Use of remote sensing in urban area navigation of mobile robots

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ABSTRACT

Navigation focuses on the process of monitoring and controlling the movement of a vehicle from one place to another. It can refer to any study that involves the determination of position and direction. In a broather sense, navigation is a process of trying to answer the questions *where am I ?, where will I go ?* and *how will I go ?* The answer given to the first phase of the process, *where am I ?* will determine the accuracy of the navigation process. Regardless of the sophistication level of the navigation path planning algorithms used, it is obvious that routes will be calculated incorrectly when wrong initial position data are used as input.

In the field of outdoor navigation of mobile robots in urban areas, GPS data as well as LASER scanners, SONAR, RADAR and LIDAR data are becoming increasingly important. These sensors are mainly used for detection of obstacles around a mobile robot, obstacle avoidance, and real-time positioning and mapping. Relationship between robot's surroundings and its location and orientation is obtained using these sensors and is used in navigation process.

In high budget mobile robot projects, very accurate and expensive GPS receivers and other sensors are used. Precise and consistent navigation operations can be performed by using these accurate sensor data. Nowadays, low cost GPS receivers used in low to medium budget robot projects have approximately a position accuracy of ± 10 meters in urban areas. This accuracy enables the determination of the position of the GPS receiver roughly in a 400 m^2 area which we will define as error probability area. For small or medium sized mobile robots, in some scenarios, an area of this size can cover the entire study area. In this case robot's exact location in the study area cannot be determined and thus navigation operations cannot be carried out precisely. Therefore increasing accuracy of the GPS location used in mobile robot navigation is of great importance.

In this paper we describe the design and implementation of a unique algorithm to increase accuracy of the GPS location that utilizes 2D laser scanner data and high resolution satellite imagery. By combining digital image processing techniques, template matching techniques and laser image, high resolution satellite imagery, compass and inertial measurement unit (IMU) data we developed an algorithm to calculate GPS error correction vector to correct erroneous GPS position obtained from low cost GPS receivers.

2D laser edge map is produced by plotting angle and distance data pairs obtained from a laser scanner. Compass and IMU data are used to correct orientation of laser edge map. Online mapping service data are used to match ground resolution of laser edge map with of satellite imagery.

Our method uses high resolution satellite imagery and Canny edge detection method to produce edge map of the robot's surroundings and uses template matching techniques to align laser edge map produced from 2D laser scanner. In this alignment process GPS error correction vector is calculated by using X and Y axis translations. This method is demonstrated in computer simulations and field experiments.

We believe that while a single method cannot be used to create a robust and efficient mobile robot localization and navigation system, our method will improve low cost GPS receivers' position accuracy in urban areas to be used as an input to localization and navigation planning algorithms.

1. INTRODUCTION

During the recent years, there is a significant increase in researches on using digital images, such as aerial photos, satellite images, LIDAR images, digital terrain models, edge maps, etc. in robot navigation in urban and not-urban areas. All these researches handle navigation and path planning from different points of view (1). Advance input of the study area map in the robot is the common method for indoor navigation. If the robot is additionally equipped with a laser scanner, there are standard techniques those allow the robot to determine its position by combining this map input and the environmental features (objects, obstacles, etc.) determined by the laser scanner (2). For the outdoor navigation and positioning; compass and encoder (3), sonar (4), laser scanner (5,6), and video camera measurements (7) are used as complementary data to the GPS data.

In a research study, the location of the robot is determined by using real-time kinematic differential GPS (DGPS), and its navigation is obtained accurately using the combination of the attached laser scanner and the SLAM (Simultaneous Localization and Mapping) method. During the navigation process, firstly the location is determined with the kinematic DGPS and then local obstacle detection and positioning are obtained by using the laser laser scanner data (5). Another study is focused on re-routing process in the case of an obstacle detection, using the IMU, GPS and laser scanner data. The positioning difference between discrete GPS signals during the navigation process is calculated using laser scanner and IMU data. Thus, it is possible to continue navigation with approximate position calculations, in case of a difference between two GPS measurements or when GPS signals are lost. Additionally, it is possible to keep laser scanner continuously parallel to the earth surface with the IMU data (6). The navigation process in all of the above mentioned studies is completed by using the GPS and additional sensors. Here, simultaneous localization and mapping methods are mainly preferred instead of using existing maps and/or satellite imagery and not any GPS position accuracy improvement method is proposed

In another research study existing digital images are used. Although using the digital imaging for the robot navigation is not a very new trend, using digital images for determination of the main points on the route was always subject to intensive studies in previous years. Especially the researches on the autonomous vehicles (intelligent transportation systems) became more important with the increasing interest of the automotive industry in this subject. In most of these studies, laser scanners are used to determine features detectable on digital images (8, 9, 10, 11, 12).

One of these studies showed how to improve the classification of objects sensed by autonomous vehicles at crossroads, by using the laser scanner measurements and precise high-level feature maps (8). In another study accurate vehicle localization information by using the range maps (maps those shows the distances of the obstacles around the lasers scanner), video camera and laser scanner are obtained (9). Another study proposed a method that allows urban localization and positioning of the vehicles moving in lower speeds (~10 kmph) by using the object positions obtained from the laser scanner and preproduced grid based feature maps (10).

Another study proposed a method for detecting objects in motion (vehicles and pedestrians) using multi-layer LIDAR. Because LIDAR is able to do vertical and horizontal scanning, it is possible, when classifying moving objects in surrounding area, to determine moving directions and speeds of these objects (11).

In another study, geo-localization information is obtained and intelligent vehicle navigation in urban areas is provided by integrating 3D-GIS data with gyroscope and laser scanner data. Here, the proposed method requires 3D-GIS information of the navigation area and 3D mapping of the navigation route before using this method for navigation. This requirement consequently decreases the applicability of the method (12).

All these studies summarized above show that laser scanners are mainly used for completing the obstacle detection and collision avoidance tasks, and obtaining geo-location data when system is not able to receive GPS data or when signal is not very accurate. In the studies where laser scanner is used for obtaining more accurate localization, the map produced by the robot itself is

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used. However, all these studies do not cover any research on increasing the accuracy of the GPS position by using a global map/image.

Instead of local and global positioning differentiation, this study aims at accurate calculation of the position on the global map using the obstacle-distance image produced from a laser scanner with the assistance of a GPS. With this aim, a GPS accuracy improvement algorithm is designed and a software implementation is still in progress.

2. PLATFORM AND DATA USED

Because this study is aimed at increasing the accuracy of the GPS position of the low cost mobile robots, test platform should be as simple as possible, easily meet the requirements and maintenance friendly in the field studies. For this purpose, the robot's design and features, development, manufacturing and control must be simple and flexible enough to add new features that may be required in the future. Therefore, we avoided using complex methods for the driving mechanisms, electronic components and control mechanism of the robot.

We used a differential driving system that has 4 off-road wheels separately powered by an electric motor for each wheel. Robot's body is designed with a closed frame to protect electrical and electronic components against external factors. Mobile test platform has an onboard computer, which operates the software that controls the mechanical functions of the robot, navigation algorithms, processing the laser scanner images and matching them with the satellite imagery. Hokuyo UTM-30-LX model, 2D laser scanner is used for obtaining the laser data. Additionally, mobile robot test platform also has a low cost GPS receiver (Garmin GLO), electronic compass, 9 axis IMU, infrared and sonar based obstacle detection sensors, motor and sensor control boards and x86 based control PC (Figure 1).

Figure 1: Mobile robot test platform and laser scanner.

The large amount of data of laser and satellite imagery used during the process, prevents their processing on the embedded systems. Infrastructure of the software utilized in this system is designed to be able to complete tasks like controlling the mechanical functions of the robot, navigation of the platform, reading/processing of the sensor data and recording/storing these data, transforming the data from the laser scanner to 2D range map, matching spatial resolution with the satellite imagery, coordinates and direction matching of two images, GPS error correction vector calculations with the alignment of the laser and satellite imagery (Figure 2).

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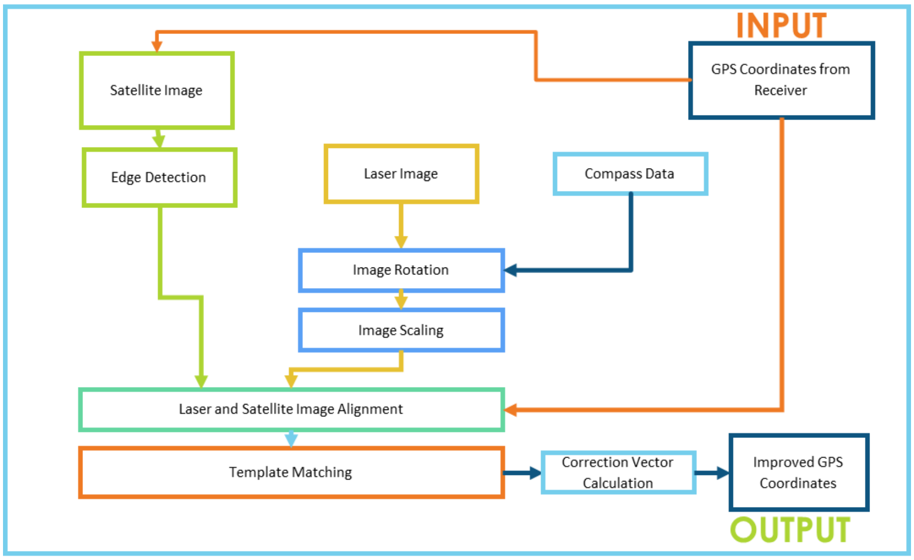

Figure 2: Method implementation.

For the instruments like GPS receivers, laser scanner and control cards used in this study the Microsoft Windows drivers exist. Therefore, the system structure is designed based on the Microsoft.NET architecture. Because of flexibility of this architecture the controls of the instrument, sensor subroutines, navigation subroutines and GPS positioning subroutines used in this project can be processed simultaneously on different threads. User interface of the developed software is shown in Figure 3.

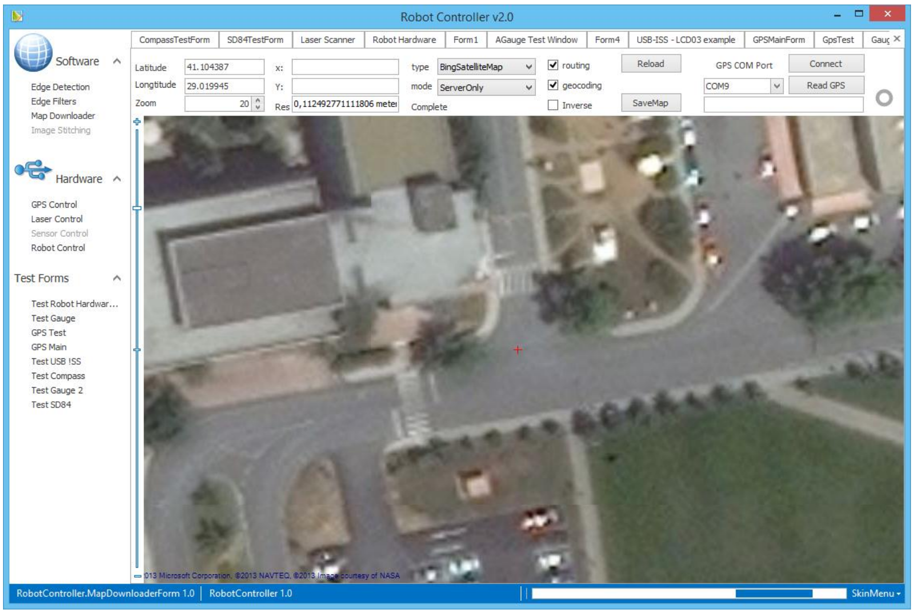

Figure 3: Control and processing software.

Using high resolution satellite imagery (Geoeye-1, IKONOS, WorldView 1-2, etc.) from free online maps provided by different Web companies, such as Google, Microsoft, Nokia, Yandeks, etc. reduces the image cost. Thus, computer will only process the images of the designated area around the robot and consequently the processing load of the computer will be reduced. For this study, GeoEye-1 jpeg images from the MS Bing Maps are used.

3. METHODOLOGY

Robot Navigation and GPS Errors

Robot navigation process is a process that is trying to answer the questions like *'where am I ?', 'how will I go ?'* and *'where will I go ?'*. The answer given to the first phase of the process, '*where am I ?*' determines the accuracy of the navigation process. Regardless of the sophistication level of the navigation path planning algorithms those are used, it is obvious that routes will be calculated incorrectly when wrong initial position data is used as input. Robot navigation can be categorized as *indoor* and *outdoor* navigation.

For the *indoor* navigation, features of the area where robot will navigate, the potential obstacles and route that robot will follow, can all be planned in advance and the location of the robot within the building can be determined by various methods. The location can be determined with the indoor positioning indicators (predefined guidance signs, barcodes, magnetic labels, etc.) or different indoor features (doors, walls, stairs, etc.). Prearranging the indoor operating environment for robot navigation and its structural features make indoor navigation easier compared to outdoor navigation.

Conversely, for the *outdoor* navigation it is almost impossible to prepare the environment for navigation in advance because of the large size and complexity of the area where robot will navigate. In order to navigate outdoor, robot should detect obstacles (buildings, trees, human, vehicles, etc.), determine its location in the environment and be able to calculate real time updated routes to its destination. GPS is the most preferred system for this type of navigation because the accuracy of the resulting location information is much more accurate than other methods, and the environment does not need to be labeled in advance with a variety of identifiers. These make GPS receivers an ideal geolocation tool for a mobile robot. The GPS coordinates of the robot are transmitted to the control computer as latitudes and longitudes so that the location and speed of the robot can be determined by using the coordinate changes within time. With the detection of the location, it is possible to make route planning on the existing or real-time produced maps.

Many factors such as SA errors, satellite geometry, satellite orbit errors, atmospheric factors, time inconsistency, effects of rounding errors in calculations and relativity can lead to GPS position errors during the calculations (14, 15). Another source of error is the arrival of GPS signals reflected from high buildings and landforms at the receiver (multipath error). In this case, reflected signals arrive at the user's receiver in a longer period which causes errors in the calculations of the distances between satellites and a receiver. In non-urban outdoor robot navigation more accurate location can be acquired because the GPS signals are less affected from the multipath effect. However, in the urban areas with more reflective surfaces (like buildings), multipath error considerably affects GPS position accuracy. With the help of GPS signal correction systems, such as WAAS and EGNOS, these errors can be decreased to ±3-5 meters giving better position accuracy. However, the GPS receivers used on mobile robots may vary based on the budget of the robot project and size of the robot. The highly accurate and expensive GPS receivers used in high-budget mobile robot projects are not feasible to use for mid and/or low budget projects, or for the small mobile robots. The low cost GPS receivers used in low budget robot projects have generally a position accuracy of ± 10 meters. This accuracy is in acceptable limits for the non-urban outdoor areas and for the large robots because of the very large navigation area and fewer obstacles. However, for the urban area navigation, more obstacles which robot may encounter and weakening of the GPS signals because of the errors like multipath, cause serious navigation errors for mid and small sized robots. For these reasons, improving GPS accuracy especially in urban areas is an important and useful task.

Field Studies

A GPS network in the Istanbul Technical University (ITU) Campus is established by the Department of Geomatics Engineering using CORS-TR with a millimeter position accuracy. The

Garmin GPS measurements are made on 23 selected points of the network and the coordinates measured are compared with the precise ITU network coordinates. The comparison results showed a GPS error of ~5,471 meters (max 11,630 m., min 1,541 m). Field studies to acquire GPS, laser scanner, compass, IMU, infrared and sonar distance data by running mobile robot test platform on different locations in the campus is in progress. Later, all data collected from these field studies will be analyzed, laser range maps will be produced and compared to satellite imagery. Producing laser scanner image, downloading satellite imagery, resolution matching and edge detection steps of the process are already completed. Template matching, design and software implementation of the GPS accuracy improvement algorithm and simulations using field study data are still in progress.

Increasing GPS Accuracy by Using High Resolution Satellite Imagery and Laser Scanner

This ongoing study aims at increasing accuracy of the low cost GPS location in urban areas with a combined analysis of the laser scanner data and high resolution satellite imagery. Proposed method is based on producing a 2D range map presenting the information obtained from the laser scanner and matching this map with the high resolution urban satellite imagery to correct GPS position errors. This method can be considered in three major topics as, (i) producing a 2D range map, (ii) processing digital satellite imagery and applying edge matching, and (iii) calculation of GPS error correction vector.

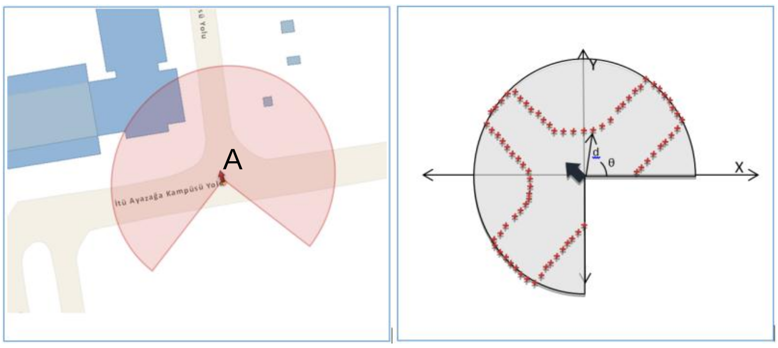

Figure 4: a) Laser scanner scan range. b) Laser scanner data.

The process of producing a range map (i) starts with transferring the 2D laser scanner (mounted on the mobile robot test platform) data to the computer. When the robot is located at point A (Figure 4), laser scanner will scan an area of 270º and measure the distances with 0,25º intervals. These data are then transmitted to the computer as ‘angle and distance’ pairs. The distance is set at 30 meters and scanning angle at 270º. When the laser scanner detects an obstacle in its range, angles and distances between detector and obstacles will be transmitted to the computer. When the scanner does not detect any obstacles, the measured angle and the maximum distance 30 meters will be transmitted to the computer. In a scan of 270º with an angular resolution of 0,25º, the system acquires 1080 pairs of angle and distances. These pairs create a matrix of 2 x 1080. In order to use this matrix for the GPS position correction algorithm, it must be converted to a 2D range map which is produced by plotting this matrix data onto a coordinate system with the points having the angle and distance values (Figure 4).

In order to make an easy visualization, the first reading of the laser scanner is set at 0º position and final reading at 270º. Black arrow shows the heading of the robot during the measurement process. These values are the raw angle values read from the laser scanner. In order to detect the distances of the obstacles to the robot, angular values must be transformed into robot’s coordinate system. Figure 5 shows the obtained coordinate system and the viewing angles of the laser scanner when laser scanner is mounted parallel to the front edge of the robot. The raw laser scanner angle values must be rotated by -45º in order to transform into robot’s coordinate system.

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With this rotation, laser measurements (d, θ) will be transformed to (d, θ-45º). The points obtained will be merged based on their measuring order to determine the unobstructed path around the robot.

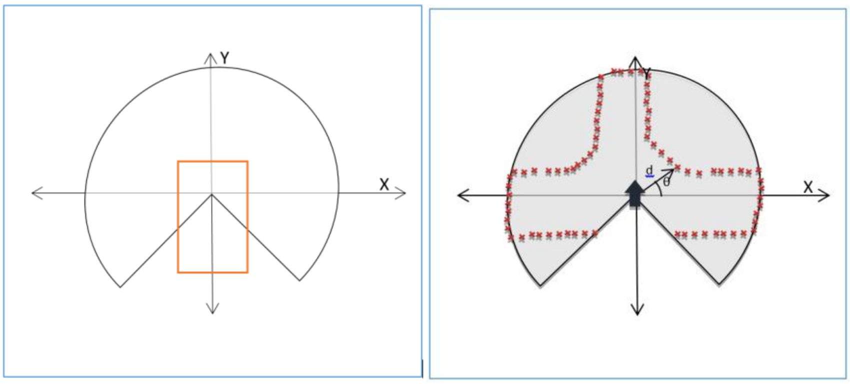

Figure 5: a) Laser scanner field of view related to robot body. b) Laser scanner data in robot's coordinate system.

In order to match the range map with satellite imagery, the north direction of the range map must be coincident with the north direction of the satellite imagery. For this purpose, the system uses data from an electronic compass attached to the robot, which makes it possible to read the angles between direction of the robot and north direction at a resolution of 0.1º. The value of each angle measurement is transformed from robot's coordinate system to the satellite imagery coordinate system using the compass angle readings. For this process, each point in the robot's coordinate system must be rotated by α (Figure 6) between north direction and the direction of the robot. After this rotation laser measurements (d, θ) will be transformed into (d,θ+α-45º).

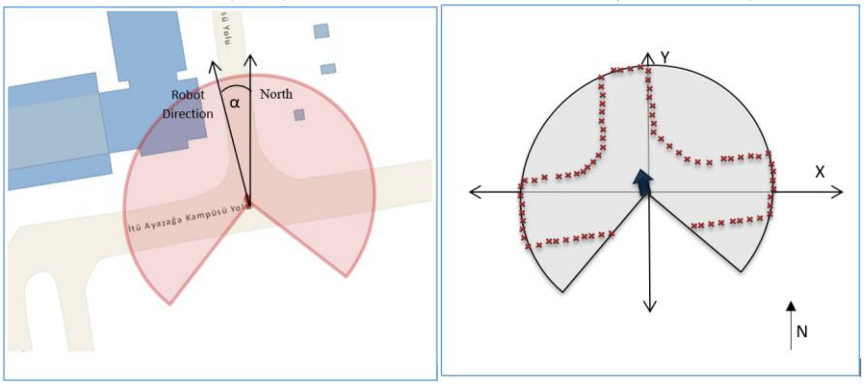

Figure 6: a) Robot's direction vs north. b) Corrected laser data on global coordinate system.

After these two transformations raw angle values obtained from the laser scanner are converted into the satellite imagery coordinate system. Total rotation value is α-45º. This process will enable matching 2D range map produced by a laser scanner with the satellite imagery.

The second step of the accuracy improvement of the GPS location algorithm is processing of the satellite imagery and edge detection (ii). This step provides obtaining the satellite imagery, matching the spatial resolution of the satellite imagery with range map and transforming the data obtained into a format supported by the developed algorithm. This step, applying different filters and transformations to the Geoeye-1 imagery (Figure 7), aims at making the features on the image more identifiable so that to match with laser images.

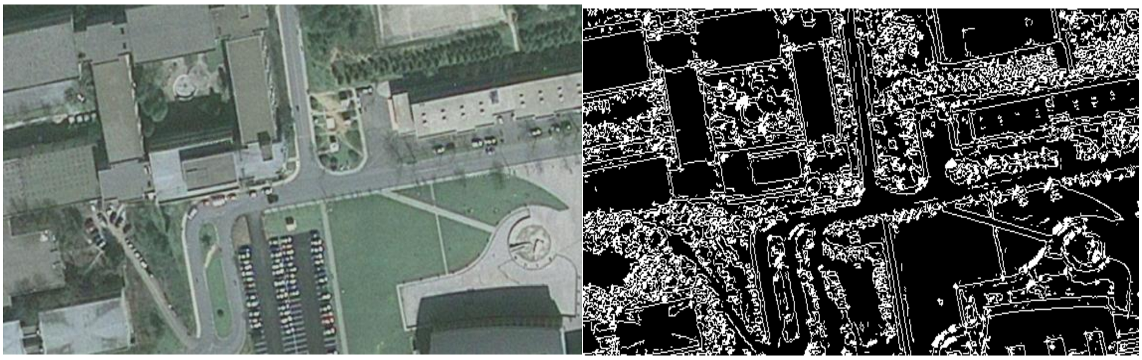

Figure 7: a) Raw satellite image. b) After edge detection.

At the process of edge matching, first step is to read location obtained from the GPS receiver attached to the robot. In order to be able to use robot's coordinates in latitudes and longitudes, for edge matching, these coordinates must be transformed to satellite imagery pixel coordinates in rows and columns (upper left corner coordinates: 0,0). It is possible to do a real coordinates (latitude and longitude) matching for each pixel of a geometrically corrected satellite imagery. When the GPS coordinates are marked on the satellite imagery (Figure 8) a probable error margin of ±10 meters causes a *~400* m^2 error probability area. This study aims at reducing this area and getting a more accurate position.

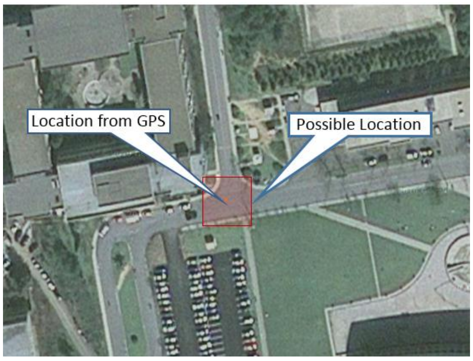

Figure 8: Location from GPS receiver.

The location obtained from the GPS receiver corresponds to origin (0,0) of the coordinate system in Figure 6. Figure 9 is obtained by matching the satellite imagery with the laser scanner image produced with this information. The edges of the satellite imagery and of the laser image do not match because of the errors in GPS readings. The algorithm on which we are currently working to develop aims at matching the points on the laser images with detectable features on the satellite imagery.

Figure 9: Laser scanner data plotted on the satellite imagery.

The matching step of the algorithm is aimed at matching the identifiable features on the satellite imagery with their correspondings on the laser image. Comparison of the shape-based, area-based and feature-based matching methods showed that the shape-based methods provide better results.

Researches exhibit that radiance difference between two images, scales of the images, and orientation and the gray values of the images have effect on the success of the image matching algorithm. First step is to transform the satellite imagery into grayscale and then perform the edge detection, before applying edge matching step of the algorithm. The resulting edge image will have two (1 and 0) gray values. Similarly, the laser scanner image is a binary image as well. During the edge matching process, laser images are used as a template and satellite edge imagery as a source image. Next step is scaling laser image using the spatial resolution of the satellite imagery (~50 cm) and matching the north direction of the laser image with north direction of the satellite imagery using the electronic compass data. This method enables to reduce matching errors caused by the differences, like color depth difference between two images, scale and orientation to minimum level.

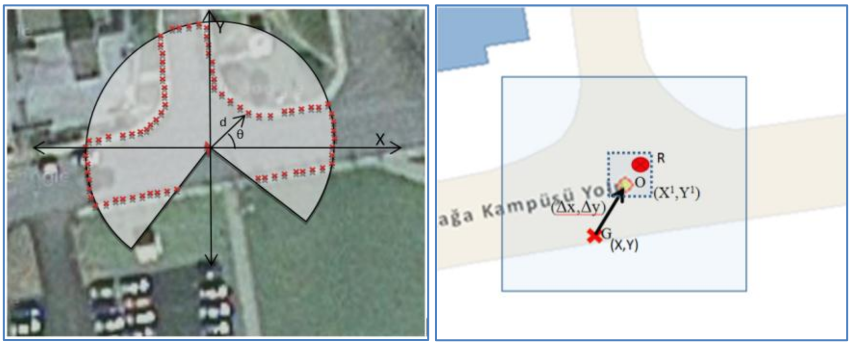

Figure 10: a) Laser data after alignment. b) GPS correction vector.

At the step of calculation of GPS error correction vector (iii), if matching is possible when sliding the template image by Δx at X-axis of the image and by Δy at Y-axis, this vector can be described as (Δx,Δy). After correcting the GPS coordinates (x,y) with GPS correction vector, corrected GPS coordinates (x_1,y_1) are obtained. Figure 10 shows GPS coordinates reading (G), corrected GPS coordinates (O) and actual location of the robot (R).

After the matching process, the ±10 meters error probability area (Figure 10b, large square) will be reduced to ±2 meters to provide a more accurate location. Accuracy improvement process of the wrong GPS location is completed after the transformation of the pixel coordinates into global coordinates.

Some of the error sources might have effect on the success of the system during the implementation of the proposed method. The most common error sources are, noise in the laser scanner data, not parallelity of the laser scanner to the earth surface, environmental changes between the receiving dates of the satellite imagery and of the laser image, errors during spatial resolution matching and coordinate transformation process, objects such as vehicles, human, etc. existing in the laser scanner data but probably not in satellite imagery.

4. RESULTS

Measurements using low cost GPS are made on the ITU Campus GPS network points with millimeter accuracy. The measurements showed that the GPS receiver used for the mobile robot test platform has an approximate position accuracy of ±10 meters. This accuracy determines the position of the GPS receiver in a 400 m^2 error probability area. An area of this size might cover all navigation field of small or mid sized robots, especially in urban navigation scenarios. In this type of scenarios, it is not possible to detect the exact location of the robot inside the navigation area and consequently it is not possible to complete the navigation task. This study aims at reducing

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±10 meters position accuracy to ±2 m. If this goal is reached, 400 m^2 error probability area of the GPS reading will be reduced to 16 m^2 and thus the size of the error probability area will be reduced to 96%, which will enable more accurate mobile robot navigation. Even if the accuracy is ±4 meters instead of ±2 meters, error probability area will increase to 64 m^2 but it will still be small when compared to 400 m^2 and it will still provide 84% smaller error probablity area. In future, a comparison of performances of different GPS receivers in different weather conditions is also aimed.

5. CONCLUSIONS

The proposed method has two important inputs. Firstly, the image produced from the laser scanner data and secondly, the satellite imagery obtained transforming the high resolution satellite imagery by using the edge detection methods.

The most common error sources that can affect the success of the system are noise in the laser scanner data, errors caused by positioning of the laser scanner not being parallel to the surface, environmental changes between the receiving date of the satellite imagery and of the laser image, errors during spatial resolution matching and coordinate transformation processes, objects such as vehicles, human etc. which exist in the laser scanner data but not in satellite imagery.

Downloading the satellite imagery from the internet and applying edge detection methods are time-consuming processes. Repeating these processes everytime when the algorithm runs will obviously cause performance losses. In order to prevent possible loss of data, the satellite imagery can be downloaded online during the processing of the method or can operate offline with the images that are uploaded into the system before the operation. Additionally, edge detection applied to satellite imagery can be done in real-time during processing of the algorithm or it can also be done before the algorithm starts. Downloading the satellite imagery in advance and then obtaining the edge-detected image using edge detection methods is more time efficient, because it will reduce the algorithm processing time. However, if the study area is unknown in advance, downloading and edge mapping can be completed in real-time and edge-detected image required for the algorithm can be obtained in all circumstances. Its online and offline working ability, and in advance or real-time processing flexibility are some advantages of the proposed method.

The other methods, such as DGPS and kinematic GPS used for improving the GPS accuracy, require prestudy of the navigation area, establishment of infrastructure or use of stationary stations/transmitters during the study. The cost of the GPS receivers used in this kind of operations is expensive compared to low-cost GPS receivers. This method does not require any investment for a potential preestablished infrastructure or a secondary GPS unit as the methods like WAAS and DGPS do (13).

Especially, up-to-date researches those automotive sector and technology companies like Google make on driverless vehicles and researches on unmanned ground vehicles for military and civilian purposes, increased the importance of the urban navigation and thus the improvement of the GPS accuracy in urban areas.

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