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An Effective Trajectory Optimization Method for Autonomous Mobile Robot Conducted by GPS Positioning using Kalman Filter Approach

The maintenance and operational tasks on construction sites and warehouses are currently performed by human operators (moving stacked crates or debris, powering other devices, plucking products from shelves). This paper would like to highlight the use of a robot capable of performing these tasks using the GPS signals with differential corrections and an effective trajectory optimization method using a Kalman filter approach, also with the aim to identify strengths and weaknesses of this study work. In this paper is also proposed the localization algorithm of an autonomous robot using differential GPS and a Kalman filter approach to smooth the trajectory of the robot, with detailed explanation of the algorithmic approach.

***Keywords**: Kalman filter, robotics, differential GPS, UTM, real-time kinematics*

1. Introduction

Tasks on construction sites and warehouses are usually performed through human operators. This paper would like to highlight the use of a robot capable of performing these tasks using the GPS signals with differential corrections while using a Kalman filter approach. The GPS provides centimeter accuracy that would be perfect for this kind of application.

With the goal to develop an autonomous mobile robot which can perform tasks in outdoor environment aided by GPS, the approach followed for the localization algorithm of the robot using differential GPS is highlighted as a hybrid strategy for a reliable mobile robot in outdoor environment.

This was started by modifying a iRobot Roomba Create robot, the reprogrammable version of the Roomba robot vacuum cleaner.

The ROI (Roomba Open Interface) allows users to take full control of the Roomba and its behavior. This is no simple remote control interface, but instead a protocol that allows complete sensor readout and full actuator control. The ROI turns the Roomba into a true robotics platform.[1] Two obstacles to use, especially for educational purposes, are: the cryptic nature of the command interface; and the difficulty in establishing a software serial port connection to the robot. [4]

The Global Positioning System is a satellite-based positioning system that functions in any weather conditions, anywhere in the world, continuously. GPS comprises three major system segments: Space, Control, and User. The Space Segment consists of a nominal constellation of 31 satellites. Each satellite broadcasts RF ranging codes and also a navigation data message. [5]

The Control Segment encompasses a network of monitoring and control facilities that are used to manage the satellite constellation and the same time update the satellite navigation data messages. The User Segment consists of a broad variety of radio navigation receivers customly or mass-market designed to receive, decode, and process the GPS satellite ranging codes and navigation data messages.

Differential GPS techniques provide higher accuracies than GPS standalone. A typical configuration would be a fixed receiver with known coordinates and another one or more user receivers. The receiver with fixed coordinates is normally called reference or master station, while the others are called rovers.

2. Analysis

This section highlights problem formulation, state of the art and theoretical approach. The problem formulation encompasses whether Real-time Kinematics Differential GPS is reliable or not for this type of application and whether Kalman filter approach would be assisting this.

Our study is based on the use of RTK (Real Time Kinematic), between a single reference station and a rover-robot station, in order to provide accurate robot position in real time. A radio link was established between robot and master station. The next step was the configuration of the two receivers, Master and Rover, in RTK mode. We used Matlab code and GRIL (GPS Receiver Interface Language) for this purpose.

The platform (see Figure 1) contains the robot as a base, a radiomodem, the rover and a battery to power the rover (mobile receiver).

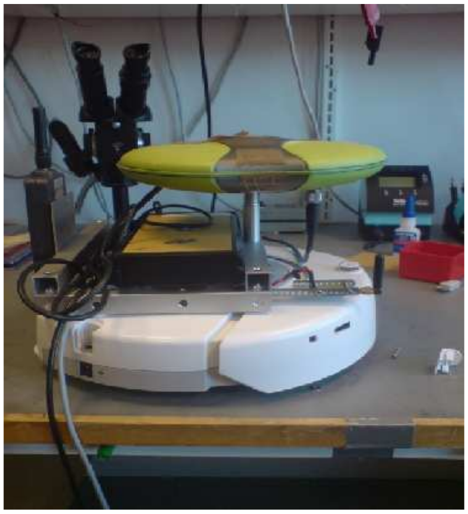

Figure 1. Robotics integrated platform

The distance parameter is represented by the distance that Roomba has traveled in millimeters since the distance it was last requested. This is the same as the sum of the distance traveled by both wheels divided by two. Positive values indicate travel in the forward direction; negative in the reverse direction. The distance is obtained from the optical interrupter sensor on the wheels. The angle parameter is represented by the angle that Roomba has turned since the angle was last requested. The angle is expressed as the difference in the distance traveled by Roomba's two wheels in millimeters, specifically the right wheel distance minus the left wheel distance, divided by two. This makes counter-clockwise angles positive and clockwise angles negative. [4]

Rudolf Kalman described a way to recursively find solutions to the discrete-data linear filtering problem, with an algorithm that uses two sets of mathematical equations to solve real-time problems.

The Kalman Filter is a set of mathematical equations and provides for an efficient recursive computation of least-squares solutions.[6] The Kalman filter, for Gaussian random variables, is regarded to be the optimal linear predictor and estimator, encompassing the ability to predict and estimate the past, present and future of a system. The Kalman filter minimizes the difference between observations and the predictions. The difference between the observed states and the states computed by the Kalman filter is called the covariance. Using this approach for real world applications, with random noise and noisy measurements taken into calculus, the accurate tracking of the robot position is not possible with regular Kalman filter, because of the non-linearity of the system. The form specified for the non-linear case is the Extended Kalman Filter (EKF), that is suitable for nonlinear state estimation, navigation systems and GPS.

The problem is approached theoretically for a system defined by the state equation

$$\mathbf{x}(k+1) = \boldsymbol{f}(\mathbf{x}(k)) + \boldsymbol{G}(k)\mathbf{w}(k) \tag{1}$$

and the measurement equation

$$\mathbf{y}(k+1) = \boldsymbol{h}(\mathbf{x}(k+1)) + \mathbf{v}(k+1). \tag{2}$$

In the previous equations w(k) and v(k+1) are uncorrelated white random processes. G(k) is a known matrix and f(x(k)) and h(x(k+1)) vector non-linear functions of the state. X represent the state variables and y the measurement variables. *f* computes the predicted state from the estimate and *h* computes the predicted measurement using the predicted state, or in other words measurements that we make (noise included) are functions of the state.

The measurements are the coordinates of the robot obtained from the DGPS and the azimuth that is calculated as explained on previous page. The coordinates of A and B points (see figure 2) are known and the robotics platform is initially adjusted to point to destination. Further adjustments are provided by the extended Kalman filter in respect to the azimuth of the robot, therefore the number of steps needed is minimized.

Given the state and estimation models from equations (1) and (2) the extended Kalman filter that can be used to estimate the state of the system is given by the equations

$$\hat{\mathbf{x}}(k+1) = \hat{\mathbf{x}}(k+1|k) + \boldsymbol{K}(k+1)\left[\mathbf{y}(k+1) - \hat{\mathbf{y}}(k+1|k)\right], \tag{3}$$

$$\hat{\mathbf{x}}(k+1|k) = \boldsymbol{f}(\hat{\mathbf{x}}(k)), \tag{4}$$

$$\hat{\mathbf{y}}(k+1|k) = \boldsymbol{h}\left(\hat{\mathbf{x}}(k+1|k)\right), \tag{5}$$

$$\boldsymbol{K}(k+1) = \boldsymbol{P}(k+1|k)\boldsymbol{H}^{T}(k+1)\left[\boldsymbol{H}(k+1)\boldsymbol{P}(k+1|k)\boldsymbol{H}^{T}(k+1) + \boldsymbol{R}(k+1)\right]^{-1} \tag{6}$$

$$\boldsymbol{P}(k+1|k) = \boldsymbol{F}(k)\boldsymbol{P}(k)\boldsymbol{F}^{T}(k) + \boldsymbol{G}(k)\boldsymbol{Q}(k)\boldsymbol{G}^{T}(k), \tag{7}$$

$$\boldsymbol{P}(k+1) = \left[\boldsymbol{I} - \boldsymbol{K}(k+1)\boldsymbol{H}(k+1)\right]\boldsymbol{P}(k+1|k). \tag{8}$$

Equations *(3)* to (*8)* highlight the tracking form of the EKF. F and H are the jacobian matrices of f and h. When developing the extended Kalman filter linearization of the measurement and system model is necessary alongside with perturbation analysis. The control theoretic form of the extended Kalman filter is defined by the below equations

$$\hat{\mathbf{x}}(k+1) = \boldsymbol{f}(\hat{\mathbf{x}}(k)) + \boldsymbol{K}(k)\left[\mathbf{y}(k) - \boldsymbol{h}(\hat{\mathbf{x}}(k))\right], \tag{9}$$

$$\boldsymbol{K}(k) = \boldsymbol{F}(k)\boldsymbol{P}(k)\boldsymbol{H}^{T}(k)\left[\boldsymbol{H}(k)\boldsymbol{P}(k)\boldsymbol{H}^{T}(k) + \boldsymbol{R}(k)\right]^{-1}, \tag{10}$$

$$\boldsymbol{P}(k+1) = \left[\boldsymbol{F}(k) - \boldsymbol{K}(k)\boldsymbol{H}(k)\right]\boldsymbol{P}(k)\boldsymbol{F}^{T}(k) + \boldsymbol{G}(k)\boldsymbol{Q}(k)\boldsymbol{G}^{T}(k). \tag{11}$$

UTM coordinates perspective defines in our case bidimensional horizontal positions.

$$\mathrm{x}(k+1)=\boldsymbol{F}(k)\mathbf{x}(k)+\boldsymbol{G}(k)\mathbf{w}(k) \tag{12}$$

By using DGPS measurements standalone, that might not be perfectly precise, or by using only odometry data from the robot, we might lead to wrong estimates.

The Extended Kalman Filter is actually fusing in this case both available sources of measurements. The robot is able to improve its position estimate over time by predicting future sensor readings based on the commands given to the robot at each step of the robot control. The difference between the predicted sensor readings and the actual sensor readings is used afterwards to update the filter. A heuristic approach is used for the extended Kalman filter on the current application. When f and h functions are highly non-linear, the use of an unscented Kalman filter would provide better performance and eliminate the need of jacobian calculations further necesarry on the extended Kalman fiilter.

3. Tests and results

Initial measurements were conducted with Topcon equipment (tripod and receivers) in order to check the reliability of the measurements. A comparison between the measured coordinates of the rover in UTM (Universal Transverse Mercator) and GoogleEarth coordinates conversed to UTM. The approach considered uses the relative position between Master and Rover, that is most relevant for our purpose.

The aim was to guide the robot trajectory from a point A to a point B (distance of exact 25m), in a predetermined path, using very good accuracy. The path was divided into several sections, depending on distance chosen between points and accuracy of measurements and estimates. At the intermediate nodal points the robot performed a comparison between its real coordinates computed using the GPS and the goal coordinates.

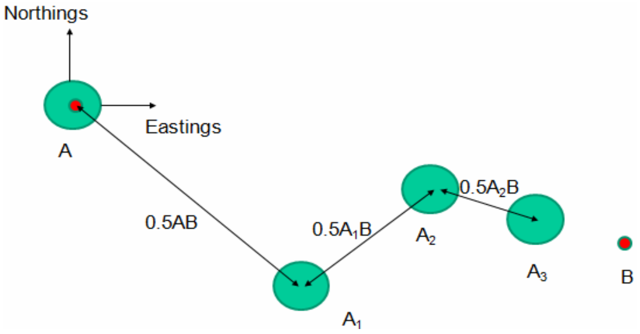

Figure 2. Step by step movement of robotics platform

In each step the robot, depicted as green circle in above figure, moves a certain distance, stops and computes the distance and azimuth between its coordinates and the goal coordinates, makes the corrections on the trajectory, and then, continues to move.

Position was obtained in mN (meters North) and mE, with typical values like 6322857.38 mN and 560120.10481 mE of UTM zone 32 and measurable errors at least of second decimal, centimeter level accuracy.

The distance the robot has to run within steps decreases according to the distance from the goal. So at the beginning we will have longer distance for each step because the robot is far away from the goal, but when it becomes closer the distance for each step becomes shorter. The same is true for the velocity which is changed at certain thresholds depending on the distance from the goal: the shorter the distance the lower the velocity. We used the azimuth as a feedback for the rotation of the wheels to get the correct trajectory, and the distance from the goal as a feedback for the speed of the robot and the distance to run. [2]

A step by step approach provides a good scenario for an onset continuous approach.

All informations requested from the sensors regarding travelelled distance and angle measurements play a key role in the success of the testing. The velocity was set to 0.5 m/s for a distance shorter than 1m, 0.1 m/s shorter 20cm and 0.025 m/s, for a distance shorter than 2 cm. When it stops, a computation of the distance is done between its position, given by GPS and B position, and also the azimuth of its position. This one is compared with the azimuth of the desired trajectory, so that the angle the robot has to turn is:

$$\alpha = Azimuth\_desired - Azimuth\_robot$$

If $\alpha<0$ the robot turns clockwise, $\alpha>0$ if the robot turns counter-clockwise.

We have decided that the robot should run 50% of the goal distance on each step. After that the robot stops and gets a new position from GPS and therefore a new distance from goal is computed [2].

4. Conclusion

GPS RTK is suitable for obtaining centimeter accuracy on the positioning of any type of robot in the outdoor environment. As shown in this paper DGPS is not difficult to setup and a Kalman filter approach is aiding to this sort of application, by maintaining the robot path as smooth as possible. Issues appear when using the robot indoors, where GPS signals cannot propagate, although lots of surfaces allow GPS signals to pass. This issue is solvable when integration of a reliable inertial navigation sensor is applied on the robotics platform.

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