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Satellite Image based Topological Map Building Method for Intelligent Mobile Robots

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Abstract— **This paper presents an efficient method for building a topological map for robots in urban environments based on satellite image maps acquired from a geographic information system (GIS). In urban space, mobile robots need a special map, such as a topological map, to generate a path toward their goal. A topological map for mobile robot navigation should include semantic data, e.g., the width and type of road. We divide the satellite image based topological map building process into two steps. The first step is defining the topological map model to fit the mobile robot navigation in an urban environment. The second step is generating a topological map from existing satellite image maps downloaded from the GIS to reduce the cost and improve the accuracy in building the map. If a GIS-based topological map is constructed once, it is possible to use the map for the navigation of various robots as common spatial data. To validate the proposed mapping method, we show details of its implementation in map building as well as in a navigation experiment in real outdoor environments, such as a campus or city district.**

I. Introduction

As the capabilities of robot develop and the fields to which robots can be applied expand, the importance of robot mobility increases [1]. In particular, unlike general industrial robots, mobility is becoming inevitable for personal/professional service robots. These robots need proper information regarding their environment, called a ‘robot map’, to accomplish their assigned tasks. A robot map is used to localize the positions of other robots, targets, and obstacles that might interrupt their movements. The positions of objects are stored in the form of a map by using sensor data and a mapping algorithm [2], [3].

Map models used in mobile robot applications can be divided into two main types: vector- and raster-based models. In a vector model, objects are represented with points, lines, and polygons, and each object is considered to have different properties. In this model, boundary information is important, and the inner part of an object is meaningless. Thus, the size of the map data does not increase significantly as the environment is expanded. DXF, topological maps [4], and feature maps [5] are examples of vector models.

In contrast, a raster model divides a space into grids or cells of equal size, and the existence of objects is presented through the values of the grids. Thus, spatial information is represented very well in this model. The size of the map, however, can be big for a large spatial environment because detailed information of all objects should be represented. The grid map, which was first introduced by Moravec and Elfes [6], is a representative example of a raster model, and is frequently used for indoor robot applications.

Recently, attempts to deploy mobile robots for outdoor applications are increasing due to the advancement in outdoor positioning technology, which is mainly contributed to by the use of a Global Positioning System (GPS). GPS offers absolute global position information, which is sufficient for outdoor navigation of mobile robots. The Urban Challenge sponsored by the Defense Advanced Research Projects Agency (DARPA) [7], and the Tsukuba Challenge held in Tsukuba University [8], are examples of applications that rely on GPS information for outdoor navigation of mobile robots. In addition, unmanned ground vehicles (UGVs) are also target applications that can make use of the technology suggested in this paper.

The outdoor navigation of mobile robots has some special issues. First, the robot navigates in a large-scale environment due to the nature of the outdoors. This implies that if a robot uses a map based on a raster model, the computational resources and processes may be overloaded due to the large size of the map data. From this point of view, a map based on a vector model is more suitable for outdoor applications. Second, in almost all cases except a few special situations, robots navigate only in specified regions such as roads. This means that the constraints for robot operation can be greatly reduced. The third issue is regarding the precision of the map provided to the robot for localization. This is due to the scale of the operating region of the robot, and thus a robot can guarantee a certain level of performance using a localization sensor such as a GPS, which has a comparatively large error bound.

Based on the considerations mentioned above, the topological map is the most suitable map type for the outdoor navigation of mobile robots. In a topological map, a space is represented as linked nodes. Thus, the spatial information is acquired by interpreting the connectivity information between nodes. The region of interest is presented as a node, and the link is considered as the road and is used for generating the path.

The map used for car navigation is the best example of a topological map. However, it is difficult for mobile robots to directly use the topological map produced for car navigation outdoors. The most different aspect between car

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and robot navigation is the control. For car navigation, a human driver has the intelligence to control a car based on his/her perception and decision-making ability. In contrast to car navigation, a mobile robot only has artificial intelligence, which is obviously far from perfect compared to human intelligence. Moreover, the performance of artificial intelligence in mobile robots depends on its sensors, which suffer from noises and disturbances, resulting in a low cognition and decision ability. Therefore, a map should provide some additional important information for the robot to achieve autonomous navigation. In addition, we should define the form of the topological map so that it is applicable to any kind of mobile robot with various types of sensors. The robot map should be widely accepted for use in any kind of mobile robot. In this paper, we used a geographic information system (GIS) based on satellite images worldwide [9], [10] to make a topological map. Using the satellite images, it is easy to gather geometric data and road information for the targeted outdoor environment.

The information in this paper is presented as follows. In section II, the topological map model is defined. The method used to make a topological map with the satellite images is presented in section III. In section IV, an experiment used to evaluate the map suggested in this paper is described. Finally, section V offers some concluding remarks.

II. Topological Map Model

A. Requirements of Topological Map

This section presents an explanation of map arrangement for mobile robots in an urban environment. We focus on four key requirements to define the form of a topological map.

1) Representation in a large-scale environment: In a real implementation, memory allocation and computational resources depend on the space representation and its properties. Indeed, complex representation and multiple properties demand a lot of memory allocation and computation. This gets worse if the size of the environment is large, such as an outdoor area. Therefore, mobile robots should use a compact GIS to reduce these burdens. For example, the representation of geometric entities in two-dimensional planes should not include height data for all the nodes used in generating a path.

2) Extensibility for supporting various robots: A topological map has been used for various robots, providing specific services such as transportation, delivery, and guidance. Some data will be inserted or deleted in the topological map according to the type of services it applies to. From this point of view, as the topological map format, we choose eXtensible Markup Language (XML), which is a set of rules for encoding documents produced by W3C. Working with a topological map constructed based on XML will be easy for many kinds of mobile robot navigation systems because some XML parsers or loaders support functions with insert, update, delete, and query capabilities.

3) Human compatibility: A map should offer system functions where human-robot interactions are expected. Therefore, a map model accepting semantic information will be more suitable for interfacing with humans. However, a topological map representing the locations and relations of nodes cannot display the robot status or send control commands to the robot. It is a good idea for GIS information, such as the satellite images correlated with the topological map, to be provided to the application. This can be used as a powerful interface to solve the issue, especially in outdoor environments like urban areas.

4) Accuracy: Topological map errors come from the performance of the mapping method and sensors. To reduce topological map errors, we have set up the origin point area where we can get precise GPS data. The measurement should be conducted at the origin for a few minutes. The parameters consisting of probabilistically based longitude and latitude data should be calculated. The parameterized origin locations of these methods should improve the accuracy positions of the nodes on the topological map beyond the mapping method and sensor technological limitation.

B. Topological Map Description

Topological map M is defined as two parts consisting of $Origin$ and $Segments$ in (1).

$$M = \{Origin, Segments\} \tag{1}$$

$Origin$ is the basic information required to build a topological map based on GIS, such as $Mapsize$, $Offset$, and GPS geo-location at the origin in (2).

$$Origin = \{Mapsize, Offset, GPS\} \tag{2}$$

$Mapsize$ includes information regarding the $width$, $height$, and $pixel\_size$ of the satellite image extracted from GIS in (3). $pixel\_size$ indicates the scale factor from the pixel domain to the metric domain.

$$Mapsize = \{width, height, pixel\_size\} \tag{3}$$

An $Offset$ is defined as the translation and rotation offsets of the origin point with respect to the left-bottom area of a satellite image. $Offset$ consists of x, y, and θ offsets in (4).

$$Offset = \{x, y, \theta\} \tag{4}$$

Mobile robots are equipped with many useful localization devices such as encoders, gyroscopes, inertial measurement units (IMUs), cameras, and so on, which measure their relative movements based on the metric domain. However, a GPS sensor, which is the most widely used sensor for localization systems in outdoor environments, provides robot position data based on the geodetic domain. Therefore, a topological map provides the GPS parameters in (5) for converting the position unit from geodetic to metric domains. In (6) and (7), GPS data is organized into hierarchies, which include $Latitude$, $Longitude$, and θ measured by real GPS sensors at the origin point.

$$GPS = \{Latitude, Longitude, \theta\} \tag{5}$$

$$Latitude = \{direction, degree, minute, second\}_{lat} \quad (6)$$

$$Longitude = \{direction, degree, minute, second\}_{lon} \quad (7)$$

A topological map is designed as a hierarchical structure containing node information. A *Segment* is defined as a region in which a mobile robot may travel along a specific route. *Segments* include several nodes as shown in (8).

$$Segments = \left\{S^1, \cdots, S^i\right\} \quad (8)$$

Each *Segment* is comprised of one or more *roads* in (9). A *road* is the subordinate of a *Segment* that is used by a path planner to generate a path.

$$S^i = \left\{R_1^i, \cdots, R_j^i\right\} \quad (9)$$

A *road* is characterized by the number of nodes in (10). A *node* is generally placed at the center of the pavement. Every *node* is specified by a unique identifier, position, number of lanes, width of road, speed limit of the mobile robot, type of traffic markers on the road, number of connected node, identifiers of connected nodes, relative angles to the connected nodes, location of central lane mark, height of curb.

$$R_j^i = \left\{N_{j,1}^i, \cdots, N_{j,k}^i\right\} \quad (10)$$

$$N_{j,k}^i = \left\{\begin{matrix} id, x, y, num\_lane, width, vel, type, \\ num\_connect, connect\_ids, \mathrm{connect\_}th, \\ cx, cy, curb \end{matrix}\right\}_{j,k}^{i} \quad (11)$$

III. Map Building based on GIS

A. Connecting GPS and GIS

To use a topological map, our method greatly depends on a GPS as the main information source of localization. A GPS sensor provides the geographical information for the nodes in the topological map. In particular, a differential GPS (DGPS) is used since it has better accuracy compared to a single GPS. The Flexpak-V2 GPS from Novatel Inc. is used to provide geodetic data at 20 Hz, as shown in Fig. 1. The data are received as National Marine Electronic Association (NMEA) messages.

In particular, a GGA message as NMEA is used to infer a node location as geodetic location (latitude and longitude coordinate) information. Geodetic location information is then converted to match our designed local Cartesian coordinate in metric units based on the topological map, i.e., *GPS* in (5). *Latitude* in (6) and *Longitude* in (7), including an origin location in the geodetic domain, permit the robot to calculate the distance and bearing in the metric domain between two geodetic positions [11]. The GPS data are received through RS232 serial communication at 115,200 bps. Two GPS receivers are used in this system. The main GPS receiver, called 'rover GPS', is installed at the main computer. Another GPS receiver, called 'based station GPS',

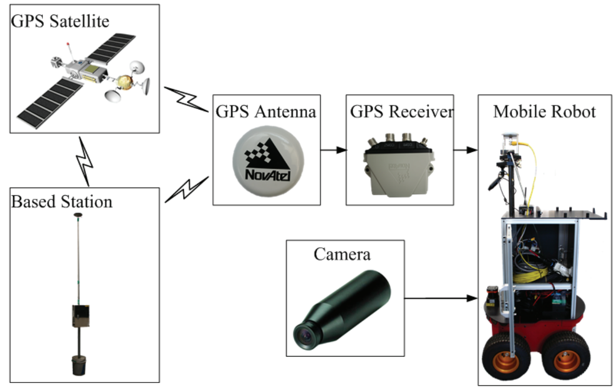

Fig. 1: The target system using a topological map based on the satellite images

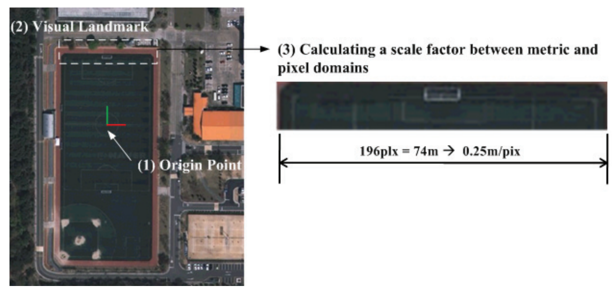

Fig. 2: The steps used to assign map properties

is employed to send the GPS correction signal to the rover GPS. Communication between a rover and base station occurs through wireless radio waves operating at 2.4 GHz. The base station GPS is located at a fixed location on the roof of the tallest building in our experiment area.

B. Map generation

The map generation consists of five steps: preparation of workspace images, map property assignment, node selection, surveying, and data conditioning.

1) Preparation of Workspace Image: A workspace image represents the surrounding environment as a single image where a robot is operated. The images are simply taken from an aerial or a satellitic views. These days, aerial/satellitic view images can be widely accessed from the Internet, for example through GIS services such as Google Earth [9]. Although the quality of the images varies depending on which area of the Earth we are looking at, urban environments such as large cities can be seen up to the level of road networks with reasonable quality, particularly for robot applications. This method is without cost, and only needs an Internet connection.

2) Map Property Assignment: After a workspace image is acquired, some map parameters should be assigned as in (2). This is related to an interpretation between image domain and metric domain (real world). The types of parameters to be assigned include image size, scale factor, and origin point, as shown in Fig. 2. Since we use a GPS as the main sensor, the origin point is represented as a geo-location (latitude

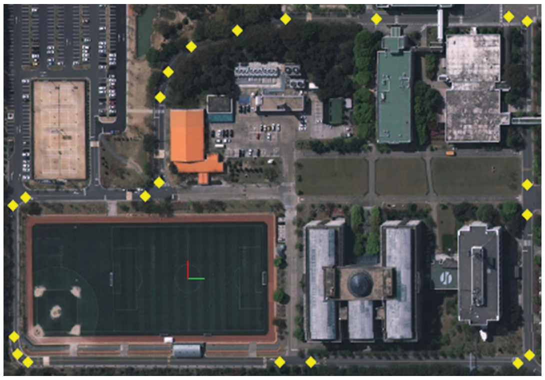

Fig. 3: Node selection for a topological map

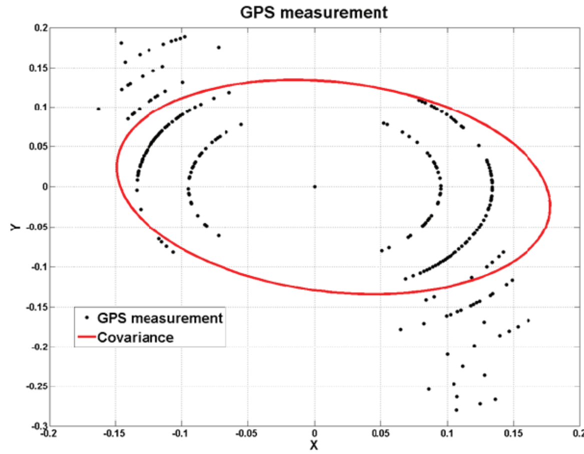

Fig. 4: Typical GPS measurement at nodes with a covariance ellipse

and longitude). All locations in the map are calculated relative to the origin point resulting in distances and bearings. Data gathering for the origin point should be conducted within a certain period. Afterward, the data are averaged for assignment as the origin point.

Image size is the parameter related to the size of the workspace image. The image size shows the resolution of the workspace image. Thus, it is an important parameter when we obtain and set the node information for the map. A scale factor is a value that maps the location from the pixel domain to metric domain. This scale factor will be used throughout the operation whenever a robot needs to infer certain information from the topological map by giving its location, i.e., map matching for GPS measurement.

3) Nodes Selection: Based on the map properties, the map maker can easily select the nodes for the topological map in the workspace. The nodes represent the topology relationships that inform the many possibilities for the robot to generate its path. In a typical urban environment, the nodes shape the road network (links) that show major common roads, as shown in Fig. 3.

4) Surveying: The purpose of surveying is to fill the information of each node and to improve the accuracy of the map, such as identification, location (x, y, and θ), and level of uncertainty at the time of surveying. The level of uncertainty is useful information for the robot to make decisions for a task. For instance, if a particular node has a large uncertainty, it means that the robot should carefully use that information and not place great dependency on it. The map maker needs to visit the physical location (in the real world) of the nodes to gather the data. Further, the map maker should average the data to assign the node information. Figure 4 shows the typical GPS measurement for one node. The black dots indicate GPS measurements, and the red ellipse is the covariance ellipse of the data. The mean of the data is assigned for location (x, y), while the covariance of the data is for the uncertainty of a node location.

5) Data Conditioning: It is well known that data from surveying sometimes contain an outlier and false data. To avoid erroneous data, the map maker should filter such data out. Since we also include the level of uncertainty in the node information, we are able to improve the localization performance at the nodes through a simple threshold filtering of erroneous data.

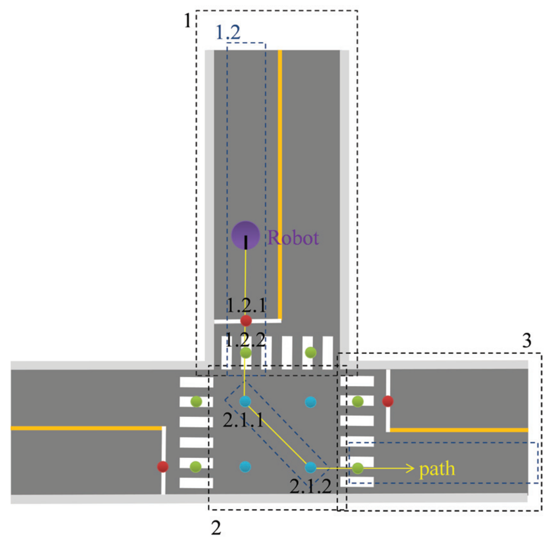

Fig. 5: The physical meaning of a topological map

IV. System Implementation and Experiment

A. Implementation

A topological map based on the satellite images has been implemented. XML was chosen as the file format of topological map. For convenience, we refer to Fig. 5 and 6 to illustrate the physical meaning of each element in an XML file. Table I enumerates some important elements in our map format. The file structure covers several elements that represent the physical meanings of the map, as shown in Fig. 6. On the top of the structure, the two important elements are *Origin* and *Segments*. The children of *Origin* are the basic information of the map, such as *Mapsize*, *Offset*, etc. The *Segments* element is the top hierarchy in representing the physical information of the road network.

TABLE I: The meaning of each element in a topological map

Element				Meaning
Origin				Basic information for maintaining and using a topological map.
	Mapsize		*width, height*	The size of the map in pixels.
			pixel_size	The scale factor to map an image from the pixel domain to the metric domain in meter/pixel.
	Offset		*x, y, th*	The translation and rotation offsets of the origin point with respect to the left-most bottom area of the workspace image.
	GPS	*Latitude*	*direction, degree, minute, second*	The latitude data measured by real GPS sensors at the origin point. *Latitude* has the *direction* information, and its magnitude. *direction* shows whether the origin is in the southern or northern hemisphere of the Earth.
		Longitude	*direction, degree, minute, second*	The longitude measured by real GPS sensors at the origin point. *Longitude* has the *direction* information, and its magnitude. *direction* shows whether the origin is in eastern or western hemisphere of the Earth.
		th		The angle offset of real GPS sensors at the origin point
Segments/segment				The largest segmentation area of a road network
	road			The children of a *segment*. *road* represents a cluster of nodes, where the robot can safely and reliably use those nodes as a path.
		node	*id, x, y, num_lane, width, vel, type, num_connect, connect_ids, connect_th, cx, cy, curb*	A *node* is a child of a *road*. A *node* has the information of location, number of lanes, width of road, velocity limit, node type, connectivity to other nodes including numbers, identifications, angles, location of central lane, height of curb. The robot performs several important tasks, such as path planning, velocity control, and localization, using *node* information.


```xml
<Origin>
  <Mapsize>
    <x unit="pixel">2955</x>
    <y unit="pixel">2483</y>
  </Mapsize>
  <Gridsize>
    <size unit="meter">0.25</size>
  </Gridsize>
  <Offset>
    <x unit="meter">366.0</x>
    <y unit="meter">131.0</y>
    <th unit="radian">0.0</th>
  </Offset>
  <GPSLatitude>
    <dir unit="direction">N</dir>
    <deg unit="degree">36</deg>
    <min unit="minute">22</min>
    <fmin uint="fminute">0.812762</fmin>
  </GPSLatitude>
  <GPSLongitude>
    <dir unit="direction">E</dir>
    <deg unit="degree">127</deg>
    <min unit="minute">21</min>
    <fmin uint="fminute">0.900929</fmin>
  </GPSLongitude>
  <GPSAngle>
    <th unit="radian">0.0</th>
  </GPSAngle>
</Origin>
<Segments>
  <num unit="number of segments">98</num>
  &lt;segment&gt;
    <id unit="identification of segment">1</id>
    <num unit="number of roads">2</num>
    <road>
      <id unit="identification of roads">1.1</id>
      <num unit="number of nodes">4</num>
      <node>
        <id unit="identification of nodes">1.1.1</id>
        <x unit="meter">223.625</x>
        <y unit="meter">314.800</y>
        <num_lane unit="number of lanes">2</num_lane>
        <width unit="meter">6.85</width>
        <vel unit="meter per second">1.0</vel>
        <type>ENTER_POINT</type>
        <num_connect unit="number of connecting IDs">1
          <id IDs="connect to IDs">1.1.2</id>
          <th unit="radian">1.5708</th>
        </num_connect>
        <cx unit="meter">221.126</cx>
        <cy unit="meter">354.864</cy>
        <curb unit="meter">0.25</curb>
      </node>
    </road>
```


Fig. 6: XML structure of a topological map

Here, we give an example of a real scenario of a robot using the topological map based on GIS shown in Fig. 5. The robot is approaching segment 3 from segment 1. Along the way, the robot will meet nodes 1.2.1 and 1.2.2, which are STOP_LINE and ZEBRA_CROSS, respectively. Also, the robot will meet the INTERSECTION node at segment 2. The INTERSECTION node is 2.1.1. Since the connectivity information at node 2.1.1 shows that the next node is 2.1.2, the robot should turn left to approach the next segment (segment 3) toward its goal. During the operation, the robot always limits its velocity depending on the node information.

B. Experiment

We conducted an experiment by applying a topological map to a real robot application at a building complex in our office area. In particular, we focused on the robot localization. The goal of the experiment was to localize the position of the robot by using the information from several sensors under an extended Kalman filter (EKF) framework [12]. The robot used an odometer (encoder), gyroscope, GPS receiver, and camera as sensors. The topological map was used to give the semantic information of the road where the robot was operating. The semantic information is the angle (direction) of the road segment. This angle is needed to project the GPS measurement to the current road segment, resulting in a compensated GPS measurement. A compensated GPS measurement is believed to be more accurate than a raw GPS measurement. During the operation, the robot always checks the topological map to obtain the most recent semantic information of the road, for instance, the start $(N^1_{1,1'})$ and end points $(N^1_{1,2'})$ of the lane line calculated using node information such as the road width and number of lanes, (12) and (13), respectively.

$$N^1_{1,1'} = \begin{bmatrix} x^1_{1,1'} \\ y^1_{1,1'} \\ \theta^1_{1,1'} \end{bmatrix} = \begin{bmatrix} x^1_{1,1} + width^1_{1,1}/2 \cdot \cos\theta^1_{1,1} \\ y^1_{1,1} + width^1_{1,1}/2 \cdot \sin\theta^1_{1,1} \\ \theta^1_{1,1} \end{bmatrix} \quad (12)$$

$$N^1_{1,2'} = \begin{bmatrix} x^1_{1,2'} \\ y^1_{1,2'} \\ \theta^1_{1,2'} \end{bmatrix} = \begin{bmatrix} x^1_{1,2} + width^1_{1,2}/2 \cdot \cos\theta^1_{1,2} \\ y^1_{1,2} + width^1_{1,2}/2 \cdot \sin\theta^1_{1,2} \\ \theta^1_{1,2} \end{bmatrix} \quad (13)$$

The compensated GPS measurement $(\mathbf{x}^{comp}_{gps})$ in (14) is a combination of the accurate lateral distance (l) measurement from a camera and the absolute position $(\mathbf{x}_{gps})$ information from a GPS under a constraint that the robot always operates on a common road, as shown in Fig. 7.

$$\mathbf{x}^{comp}_{gps} = \mathbf{x}^{proj}_{gps} + \frac{l}{\left\|\overrightarrow{\mathbf{x}^{proj}_{gps}\mathbf{x}_{gps}}\right\|} \cdot \overrightarrow{\mathbf{x}^{proj}_{gps}\mathbf{x}_{gps}} \quad (14)$$

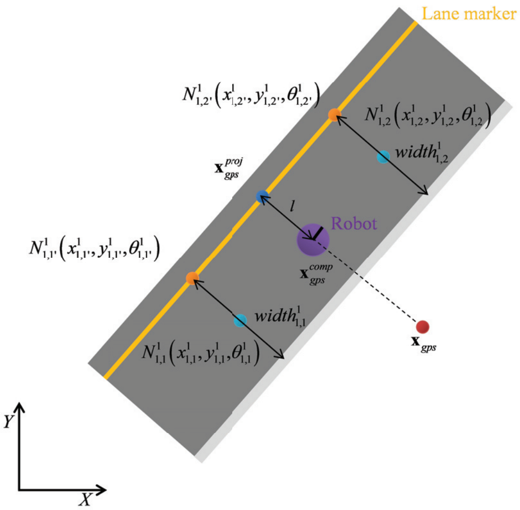

Fig. 7: The projection of a GPS measurement to a lane marker using semantic information from a topological map

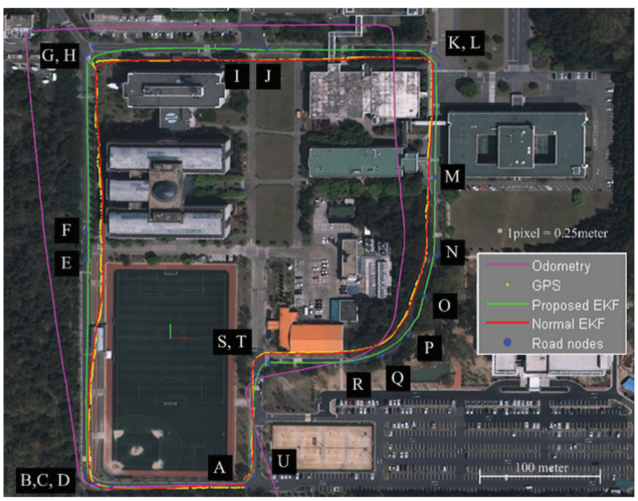

Fig. 8: Experiment results for one type of robot application using a topological map

Before the experiment, we created a topological map according to the steps explained in section III. We used a satellite image downloaded from Daum Map [10]. The origin point was the middle of a football field since it has the best GPS reception and is clearly shown in the satellite image, as can be seen in Fig. 8. The scale factor was calculated by comparing the actual size of a real-world landmark (meter unit) and the landmark displayed in the image (pixel unit). The landmark was a line of the football field shown in Fig. 2. Twenty-one nodes were created to represent the road network. A P3AT robot made by MobileRobots Co., shown in Fig. 1, was used as the robot platform. A computer with 1.6 GHz dual core processor was used to control the robot and to gather its sensors measurements. The robot was driven strictly at the limited velocity indicated in a topological map on the road, and its position was maintained (lane keeping) a certain distance from the center road marker. The length of the closed loop of the robot's trajectory is approximately 1110 m. The results in Fig. 8 show that the topological map was helpful for robot localization. Without semantic data (node information) from the topological map, the localization process would fail. In contrast, the robot was successfully localized from the start to end points using the proposed EKF localization based on a topological map.

V. Conclusions

We proposed a map building method for a topological map based on the satellite image maps for mobile robots in an urban environment. We identified four key requirements for topological map building: scalability, extensibility, human compatibility, and accuracy. From this point of view, topological map creation based on the satellite images is divided into two steps: defining the form and developing the mapping process of the topological map from existing the satellite image maps. The representation of a topological map was designed as a hierarchical structure based on XML containing semantic data, e.g., the width and type of road. In addition, we have developed a construction method and process for topological map building from existing the satellite image maps downloaded from GIS to reduce the costs. We also explained the details of implementation for building a topological map, and described a navigation experiment held in a real outdoor environment. The topological map was tested with a real mobile robot and was shown to successfully help improve the performance of GPS localization. Our work has demonstrated that the topological map can be applied to, and benefit, robot application.

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