論文 / 著書情報
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題目(和文)	統計的依存性を利用した移動ロボットのナビゲーション
Title(English)	Mobile Robot Navigation Using Statistical Dependence
著者(和文)	入江清
Author(English)	Kiyoshi Irie
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（博士課程）
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論 文 要 旨

THESIS SUMMARY

専攻： Department of	計算工学　　　　専攻	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of　（ 工学 ）
学生氏名： Student's Name	入江 清	指導教員（主）： Academic Advisor(main)	小池 英樹　教授
		指導教員（副）： Academic Advisor(sub)	杉山 将　特定教授

要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Navigation is an important capability for mobile robots and has a variety of application such as autonomous driving vehicles and service tasks. Although we humans perform navigation daily and easily, no robot has been developed yet that can arbitrarily navigate in unrehearsed, complex real environments. For example, to operate current navigation systems, we firstly need to construct a detailed map of the target environment by manually navigating the robot and collecting data.

This thesis is devoted to extending robots' navigation ability aiming to realize navigation in unrehearsed environments. We have found that statistical dependence is a promising tool for the problem. We explored applications of statistical dependence to unresolved navigation issues and developed two new methods of: a) street-map-based localization and b) target-less multi-modal sensor extrinsic calibration.

First, we consider the problem of localization based on a 2D street map. Localization, a process of estimating the position and orientation of a mobile robot with respect to a map, is one of the essential aspects of navigation. The current state-of-the-art methods localize a robot on a detailed 3D map, which is typically constructed by a simultaneous localization and mapping (SLAM) technique. However, the construction cost of such a map dedicated to robot increases rapidly as the expansion of the target environment. We aim to overcome the problem by reusing 2D street maps that people use daily. One of the major challenges in using 2D street maps is finding the correct correspondence in completely different information, that is, the map and sensor data collected by the robot.

We propose a novel localization method, dependence maximization localization, which is inspired by multi-modal image registration. The localization problem is formulated as registration between sensor data and the map. Registration is performed through maximization of statistical dependence measured by least-squares mutual information (LSMI).

We also applied our method to a position tracking problem (i.e., time-series localization of a moving robot). A particle filter that fuses the robot's motion estimation and observation is employed. In the update step of the particle filter, we compute LSMI between sensor data and the map for each particle. The particles are then weighted and resampled according to the LSMI values.

Extensive experiments were conducted using data sets collected in real urban environments, and we empirically found out that LSMI exhibits superior performance among several dependence estimators. Successful results obtained for long distance (up to 4.5 km) position tracking experiments support the efficacy of the proposed method.

Second, we consider the problem of extrinsic calibration (identifying the relative pose) between multi-modal sensors. In the localization experiments mentioned above, a combination of a camera and a light detection and ranging (LiDAR) sensor is employed. Such a sensor combination is a popular means of acquiring colored point clouds and widely used for outdoor mobile robots. Automatic recalibration of the sensors is important for maintaining the quality of the colored points because the sensor configurations can change over time. Conventional calibration methods employ special calibration targets such as a board with a checker pattern; however, relying on such a calibration target can hinder the automation of the calibration process. Therefore, calibration in natural scenes (so-called target-less calibration) is receiving increasing interest from the robotics community.

We propose a novel method for target-less extrinsic calibration between a camera and a LiDAR. Although there exist several calibration methods of the same purpose using statistical dependence, they are found to perform poorly under strong sunlight. The cause of the problem was that the employed features and dependence estimators were susceptible to noise; the objective functions employed in the previous methods become non-smooth on noisy data and make gradient-based search ineffective. Using richer features is necessary to overcome the problem; however, the dependence estimators employed in the previous methods are not capable of handling high-dimensional features. Therefore, we develop a novel dependence estimator, bagged least-squares mutual information (BLSMI), which can robustly estimate dependence of high-dimensional data.

BLSMI is a combination of bootstrap aggregating (bagging) and LSMI which is a kernel-based, robust dependence estimator. It is demonstrated that the combination provides highly smooth objective function even on noisy data. We tested our method using real-world data sets collected in both indoor and outdoor environments. Our proposed method outperformed existing methods in terms of calibration accuracy. The advantage of our method in accuracy was particularly significant on outdoor data sets.

We conclude that these successful applications of statistical dependence form a significant contribution to the study of mobile robot navigation and worth a further study in the future.