Performance Improvement of Outdoor Localization Using Elevation Moment of Inertia (EMOI)

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Abstract: This research proposes a novel approach to outdoor localization based on map matching. The main map for localization is an elevation map which is a grid map with elevation information on each cell. This research presents an elevation moment of inertia (EMOI) which represents the distribution of elevation around a robot in the elevation map. A robot continues to build a local elevation map using a laser sensor and calculates its EMOI. This EMOI is then compared with the EMOIs for all cells of the given reference elevation map to find a robot pose with respect to the reference map. The experimental results of particle filter-based localization show that the proposed EMOI-based approach can be successfully used for outdoor localization with an elevation map.

Keywords: Outdoor Localization, Monte Carlo Localization, Elevation Map.

I. INTRODUCTION

Localization is one of the most important techniques for mobile robot navigation in the indoor and outdoor environments, and various types of maps such as a grid map, elevation map, topological map, and so on, can be exploited for localization. A 2D grid map is the efficient and sufficient map when a robot navigates in the indoor environment with a range sensor. In this case, the motion of a robot can be expressed by 3 degrees of freedom (x, y, θ) in 2D space. However, outdoor navigation usually requires the estimation of 6 DOF motion (x, y, z, roll ψ, pitch θ, yaw φ) in 3D space, and therefore the environment should be represented by a 3D map for localization.

An elevation map is the most popular map to represent 3D outdoor environment. In this map, the environment is regularly divided into small cells, say, 0.1m*0.1m, and each cell has height information. An accurate elevation map can be generated using the airplane mapping system equipped with both a GPS/INS for localization and a lidar sensor for range data acquisition. This type of map is suitable for large outdoor environment and used as a main map for special applications such as military robots. In this research, an elevation map is used as a main map for localization.

Research in city modeling using DSM (digital surface map) has been conducted in Fruh [1]. DSM is used as a reference elevation map and a vehicle pose with respect to the DSM is estimated through the MCL (Monte Carlo localization) method. The range data obtained by a laser scanner is compared with that predicted from the DSM to estimate a vehicle pose. The path generated by MCL is very accurate without error accumulation even after traveling more than 10km because it estimates a pose with respect to the reference map. However, it takes very long to generate the path because of high computational complexity.

The concept of moment of inertia is widely exploited in various fields. 2D/3D object recognition is an example to use the moment of inertia in Laga [2] and Ohbuchi [3]. The characteristics of various 3D objects are defined according to the surface moment of inertia which represents the distribution of surface about three principal axes. By comparing the moment of inertia of the unknown model with those of the known models in the database, the most similar model could be found.

This research proposes the elevation moment of inertia (EMOI) which is used for matching of elevation maps to find a robot pose with respect to the pre-given elevation map. The EMOI quantifies the distribution of elevation using the concept of moment of inertia. Then the similarity between the reference map and the locally built map is evaluated using the EMOI. A particle filter is used for localization, and the probability of each particle is updated using the results of similarity comparison. Since probability update based on EMOI is simple and fast, the robot pose can be found globally without knowledge of the initial position in the large outdoor environment.

II. ELEVATION MAP BUILDING

Figure 1 shows the experimental setup consisting of a Pioneer 3AT mobile robot and a SICK laser scanner. This laser scanner senses the environment within 32 m and is tilted from -45° to 45° by a DC motor. The absolute roll and pitch angles of a robot are sensed by the IMU (inertial measurement unit), and the yaw angle and small motion increments are sensed by both the wheel encoder and IMU. Combining these data allows the estimation of the 6 DOF motion in the global coordinate frame in Lacrois [4].

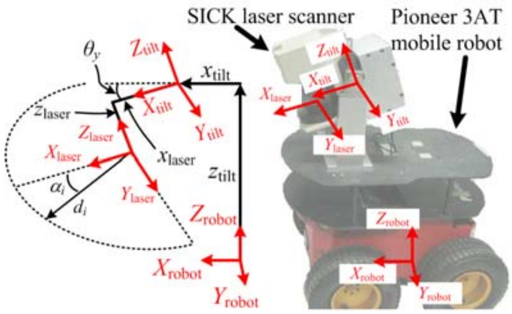

Fig. 1. Experimental setup and local coordinate frames.

An obstacle is sensed by a tilted laser scanner, and its elevation can be calculated based on a 6 DOF robot pose. The elevation of each cell is updated when it is sensed as follows.

$$e_t(i,j) = \begin{cases} z_t(i,j), & \text{if } z_t(i,j) > e_{t-1}(i,j) \\ e_{t-1}(i,j), & \text{otherwise.} \end{cases} \quad (1)$$

where $e_t(i,j)$ is the elevation of cell (i,j) at time t, and $z_t(i,j)$ is the sensed elevation of cell (i,j). If the newly sensed elevation of cell (i,j) is higher than the previous elevation, the elevation of cell (i,j) is replaced by this new elevation. This is a simple and common method for building of an elevation map. Figure 2 shows an example of the environment under consideration and its elevation map.

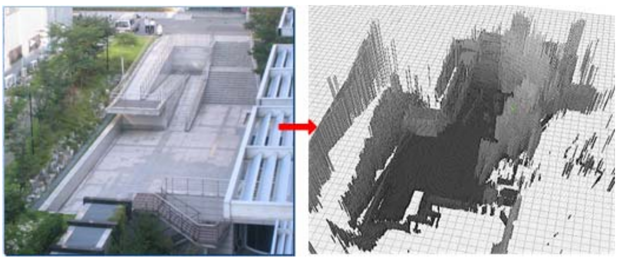

Fig. 2. Example of elevation map.

III. ELEVATION MOMENT OF INERTIA

The elevation and distance are the most important information when the elevation map is adopted as a model for the environment. These two properties, therefore, should be combined to design a new feature for elevation map matching. In this research, we propose an elevation moment of inertia. It means the distribution of elevation along the distance from a certain position of interest, as shown in Fig. 3. EMOI is calculated using the elevation values of all cells within a circular region of radius R. The EMOI calculation is not affected by the orientation of a robot, which makes the matching process simple and fast. The reference elevation of an elevation map is not fixed. For example, the elevation can be calculated with respect to a sea level, start position, and so on. Therefore, the difference in elevation, Δe, from the center of the region is exploited, and the EMOI is defined as follows.

$$\text{EMOI}(x,y) = \int r^2 de, \ \text{for } r \le R \quad (2)$$

where (x,y) represents the center of the region at which the EMOI is calculated, r is the distance from the center to a certain cell of which the elevation difference is Δe, and R represents the radius of the region of interest. In this research, (2) is implemented in a real elevation map as follows.

$$\begin{aligned} \text{EMOI}(i,j) &= \frac{1}{n}\sum_{k=1}^{n} r_k^{\,2}\Delta e_k \\ &= \frac{1}{n}\sum_{p=i-R'}^{i+R'}\sum_{q=j-R'}^{j+R'}[(p-i)^2+(q-j)^2][e(p,q)-e(i,j)], \quad (3) \\ &\text{for } \sqrt{(p-i)^2+(q-j)^2} < R' \end{aligned}$$

where (i,j) represents the cell at which the EMOI is calculated, $e(i,j)$ is the elevation of cell (i,j) updated by (1), and n is the number of cells within the circular region of interest. R' is the radius of the region expressed in the unit of grids. For example, if the size of a cell is 0.1 m * 0.1 m, then 10 cells exist along a distance of 1m, and thus R' is a rounded value of $(10*R)$. The term $\sqrt{(p-i)^2+(q-j)^2}$ is the distance from cell (i,j) to cell (p,q) and if this distance is less than R', cell (p,q) is within the region of interest and it is used for EMOI calculation. If the cell size is changed, the number of cells used for EMOI calculation is also changed and it affects the EMOI values. To eliminate this effect, the result is averaged by division of *n*.

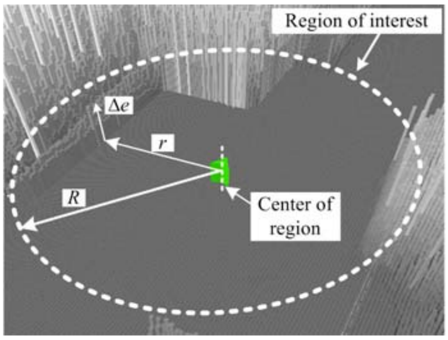

Fig. 3. Concept of elevation moment of inertia (EMOI)

Figure 4(a) shows the elevation map of the experimental environment of 90 m * 70 m in size. Figure 4(b), (c), and (d) represent EMOIs of all cells with several values of *R*. The size of a cell is 0.1 m * 0.1 m and the resolution of elevation is 0.1m. A high EMOI means that the distribution of elevation within the region of interest changes substantially and is not uniform. If the reference elevation map is given for localization, the EMOIs of all cells can be calculated in advance, as shown in Fig. 4, and it makes the matching process very fast.

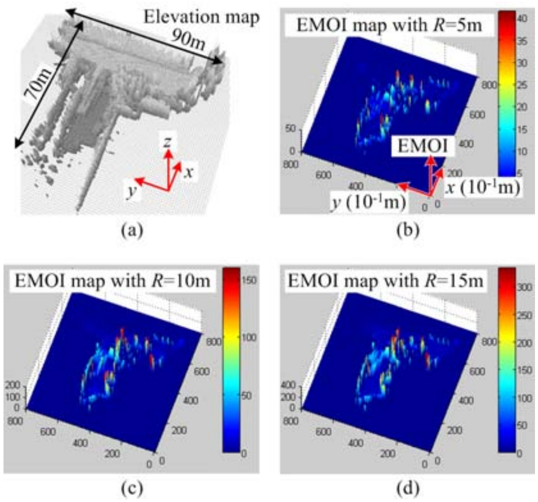

Fig. 4. EMOI calculated from all grids of elevation map with *R* = 5, 10, 15 m.

IV. EXPERIMENTAL RESULTS IN OUTDOOR LOCALIZATION

A particle filter is used for localization in this research. A particle filter is one of the popular Bayesian filters that can track the distribution of probability using a set of particles. At each time step, the probabilities of particles are updated using a motion model and a sensor model, and then the particles are re-sampled. The state, a robot pose in this case, is represented by the weighted sum of all particles. More detail on particle filter-based localization can be referred to Thrun [5].

In this research, the EMOI is used as an observation. To calculate the EMOI using sensor data, the local elevation map is generated as shown in Fig. 5 by the mapping method described in Section 2. As a robot continues to move around, it senses the environment more and more. Suppose a robot moves forward about 5 m. Then a circular region with a radius of 5 m around a robot can be mapped sufficiently. The EMOI with *R* = 5, therefore, can be calculated from this local elevation map, and the probabilities of particles are updated using a sensor model. Then, the local elevation map is erased and a new elevation map is built again to calculate the EMOI at a different location. If the value of *R* for EMOI calculation is small, an update by a sensor model is frequently executed. However, the EMOI of cells may be almost uniform in some environments because the region of interest for the EMOI is small and only a few obstacles may be within that region. If *R* for EMOI calculation is large, many obstacles are considered in calculating the EMOI, but an update by EMOI is executed less frequently. Therefore, different values of *R* can be exploited according to the environmental characteristics.

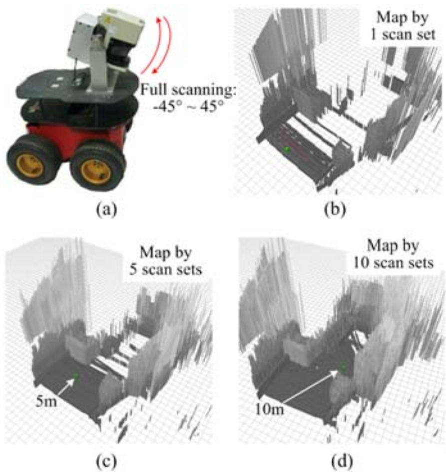

Fig. 5. Building of local elevation map with different scan sets.

Figure 6 shows the experimental results of particle filter-based localization using the EMOI. The outdoor environment is 70 m * 90 m in size and 20,000 particles are used to find a robot pose globally with respect to the reference map. The EMOI is computed for R = 5 m and thus the probabilities of all particles are updated about every 5 m. During localization, a robot moves at a speed of 0.3 m/s and all processes run in real-time on a Dual Core 1.7 GHz notebook. Figure 7 shows the number of particles and standard deviation of particle positions as a function of travel distance. Though a robot pose is estimated by correct particles in Fig. 6(e) and (f), they converge and diverge slightly depending on the nearby environment.

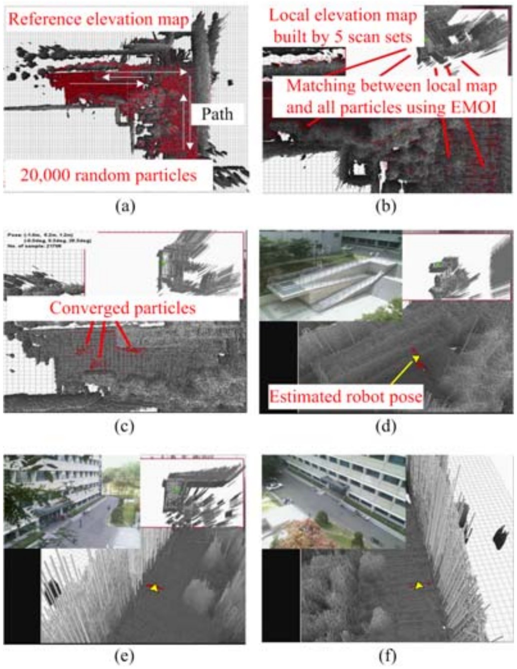

Fig. 6. Experimental results of particle filter-based localization using EMOI in outdoor environment.

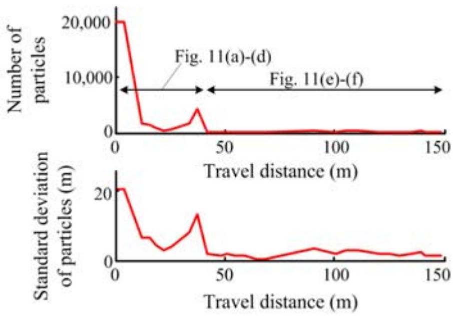

Fig. 7. Number of particles and standard deviation of particle positions.

V. CONCLUSION

This paper describes a localization scheme with an elevation map in the outdoor environment. To find a robot pose, a local map built by the range sensor is compared with the entire reference elevation map. To this end, a new feature for elevation map matching was proposed based on the concept of moment of inertia. The characteristics and performance of the proposed feature, EMOI, were verified by a series of experiments. From this research, the following conclusions have been drawn.

1. The proposed EMOI applies the concept of moment of inertia to elevation map matching. Each position has its own EMOI, and the EMOI can be exploited as a feature for finding a position.
2. The probabilities of all particles in the particle filter can be updated by the EMOI, and a robot pose can be estimated in real time during movement in the large outdoor environment.

The EMOI is a scalar value and the whole distribution of elevation in a certain region is compressed into this scalar value. It can make local tracking inaccurate as well as simple and fast. The local peak near the travel distance of 40 m in Fig. 7 occurred because of this situation. This is a weak point of this proposed localization scheme using EMOI, and the research on improving the performance of local tracking is under way.

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