching phase, distortion of the input scan is one of the challenges which makes the misalignment of the input scan to the map. In this work, distortion is removed in the optimization process. In fact, in each iteration of the optimization, the scan is reshaped by the new results and the distortion is removed to fit better to the map.

This dissertation also includes an overview of the state of the art localization methods, and also a discussion about the different source of the error in self-localization based on map-matching.