Data Fusion of Dual Foot-Mounted INS to Reduce the Systematic Heading Drift

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Background

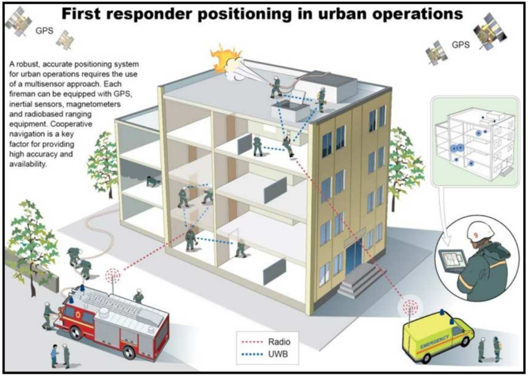


Figure: First Responder System

First Responder System

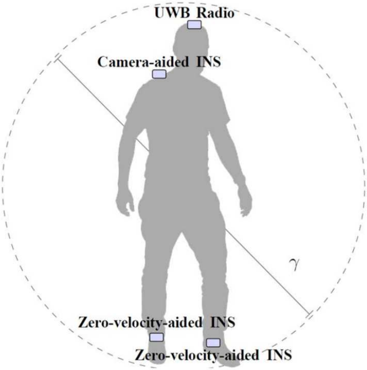


Figure: Illustration of the possible placements of the subsystem in a pedestrian navigation system and the maximum spatial separation γ between the subsystems.

- The different systems tracks the states of different points on the body.
- There is a non-rigid relationship between the navigation points.
- There is an upper limit γ how spatially separated the systems can be.

Image source: I. Skog, J.-O. Nilsson and P. Handel, "Fusing the information from two navigation systems using an upper bound on their maximum spatial separation," to appear in IPIN dec 2012.

Gait Cycle Phases

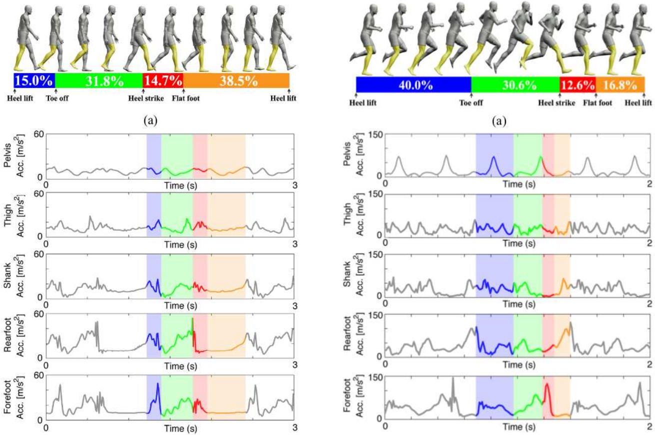
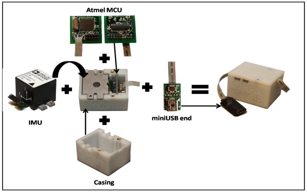


Figure: Gait cycle phases during walking and running - (blue) push-off, (green) swing, (red) heel-strike, (orange) stance

Image Source: Kwakkel, S.P., Lachapelle, G., Cannon, M.E., "GNSS Aided In Situ Human Lower Limb Kinematics During Running," *Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008)*, Savannah, GA, September 2008, pp. 1388-1397.

Problem Description



(a) Building an OpenShoe Unit

(b) Shoe equipped with OpenShoe unit

1. The main drawback of the existing foot-mounted ZUPT aided INS is the Systematic Heading Drift.
2. The estimated trajectories drift away from the actual path as time progresses (despite having a calibration phase).
3. One possible way these errors can be mitigated is to use foot-mounted INS on both feet such that the symmetrical modeling errors cancel out.
4. In our paper, we have assumed the maximum separation between the two foot-mounted IMUs as γ.

For more details visit http://openshoe.org

Systematic Heading Drift - Simulation

Figure: OpenShoe unit mounted on the left foot of a user asked to walk on a level path in the first floor of the Signal Processing Building, Indian Institute of Science, Bangalore, India.

Observations

- The duration of the phases[1] of the gait cycle for walkers shows that for more than 50% of the time the foot occupies Heel-strike and Stance phase.
- And the errors are minimized when the foot is stationary. (ZUPT occurrences)

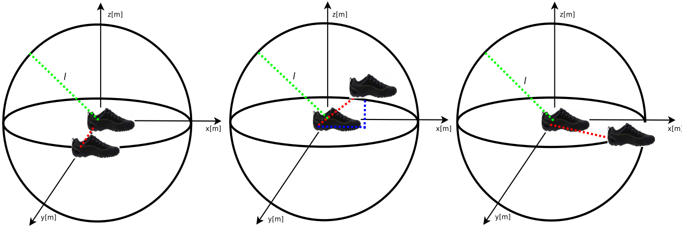


Figure: Illustration of the motion of the feet during motion. The sphere indicates the range constraint on the spatial separation between the two feet with the feet that is stationary as the center of the sphere.

[1] Kwakkel, S.P., Lachapelle, G., Cannon, M.E., "GNSS Aided In Situ Human Lower Limb Kinematics During Running," *Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008)*, Savannah, GA, September 2008, pp. 1388-1397.

Zero-Velocity Updates

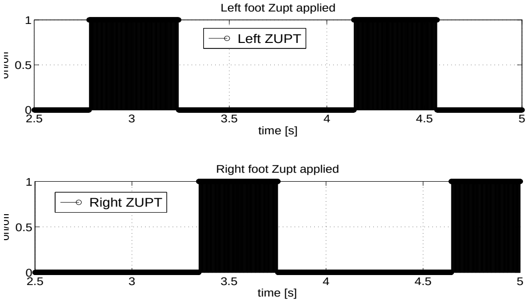
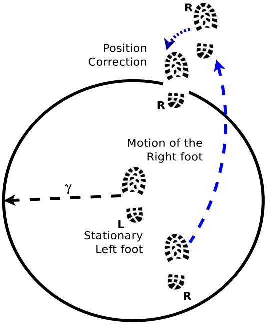


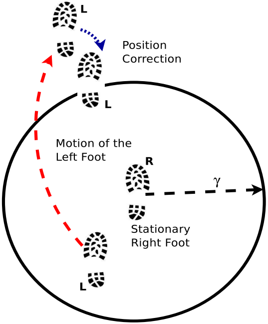
Figure: A snapshot of the ZUPTs occurrences for left and right foot from time instance 2.5[s] to 5[s] for a Straight Path trajectory using the GLRT algorithm[2]

[2] I. Skog, P. Handel, J. Nilsson, and J. Rantakokko, "Zero-velocity detection - an algorithm evaluation," *Biomedical Engineering, IEEE Transactions on*, vol. 57, pp. 2657 –2666, nov. 2010.

Sphere Limit Method - Position Correction Illustration



(a) Right foot position estimates after correction.



(b) Left foot position estimates after correction.

Figure: Cross section of a sphere of radius γ, which is the maximum possible spatial separation between the two feet.

Proposed Solution - Position Correction

- Let $d_k^i = norm([\hat{\mathbf{x}}_k^i]_{1:3} - [\hat{\mathbf{x}}_k^j]_{1:3})$ represent the separation between the two navigation systems $i, j \in \{l, r\}$ and $i \neq j$, at any given instance of time k where $\hat{\mathbf{x}}_k^i$ is a 9-state vector consisting of position, velocity and attitude information.
- If the i^{th} navigation systems is in stance phase (ZuPT is ON), the j^{th} navigation system is not in stance phase and the separation between them is $d_k^j > \gamma$, then the new position coordinates of the j^{th} navigation system is obtained as follows

$$\hat{\mathbf{p}}_k^j = \frac{1}{d_k^i}\left((d_k^i - \gamma)[\hat{\mathbf{x}}_k^i]_{1:3} + \gamma[\hat{\mathbf{x}}_k^j]_{1:3}\right). \tag{1}$$

- Equation (1) represents the orthogonal projections of the position estimates of the foot that is in motion on to the surface of the sphere.

Existing Algorithm - Pseudo Code

Pseudo code for the algorithm *without* range constraint on the spatial separation of the two navigation systems i, j where $i, j \in \{l, r\}$ and $i \neq j$.

$k \leftarrow 0$
$\mathbf{P}^i_k, \mathbf{Q}^i_k, \mathbf{R}^i_k, \mathbf{H}^i_k \leftarrow$ **Process**{Initialize Filter}
$\mathbf{P}^j_k, \mathbf{Q}^j_k, \mathbf{R}^j_k, \mathbf{H}^j_k \leftarrow$ **Process**{Initialize Filter}
$\hat{\mathbf{x}}^i_k \leftarrow$ **Process**{Initial Nav State}
$\hat{\mathbf{x}}^j_k \leftarrow$ **Process**{Initial Nav State}
loop
    $k \leftarrow k + 1$
    $\hat{\mathbf{x}}^i_k \leftarrow$ **Process**{Nav Equations}
    $\hat{\mathbf{x}}^j_k \leftarrow$ **Process**{Nav Equations}
    $\mathbf{P}^i_k \leftarrow \mathbf{F}^i_k \mathbf{P}^i_{k-1} {\mathbf{F}^i_k}^T + \mathbf{G}^i_k \mathbf{Q}^i_k {\mathbf{G}^i_k}^T$
    $\mathbf{P}^j_k \leftarrow \mathbf{F}^j_k \mathbf{P}^j_{k-1} {\mathbf{F}^j_k}^T + \mathbf{G}^j_k \mathbf{Q}^j_k {\mathbf{G}^j_k}^T$
    for $s \in \{l, r\}$ **do**
        if zupt^s_k **is on then**
            $\mathbf{K}^s_k \leftarrow \mathbf{P}^s_k {\mathbf{H}^s_k}^T [\mathbf{H}^s_k \mathbf{P}^s_k {\mathbf{H}^s_k}^T + \mathbf{R}^s_k]^{-1}$
            $\delta \mathbf{x}^s_k \leftarrow -\mathbf{K}^s_k [\hat{\mathbf{x}}^s_k]_{4:6}$
            $\hat{\mathbf{x}}^s_k \leftarrow$ **Process**{Correct Nav States}
            $\mathbf{P}^s_k \leftarrow [\mathbf{I} - \mathbf{K}^s_k \mathbf{H}^s_k] \mathbf{P}^s_k$
        end if
    end for
end loop

- $k \leftarrow$ sample index.
- $\mathbf{P}_k \leftarrow$ 9-state covariance matrix.
- $\mathbf{Q}_k = \mathbb{E}\{\mathbf{w}^1_k (\mathbf{w}^1_k)^T\}$ is the process noise due to gyroscope and accelerometer and $\mathbf{w}^1_k \in \mathbb{R}^6$.
- $\mathbf{R}_k = \mathbb{E}\{\mathbf{w}^2_k (\mathbf{w}^2_k)^T\}$ is the zupt occurrence measurement noise and $\mathbf{w}^2_k \in \mathbb{R}^3$.
- $\mathbf{H}_k = \begin{bmatrix} \mathbf{0}_3 & \mathbf{I}_3 & \mathbf{0}_3 \end{bmatrix}$ is the observation matrix for zupt algorithm.
- $\hat{\mathbf{x}}_k$ is the estimated 9-state vector containing position, velocity and attitude estimates.
- $\mathbf{F}_k$ and $\mathbf{G}_k$ define the state space model.
- l and r represent the left and right navigation system respectively.

- Data Collection
  - Collected the data on the first floor of Signal Processing Building, Indian Institute of Science, Bangalore, India.
  - The tiles in the building were used as marker beacon to collect data in a controlled manner. Each tile of length 2 feet $\times$ 2 feet.
  - The maximum stride length never exceeded 0.6096[m].
- Assumptions
  - The two IMUs are aligned in the same direction.
  - Sampling happens at full speed (820 Hz).

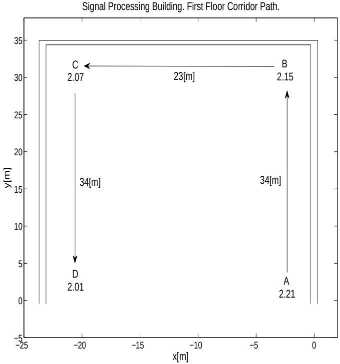
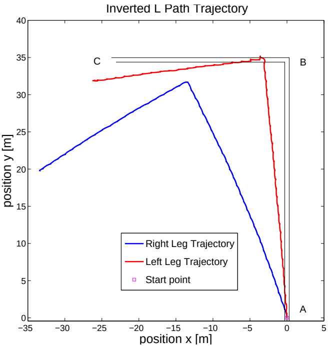
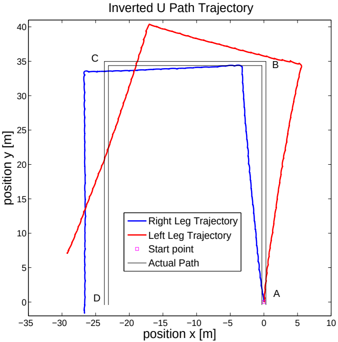


Figure: A layout of the first floor of the Signal Processing Building. It is in inverted U shape. The parallel arms are 34[m] in length and the perpendicular arm is 23[m] in length.

Simulation Results - Existing Algorithm



(a) Left and Right foot trajectory for Inverted 'L' Path along segment AB and BC.



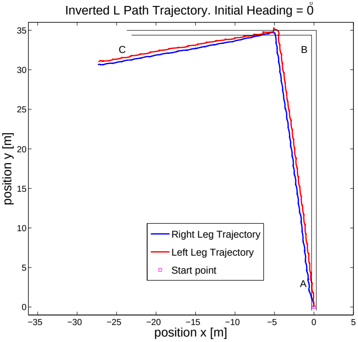
(b) Left and Right foot trajectory for Inverted 'U' Path along segment AB, BC and CD

Figure: Trajectories obtained after applying the algorithm without any range constraint on the spatial separation between two feet. Initial heading value is equal to 0° for all data sets.

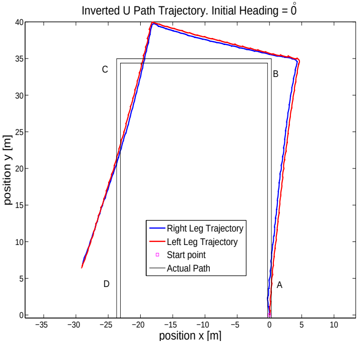
Proposed Algorithm - Sphere Limit Method - Pseudo Code

$k \leftarrow 0$
$\mathbf{P}_k^i, \mathbf{Q}_k^i, \mathbf{R}_k^i, \mathbf{H}_k^i, \mathbf{H'}_k^i \leftarrow$ **Process**{Initialize Filter}
$\mathbf{P}_k^j, \mathbf{Q}_k^j, \mathbf{R}_k^j, \mathbf{H}_k^j, \mathbf{H'}_k^j \leftarrow$ **Process**{Initialize Filter}
$\hat{\mathbf{x}}_k^i \leftarrow$ **Process**{Initial Navigation State}
$\hat{\mathbf{x}}_k^j \leftarrow$ **Process**{Initial Navigation State}
loop
  $k \leftarrow k+1$
  $\hat{\mathbf{x}}_k^i \leftarrow$ **Process**{Navigation Equations}
  $\hat{\mathbf{x}}_k^j \leftarrow$ **Process**{Navigation Equations}
  $\mathbf{P}_k^i \leftarrow \mathbf{F}_k^i \mathbf{P}_{k-1}^i \mathbf{F}_k^{i\,T} + \mathbf{G}_k^i \mathbf{Q}_k^i \mathbf{G}_k^{i\,T}$
  $\mathbf{P}_k^j \leftarrow \mathbf{F}_k^j \mathbf{P}_{k-1}^j \mathbf{F}_k^{j\,T} + \mathbf{G}_k^j \mathbf{Q}_k^j \mathbf{G}_k^{j\,T}$
  for $i, j \in \{l, r\}$ and $i \neq j$ **do**
    if zupt$_k^i$ is **on then**
      $\mathbf{K}_k^i \leftarrow \mathbf{P}_k^i \mathbf{H}_k^{i\,T} [\mathbf{H}_k^i \mathbf{P}_k^i \mathbf{H}_k^{i\,T} + \mathbf{R}_k^i]^{-1}$
      $\delta \mathbf{x}_k^i \leftarrow -\mathbf{K}_k^i [\hat{\mathbf{x}}_k^i]_{4:6}$
      $\hat{\mathbf{x}}_k^i \leftarrow$ **Process**{Correct Nav. States}
      $\mathbf{P}_k^i \leftarrow [\mathbf{I} - \mathbf{K}_k^i \mathbf{H}_k^i] \mathbf{P}_k^i$
      if zupt$_k^j$ is **off** and $d_k^j > \gamma$ **then**
        $\hat{\mathbf{p}}_k^j \leftarrow$ **Process**{Correct Position}
        $\mathbf{K'}_k^j \leftarrow \mathbf{P}_k^j \mathbf{H'}_k^{j\,T} [\mathbf{H'}_k^j \mathbf{P}_k^j \mathbf{K'}_k^{j\,T} + \mathbf{R'}_k^j]^{-1}$
        $\delta \mathbf{x}_k^j \leftarrow \mathbf{K'}_k^j (\hat{\mathbf{p}}_k^j - [\hat{\mathbf{x}}_k^j]_{1:3})$
        $\hat{\mathbf{x}}_k^j \leftarrow$ **Process**{Correct Nav. States}
        $\mathbf{P}_k^j \leftarrow [\mathbf{I} - \mathbf{K'}_k^j \mathbf{H'}_k^j] \mathbf{P}_k^j$
      end if
    end if
  end for
end loop

- $k \leftarrow$ sample index.
- $\mathbf{P}_k \leftarrow$ 9-state covariance matrix.
- $\mathbf{Q}_k = \mathbb{E}\{\mathbf{w}_k^1 (\mathbf{w}_k^1)^T\}$ is the process noise due to gyroscope and accelerometer and $\mathbf{w}_k^1 \in \mathbb{R}^6$.
- $\mathbf{R}_k = \mathbb{E}\{\mathbf{w}_k^2 (\mathbf{w}_k^2)^T\}$ is the zupt occurrence measurement noise and $\mathbf{w}_k^2 \in \mathbb{R}^3$.
- $\mathbf{R'}_k = \mathbb{E}\{\mathbf{w}_k^3 (\mathbf{w}_k^3)^T\}$ is the position correction measurement noise and $\mathbf{w}_k^3 \in \mathbb{R}^3$.
- $\mathbf{H}_k = \begin{bmatrix} \mathbf{0}_3 & \mathbf{I}_3 & \mathbf{0}_3 \end{bmatrix}$ is the observation matrix for zupt algorithm.
- $\mathbf{H'}_k = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0}_3 & \mathbf{0}_3 \end{bmatrix}$ is the observation matrix for position correction algorithm.
- $\hat{\mathbf{x}}_k$ is the estimated 9-state vector containing position, velocity and attitude estimates.
- $\mathbf{F}_k$ and $\mathbf{G}_k$ define the state space model.
- l and r represent the left and right navigation system respectively.

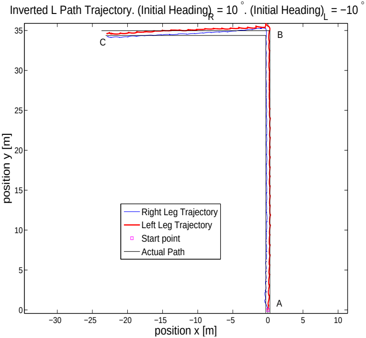


(a) Left and Right foot trajectory for Inverted 'L' Path along segment AB and BC using proposed algorithm.

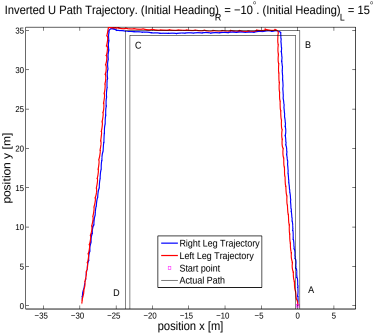


(b) Left and Right foot trajectory for Inverted 'U' Path along segment AB, BC and CD using proposed algorithm

Figure: Trajectories obtained after applying the proposed algorithm with initial heading value equal to 0°. $\gamma = 0.6096$[m] for all the above trajectories.



(a) Left and Right foot trajectory for Inverted 'L' Path along segment AB and BC using proposed algorithm with initial heading for left equal to -10° and initial heading for right equal to 10°.



(b) Left and Right foot trajectory for Inverted 'U' Path along segment AB, BC and CD using proposed algorithm with initial heading for right equal to -10° and initial heading for left equal to 15°.

Figure: Trajectories obtained after applying the proposed algorithm with an estimate of initial heading value available before hand. $\gamma = 0.6096$[m].

Experimental Setup - 2

- A user was equipped two OpenShoe navigation system and asked to walk along a straight line for 110[m].
- As reference points plates with imprints of the shoes were positioned at 0[m], 10[m], and 110[m].
- Twenty trajectories with 4 different OpenShoe units were collected.
- The data was the processed with the proposed method and compared with the existing methods.

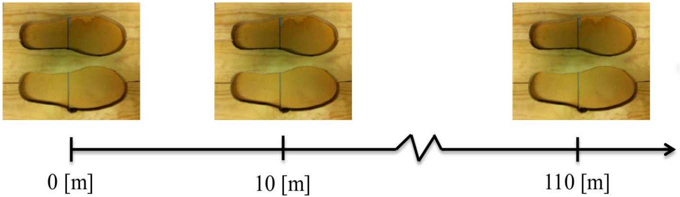


Figure: Illustration of experimental setup.

Image source: Isaac Skog, John-Olof Nilsson, Dave Zachariah, and Peter Hndel. Fusing the Information from Two Navigation Systems Using an Upper Bound on Their Maximum Spatial Separation, In proc. IPIN 2012, nov 2012.

Simulation Results

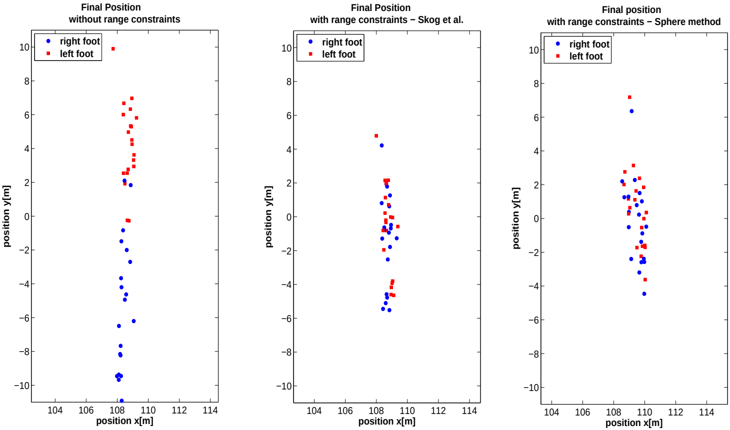


Figure: Scatter plot of end position of the two systems *with* and *without* range constraint for existing[3] and proposed algorithm from walking along a 110[m] straight line. The scatter plots obtained are for $\gamma = 1$[m] for all the datasets for the existing and proposed algorithm. The heading estimate is obtained at 10[m].

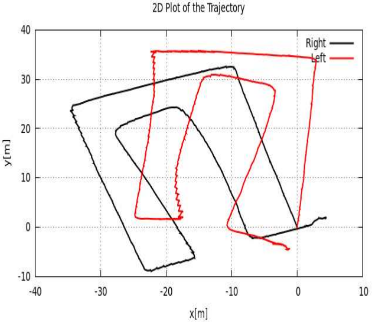
[3] Isaac Skog, John-Olof Nilsson, Dave Zachariah, and Peter Handel. Fusing the Information from Two Navigation Systems Using an Upper Bound on Their Maximum Spatial Separation, In proc. IPIN 2012, nov 2012.

Figure: Two OpenShoe units without the proposed algorithm.

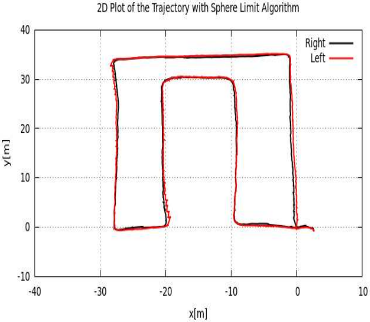
Real-time Simulation - C++ Implementation - With Data Fusion

Figure: Two OpenShoe units with the proposed Sphere Limit Method.

Real-time Simulation - C++ Implementation - Comparison



(a) Without any Data Fusion algorithm



(b) With Sphere Limit Algorithm

Figure: Final plot of the trajectory obtained for data collected on SP Building roof top, IISc Bangalore.

Thank you