Urban Localization Method for Mobile Robots Based on Dead Reckoning Sensors, GPS, and Map Matching

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ECGR 6185 Adv. Embedded Systems

January 30th 2013

Mobile robot- hardware

- The GPS Flexpak-V2 from Novatel Inc receivers are used as a location measurement device which operates at 20 Hz
- Two GPS receivers are used. One of the GPS receivers called “rover GPS” is installed at the top of the robot. The second GPS receiver called “base station GPS” is installed at the roof of tallest building in the experiment area.
- The gyroscope(CruizCore R1001H) is installed at the center of the robot body as a heading sensor.

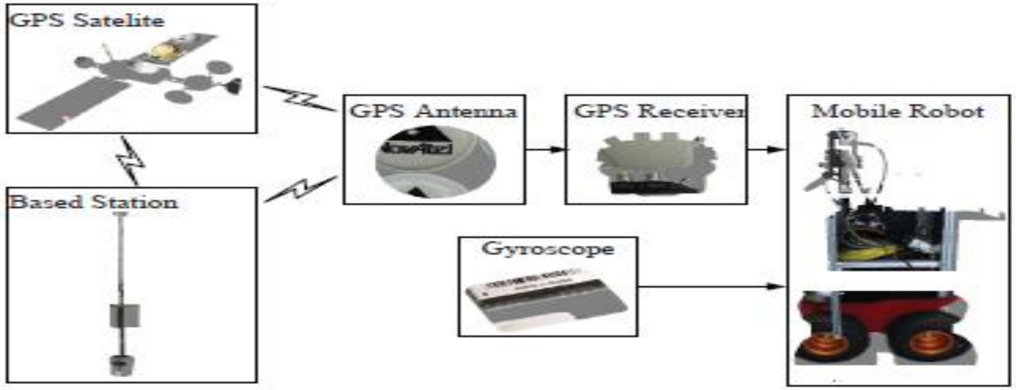

Fig 1. Mobile robot hardware setup

Map Construction

- The grid-based map is used for map matching and the topological map is used for path planning
- The topological map contains information about the position of the nodes for the robot's waypoints. The positions of the nodes are achieved by gathering the GPS static positions for some sufficient periods of time.

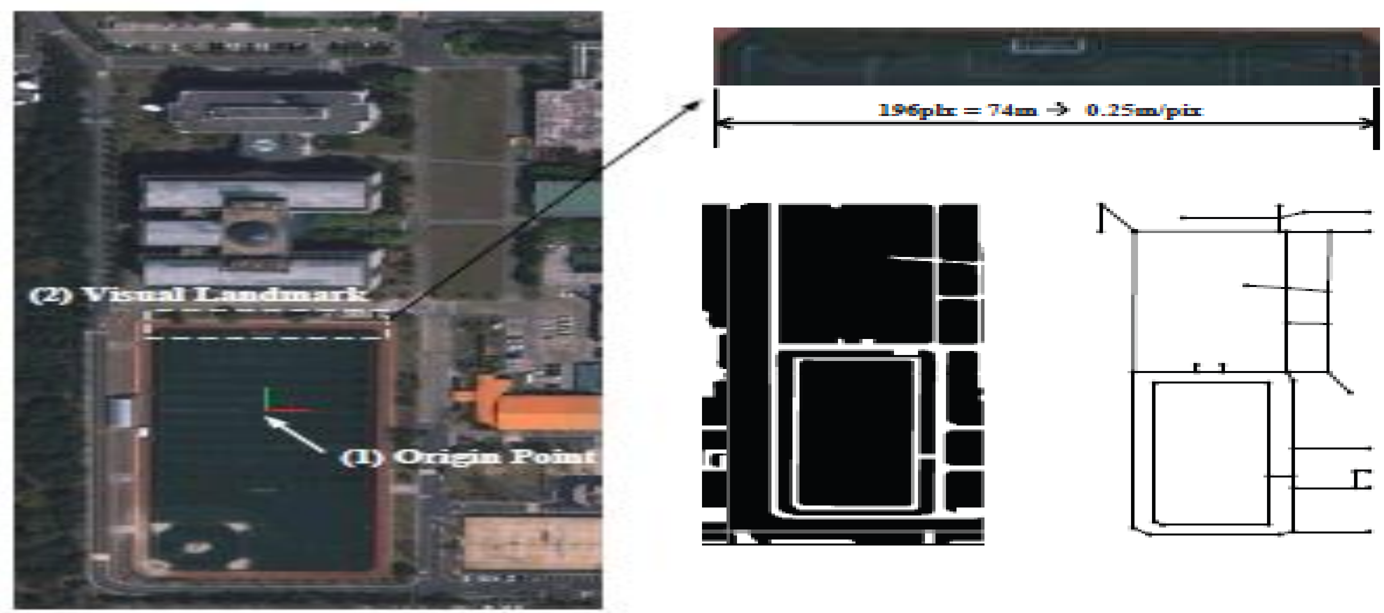

Fig 2. Map contruction

Calculating control action for robot

- The position of the robot at any instance is given by the robot controller API based on the odometer .

$$\mathbf{x}_t^o = [\ x_t \quad y_t \quad \theta_t\ ]^T$$

- During the period from time t-1 to t, the odometer gives three actions information: first rotation Δθ1, translation d, and second rotation Δθ2 using which the control action for the robot is calculated.

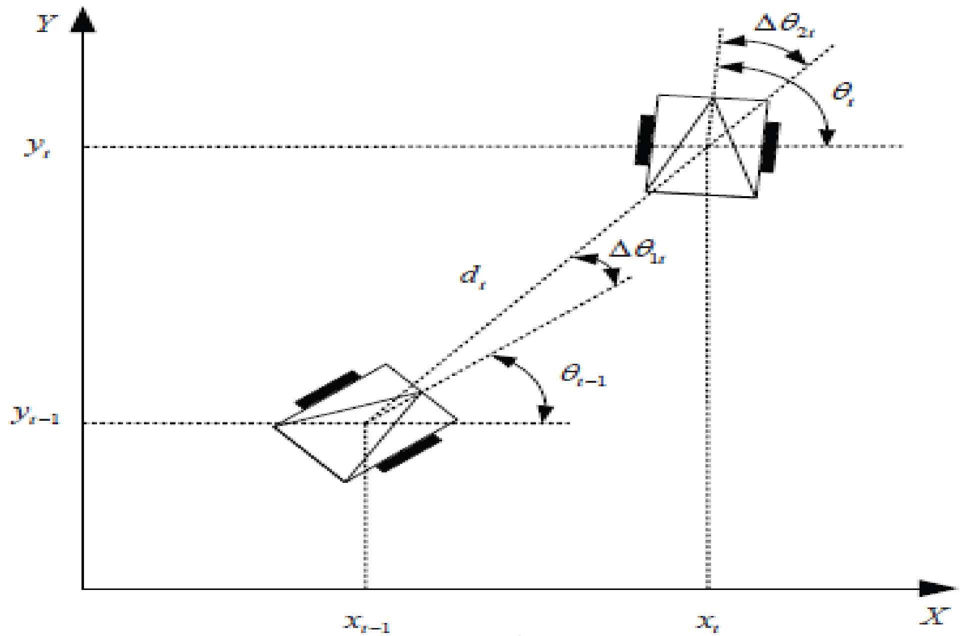

Fig 3. Kinematics of robot

$$\mathrm{u}_t = \begin{bmatrix} d_t \\ \Delta\theta_{1\,t} \\ \Delta\theta_{2\,t} \end{bmatrix} = \begin{bmatrix} \sqrt{\left(x_t^o - x_{t-1}^o\right)^2 + \left(y_t^o - y_{t-1}^o\right)^2} \\ \tan^{-1}\left(\frac{y_t^o - y_{t-1}^o}{x_t^o - x_{t-1}^o}\right) - \theta_{t-1} \\ \theta_t - \tan^{-1}\left(\frac{y_t^o - y_{t-1}^o}{x_t^o - x_{t-1}^o}\right) \end{bmatrix}$$

Extended Kalman Filter (EKF)

- The extended Kalman filter (EKF) is the nonlinear version of the Kalman filter.

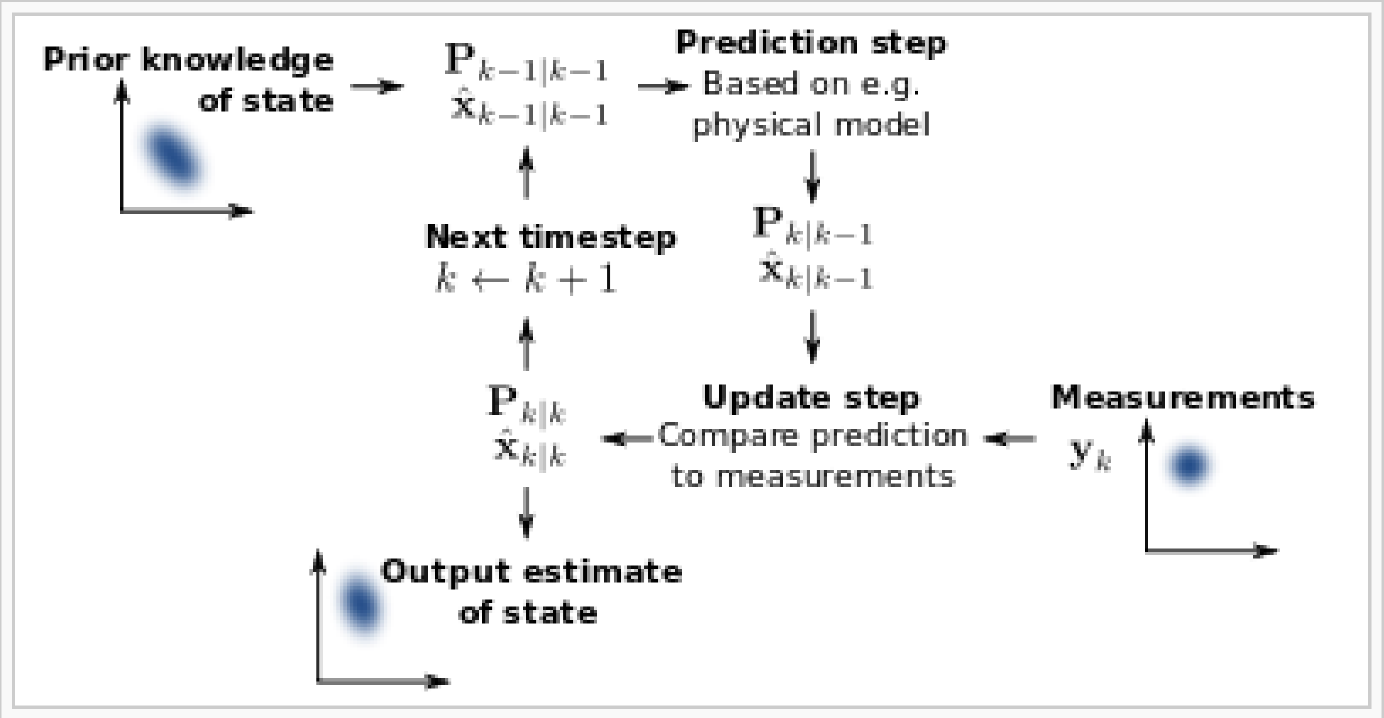

Fig 4. Kalman Filter working principle

Extended Kalman Filter (EKF)

- EKF consists of four steps, which include prediction, position measurement, validation on position measurement and the update step.
- EKF formulates the predicted position under the influence of noise w_t which might exist in control actions information. The noise at prediction step is assumed to be Gaussian noise with zero mean and its covariance matrix Q.

$$\hat{\mathbf{x}}_t = \mathbf{g}\left(\mathbf{x}_{t-1}, \mathbf{u}_t\right) + \mathbf{w}_t; \quad \mathbf{w}_t \sim \mathbf{N}\left(\mathbf{0}, \mathbf{Q}\right)$$

$$\mathbf{g}\left(\mathbf{x}_{t-1}, \mathbf{u}_t\right) = \begin{bmatrix} x_{t-1} + d_t \cdot \cos\left(\theta_{t-1} + \Delta\theta_{1\,t}\right) \\ y_{t-1} + d \cdot \sin\left(\theta_{t-1} + \Delta\theta_{1\,t}\right) \\ \theta_{t-1} + \Delta\theta_{1\,t} + \Delta\theta_{2\,t} \end{bmatrix}$$

Step 2:Position Measurement

- The Kalman gain and the residual between measurement likelihood and real measurement needs to be calculated before the update step

$$\hat{\mathbf{z}}_t = \mathbf{h}(\hat{\mathbf{x}}_t) + \mathbf{v}_t; \quad \mathbf{v_t} \sim \mathbf{N}(\mathbf{0}, \mathbf{R})$$

$$\mathbf{R} = \begin{bmatrix} \Sigma_{gps} & \mathbf{0} \\ \mathbf{0} & \Sigma_{gyro} \end{bmatrix} = \begin{bmatrix} \sigma^2_{x\ gps} & 0 & 0 \\ 0 & \sigma^2_{y\ gps} & 0 \\ 0 & 0 & \sigma^2_{\theta\ gyro} \end{bmatrix}$$

- Since the robot receives the measurement as position (x_{gps},y_{gps}) from the GPS and heading angle θ_{gyro} from the gyroscope, the likelihood of measurement h ($\hat{x}_t$) is the predicted position itself

$$\mathbf{h}(\hat{\mathbf{x}}_t) = \begin{bmatrix} \hat{x}_t \\ \hat{y}_t \\ \hat{\theta}_t \end{bmatrix}, \nabla\mathbf{h}(\hat{\mathbf{x}}_t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Step 3- Validation of Position Measurement

- The measurement of GPS and gyroscope at time t is wrapped z_t

$$\mathbf{z}_t = \begin{bmatrix} x_{gps} & y_{gps} & \theta_{gyro} \end{bmatrix}^T$$

- Before the robot uses the information from GPS and gyroscope to update the predicted position, we need to confirm the correctness of GPS measurement

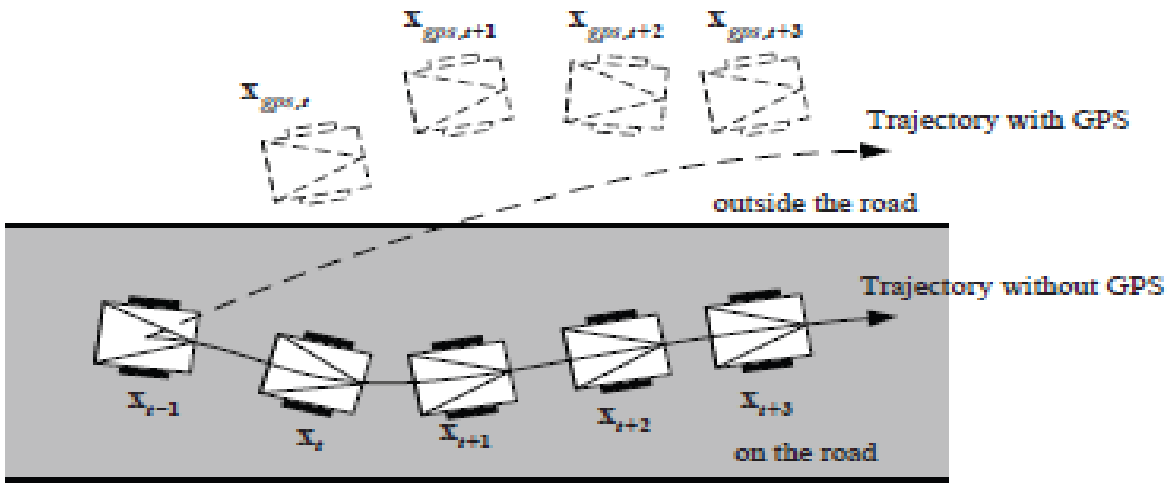

Fig 5. The map matching process to filter out false GPS measurement

Step 3- Validation of Position Measurement

- The correctness of the GPS measurement is verified by following the below two steps:
    1. Map Matching of GPS-If the GPS position falls outside the main road, the information will be discarded and the update step will not be performed
    2. Mahanolobis Distance- The robot calculates two Mahanolobis distance of location d_{Loc} and heading angle d

$$\Sigma_{Loc} = \hat{\Sigma}_{Loc} + \Sigma_{gps}$$
$$\Sigma_{\theta} = \hat{\Sigma}_{\theta} + \Sigma_{gyro}$$

$$d_{Loc} = \left(\begin{bmatrix} x_{gps} & y_{gps} \end{bmatrix} - \begin{bmatrix} \hat{x}_t & \hat{y}_t \end{bmatrix} \right) \cdot \left[\Sigma_{Loc} \right]^{-1} \cdot \left(\begin{bmatrix} x_{gps} & y_{gps} \end{bmatrix} - \begin{bmatrix} \hat{x}_t & \hat{y}_t \end{bmatrix} \right)^T$$

$$d_{\theta} = \left(\theta_{gyro} - \hat{\theta}_t \right) \left[\Sigma_{\theta} \right]^{-1} \left(\theta_{gyro} - \hat{\theta}_t \right)^T$$

Step 3-Validation of Position Measurement

- If the $d_\theta > d_{\theta T}hreshold$, the GPS measurement will not be used for the update. Same policy is also applied for the gyroscope measurement if the $d_{Loc} > d_{LocT}hreshold$

Case 1: if $d_\theta > d_{\theta_T hreshold}$, and $d_{Loc} > d_{Loc_T hreshold}$

$$\mathbf{W} = \begin{bmatrix} (\sigma^2_{x\ gps})^{-1} & 0 & 0 \\ 0 & (\sigma^2_{y\ gps})^{-1} & 0 \\ 0 & 0 & \left(\sigma^2_{\theta\ gyro}\right)^{-1} \end{bmatrix}$$

$$\mathbf{z}_t = \begin{bmatrix} x_{gps} & y_{gps} & \theta_{gyro} \end{bmatrix}^T$$

Case 2: if $d_\theta < d_{\theta_T hreshold}$, and $d_{Loc} \geq d_{Loc_T hreshold}$

$$\mathbf{W} = \begin{bmatrix} (\sigma^2_{x\ gps})^{-1} & 0 & 0 \\ 0 & (\sigma^2_{y\ gps})^{-1} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{z}_t = \begin{bmatrix} x_{gps} & y_{gps} & 0 \end{bmatrix}^T$$

Case 3: if $d_\theta > d_{\theta_T hreshold}$, and $d_{Loc} < d_{Loc_T hreshold}$

$$\mathbf{W} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \left(\sigma^2_{\theta\ gyro}\right)^{-1} \end{bmatrix}$$

$$\mathbf{z}_t = \begin{bmatrix} 0 & 0 & \theta_{gyro} \end{bmatrix}^T$$

Step 4- Update & Psuedo-code

- If the GPS and gyroscope measurement are found to be valid, then Kalman gain is calculate using equation

$$\mathbf{K}_t = \left(\hat{\Sigma}_1^{-1} + \mathbf{W}\right)^{-1} \cdot \mathbf{W}$$

Algorithm:Urban Localization

```
Initialization:
    x_0 and Σ_0 are initialized
Input:
    Number of sensor measurement(N)
for 1 to N do
    Position Prediction:
        x̂_t is calculated in (4).
    Map Matching:
        if (x_gps, y_gps) is outside the road
            return
    Mahalanobis distance:
            z_t is validated in (17) to (19)
    Position estimation:
            x_t and Σ_t are calculated in (21) to (22)
end for
```

Table 1. Psuedo code of proposed method

Experimental Results

- Two experiments were conducted in urban environments one using a mobile robot and another using cart similar to mobile robot.
- The closed loop trajectory is approximately 1420 m and the velocity of the cart is .2m/s.
- The resolution for the map is .25m/s

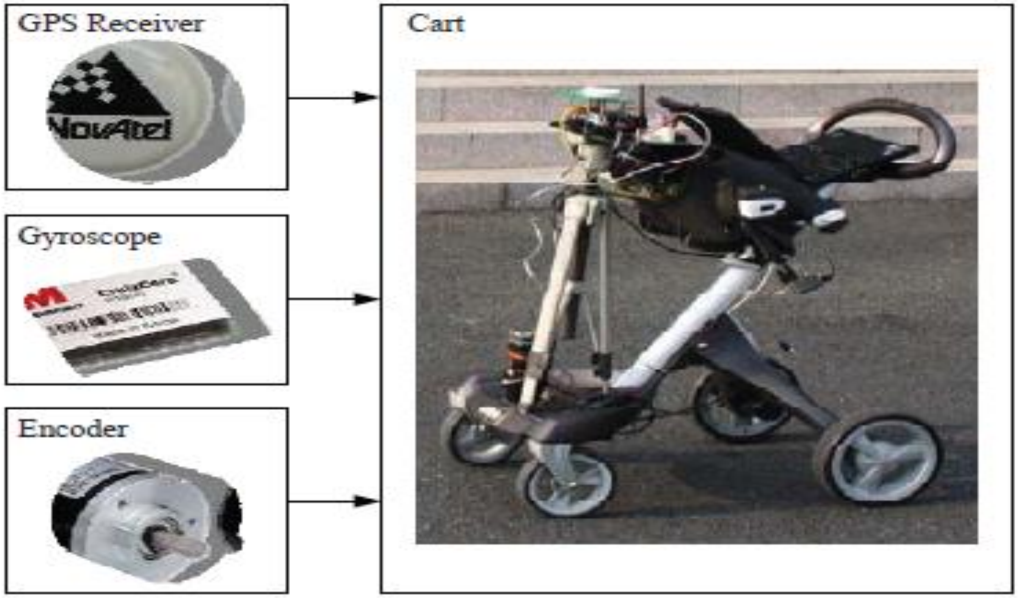

Fig 6. Cart platform with GPS, encoder and gyroscope

Experimental Results

- GPS measurement are marked as yellow dot and yellow rectangular point shows the GPS measurement which fell outside the road

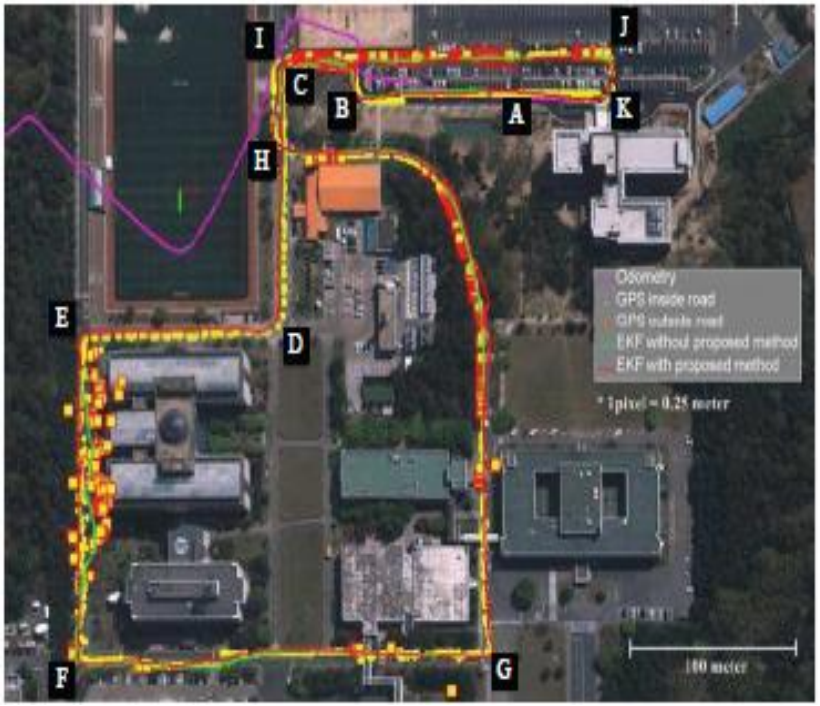

Fig 7. Experiment results using cart similar to mobile robot

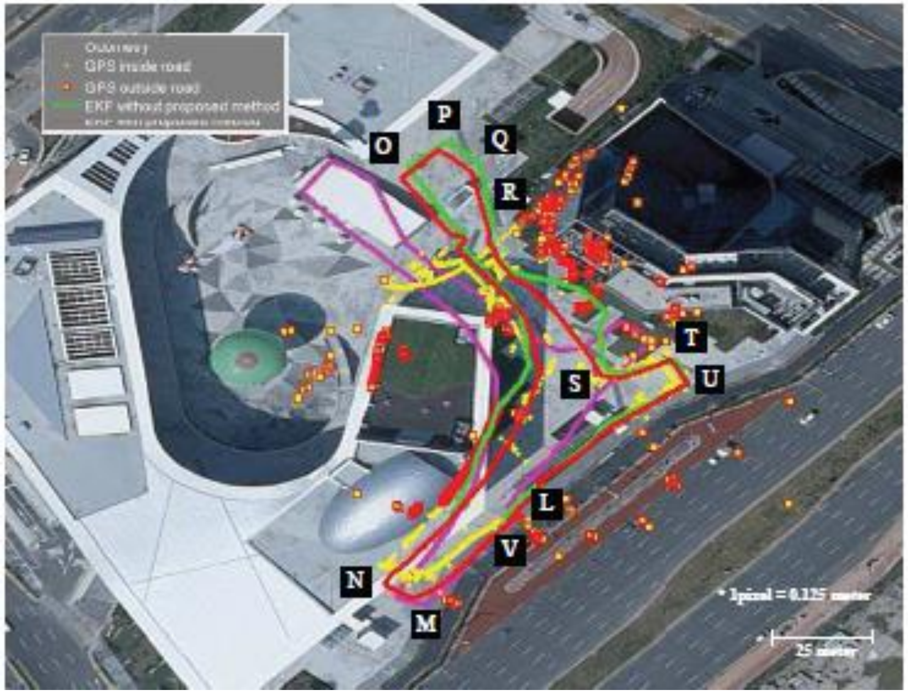

Fig 8. Experimental results using P3AT mobile robot

Experimental Results

- GPS failed to show the real robot trajectory especially around nodes E and F(Fig.7), also in between nodes R and S(Fig.8) due to blocking and multipath effect from seven –stories building and dense trees respectively.
- The line connecting nodes E and F is chosen as reference and error of EKF is calculated . The comparison of EKF with and without proposed method is shown in Fig.9

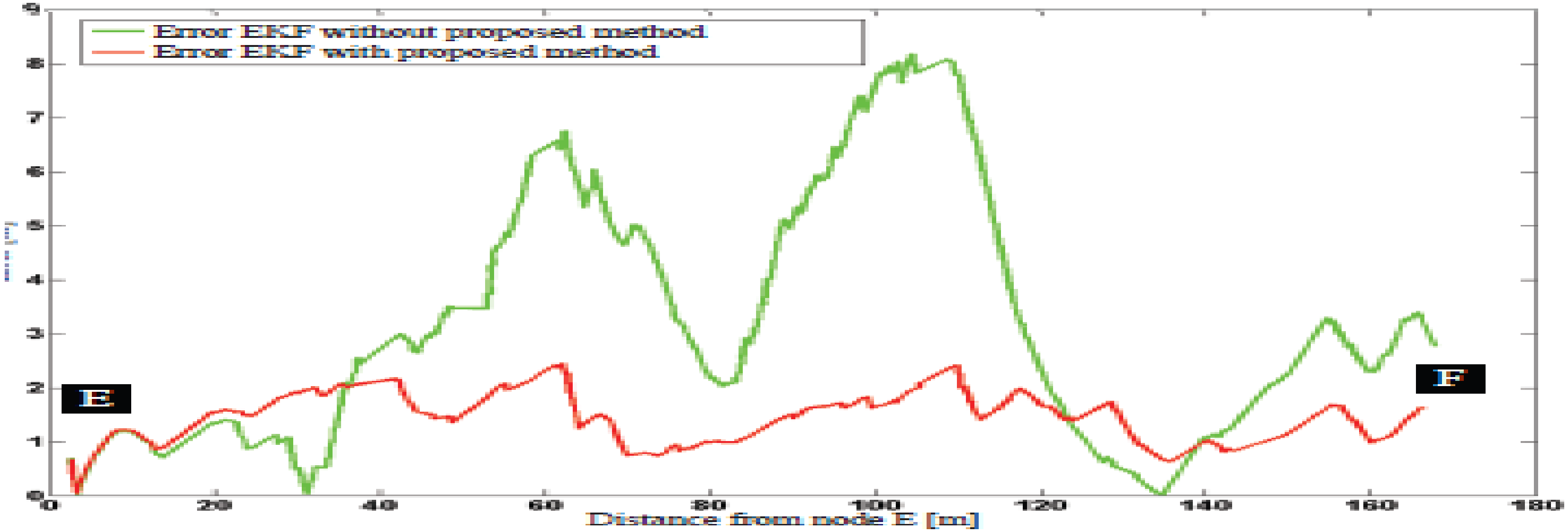

Fig 9. Error comparison between EKF with and without proposed method

Conclusion

- The proposed method takes benefits of the map matching process combined with Mahanolobis distance approach to filter out the erroneous GPS measurement under the assumption that the robot operates only at the main road.
- The proposed method shows superior result compared to the standard EKF
- By using proposed method, the robot can be successfully localized until the final goal.
- Future works would include research to avoid the assumption that mobile robots are always on the road and attempt to perform road segmentation automatically.

References

[1] Working principle of Kalman filter (Fig 4).
[Web Photo] http://en.wikipedia.org/wiki/Kalman_filter

[2] Yu-Cheol Lee; Christiand, C.; Wonpil Yu; Sunghoon Kim, “Urban Localization Method for Mobile Robots Based on Dead Reckoning Sensors, GPS, and Map Matching”, IEEE Conference on System, Man and Cybernetics (SMC), 2011