Kitti DataSet localization model.

(Autonomous Vehicle Localization Using Onboard Sensors and HD-Geolocated Maps [MATLAB Project #20] - Spring 2024 Semester).

Project Link - Our submission

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Data Loading, Visualization, And Storing.

```
%Loading Dataset from extracted folder on our local machine
%Add dataset path below
dataset_path = 'C:\Users\Hazem Abdelaziz\Downloads\GP-
Github\Autonomous-Vehicle-Localization-Using-Onboars-Sensor-and-HD-Geolocated-
Maps-Project-Solution\KITTI\2011_09_29_drive_0071\2011_09_29_drive_0071_sync';
%Start loading UNSYNC OXTS data to perform same for IMU based estimates
unSyncDataset_path = 'C:\Users\Hazem Abdelaziz\Downloads\GP-
Github\Autonomous-Vehicle-Localization-Using-Onboars-Sensor-and-HD-Geolocated-
Maps-Project-Solution\KITTI\2011_09_29_drive_0071\2011_09_29_drive_0071_extract';
```

```
%for GPS data (Where LLA_to_Local function script exists)
mainDirectory = 'C:\Users\Hazem Abdelaziz\Downloads\GP-Github\Autonomous-Vehicle-
Localization-Using-Onboars-Sensor-and-HD-Geolocated-Maps-Project-Solution\KITTI';
%Go to images folder and check for how many images in there to represents
%number of frames
rgbFolderPath = strcat(dataset_path, '\image_02\data');
grayFolderPath = strcat(dataset_path, '\image_00\data');
pngFiles = dir(fullfile(rgbFolderPath, '*.png'));
rgbVector = cell(1, numel(pngFiles));
grayVector = cell(1, numel(pngFiles));
%For Unsynced data
%Go to OXTS folder and check for how many Samples in there to represents
%number of frames
unsyncOxtsFolderPath = strcat(unSyncDataset_path, '\oxts\data');
unsyncOxtsFiles = dir(fullfile(unsyncOxtsFolderPath, '*.txt'));
%Setting number of frames and Sampling time according to certain dataset
framesNum = numel(pngFiles);
Ts = 0.1;
%And for Unsynced Data
unsyncFramesNum = numel(unsyncOxtsFiles);
unsyncIMUTs = 0.01;
```

```
%Store stereo camera first frame (For center cameras 0: Gray & 2: RGB)
gray_image = imread(fullfile(dataset_path, 'image_00\data', '0000000000.png'));
rgb_image = imread(fullfile(dataset_path, 'image_02\data', '0000000000.png'));
```

```
% Display the images
figure;
imshow(gray_image);
title('Gray Scale Image');
figure;
imshow(rgb_image);
title('Colored Image');
```

```
%Store Colored image in an image vector
% !! If the data set contains many frames this might take a while
for i = 1:numel(pngFiles)
    %Construct the full file path
    filePath = fullfile(rgbFolderPath, pngFiles(i).name);
    %Read the image and store it
    rgbVector{i} = imread(filePath);
end
```

```
%Store Gray Colored image in an image vector
camAvI = zeros(framesNum,1);
for i = 1:numel(pngFiles)
    %Construct the full file path
    filePath = fullfile(grayFolderPath, pngFiles(i).name);
    %Read the image and store it
    grayVector{i} = imread(filePath);
    camAvI(i) = mean(mean(grayVector{i}));
```

```
end
```

```
%This Cell is to save a video consisting of multiple images in a vector
%Each image of type cell
%cd('') %Here you can enter the save location
%{
outputVideo = VideoWriter('output_video.avi');
outputVideo.FrameRate = 10; %Frame rate that the images vector recorded at for a
better display
open(outputVideo);

for i = 1:numel(rgbVector)
    % Convert image from cell to matrix
    frame =rgbVector{i};

    %write the frame to the video
    writeVideo(outputVideo, frame);
end

% Close the video file
close(outputVideo);
%}
```

```
%This cell is to display the sequence of rgb colored image frames
for i = 1:numel(rgbVector)
    % Display the current image
    imshow(rgbVector{i});
    title(['Frame ', num2str(i)]); %Adding frame number as a title
    pause(0.1); %Pausing the video according to recorded frame rate
end
```

```
pcdFolderPath = strcat(dataset_path, '\velodyne_points\data');
pcdFiles = dir(pcdFolderPath);
% || CAUTION || %
%This section is to convert from bin file data to
% !! This section is to be run once to avoid overwriting and saving files
%multiple times, to convert it for the first time uncomment the section
%bellow
%{
cd(pcdFolderPath);
for i = 1:length(pcdFiles)
    filename = pcdFiles(i).name;
    if(length(filename) > 10)
        binOpen = fopen(filename, 'rb'); %Open binary in read mode
        binData = fread(binOpen, [4, inf], 'single')'; %Reading data from binary
file
        fclose(binOpen);
        extension_to_remove = '.bin';
        original_str = filename;
        start_idx = strfind(original_str, extension_to_remove);
        end_idx = start_idx + length(extension_to_remove) - 1;
        modified_str = original_str;
        modified_str(start_idx:end_idx) = '';
        save(strcat(modified_str,'.mat'), 'binData');
    end
end
%}
```

```
%visualize a LiDAR point cloud from a frame
point_cloud = load(fullfile(pcdFolderPath, '0000000000.mat'));
pcdX = point_cloud.binData(:,1);
pcdY = point_cloud.binData(:,2);
pcdZ = point_cloud.binData(:,3);
point_cloud_data = [pcdX, pcdY, pcdZ];
pcshow(point_cloud_data)
xlabel('X');
ylabel('Y');
zlabel('Z');
title('Point Cloud Visualization');
```

```
pcdMat = NaN(5000, 4, framesNum); %This matrix will hold our point cloud
pcdR = zeros(framesNum, 1); %Vector to hold average reflectivity for each frame
matFiles = dir(fullfile(pcdFolderPath, '*.mat'));
for i = 1:numel(matFiles)
    point_cloud = load(fullfile(pcdFolderPath, matFiles(i).name));
    pcdMat(1:size(point_cloud.binData(:,1)),1,i) = point_cloud.binData(:,1);
    pcdMat(1:size(point_cloud.binData(:,2)),2,i) = point_cloud.binData(:,2);
    pcdMat(1:size(point_cloud.binData(:,3)),3,i) = point_cloud.binData(:,3);
    pcdMat(1:size(point_cloud.binData(:,4)),4,i) = point_cloud.binData(:,4) *
255; %Multiplication to get actual value, denormalization
    pcdR(i) = mean(pcdMat(:,4,i));
    if(i==1)
        fprintf('Out of %d frames, Processing point cloud matching on frame
No.',framesNum);
    end
    fprintf('\b\b\b\b\b%d', i);
end
```

```
Out of 1059 frames, Processing point cloud matching on frame No.
1059
```

```
%Creating point cloud vector to downsample and filter (Preprocessing)
pointCloudObjects = cell(framesNum);
for i = 1:framesNum
    % Convert the array to a pointCloud object
    pointCloudObjects{i} = pointCloud(pcdMat(:,1:3,i));
    pointCloudObjects{i} = pcdownsample(pointCloudObjects{i}, 'gridAverage',
0.5);
    %PCD With outliers removal
    pointCloudObjects{i} = pcdenoise(pointCloudObjects{i}, 'Threshold', 0.5);
    if(i==1)
        fprintf('Out of %d frames, Processing point cloud matching on frame
No.',framesNum);
```

```
    end
    fprintf('\b\b\b\b\b%d', i);
end
```

```
Out of 1059 frames, Processing point cloud matching on frame No.
1059
```

```
%To display 3D lidar data
xlimits = [-40 40];
ylimits = [-40 40];
zlimits = [ -5 5];
coder.extrinsic('isOpen', 'pcplayer')
player = pcplayer(xlimits, ylimits, zlimits);
for i = 1:numel(matFiles)
    pcdX = pcdMat(:,1,i);
    pcdY = pcdMat(:,2,i);
    pcdZ = pcdMat(:,3,i);
    point_cloud_data = [pcdX, pcdY, pcdZ];
    % Update the plot with the point cloud for the current frame
    view(player, point_cloud_data);
    pause(0.1); % Adjust the pause duration as needed
end
```

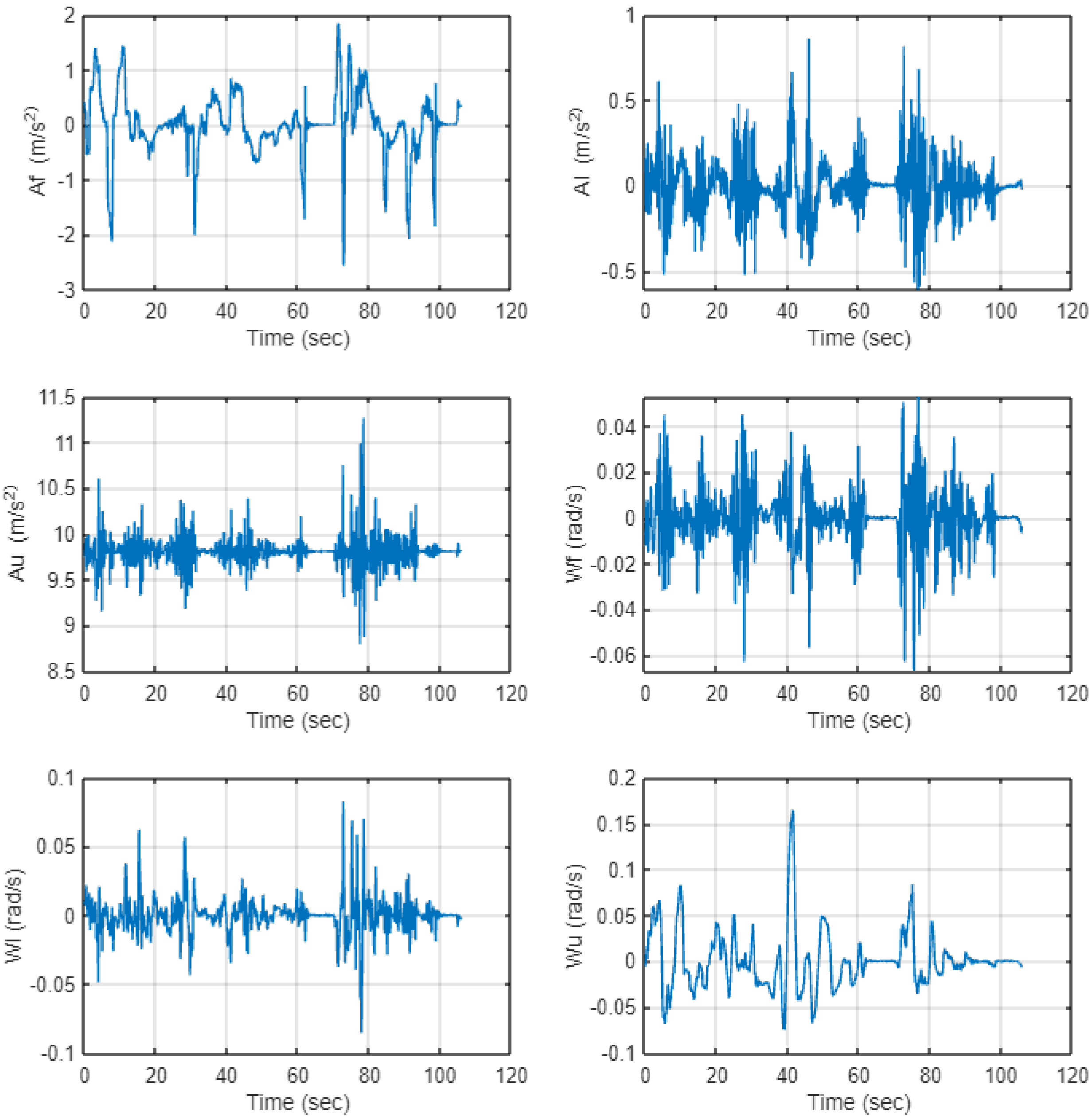
```
%To display 3D lidar data (Downsampled)
xlimits = [-40 40];
ylimits = [-40 40];
zlimits = [ -5 5];
coder.extrinsic('isOpen', 'pcplayer')
player = pcplayer(xlimits, ylimits, zlimits);
for i = 1:numel(matFiles)
    % Update the plot with the point cloud for the current frame
    view(player, pointCloudObjects{i});
    pause(0.1); % Adjust the pause duration as needed
end
```

```
%Reading GPS/IMU data from OXTS folder
%Data are stored in the format show at dataformat.txt file
oxtsFolderPath = strcat(dataset_path, '\oxts\data');
oxtsFiles = dir(oxtsFolderPath);
cd(oxtsFolderPath);
OXTS = zeros(framesNum,30);
j = 1;
for i = 3:length(oxtsFiles) % 3 to avoid backward in location
    filename = oxtsFiles(i).name;
    if(length(filename) > 5)
        OXTS(j,:) = importdata(filename);
    end
    j = j +1;
end
%Go back to where the live script located to be used in further processing
%for GPS data (Where LLA_to_Local function script exists)
cd(mainDirectory);
```

```
%Seperating OXTS folder to Data vectors needed for further processing
%To Get GPS-Based Position(Ground Truth Position)that will be converted to local
frame:
latitude = OXTS(:,1);
longitude = OXTS(:,2);
altitude = OXTS(:,3);

%To Get (To evaluate integration model and difference):
roll = OXTS(:,4);
pitch = OXTS(:,5);
yaw = OXTS(:,6);

%To get velocity of vehcile (To evaluate integration model and difference):
vn = OXTS(:,7);
ve = OXTS(:,8);

%IMU Readings (To obtain Pose estimation based on IMU data only):
    %Accelerometer reading:
af = OXTS(:,15);
al = OXTS(:,16);
au = OXTS(:,17);
    %Groscope reading:
wf = OXTS(:,21);
wl = OXTS(:,22);
wu = OXTS(:,23);

%Loading GPS accuracy and numbers of satellites
posAcc = OXTS(:,24);
numSats = OXTS(:,27);

%Creating time frame starting from Second 0
timeVector = 0:0.1:(framesNum-1)*0.1;

%Get absolute velocity from either derivative of acceleration of
%sqrt(vn^2+ve^2)
vAbs = sqrt(vn.^2 + ve.^2);
%To get the scale factor or abs Dist, that will be used in camera algorithm
%we divide vAbs / camera frequency, which in this case is equals to 10
scaleFactor = vAbs / 10;
```

```
%Creating subplots to visualize IMU data
figure;
figure('Position', [50, 50, 2000, 2000]); % [left bottom width height]

subplot(3,2,1);
plot(timeVector, af);
xlabel('Time (sec)');
ylabel('Af (m/s^2)');
grid("on");

subplot(3,2,2);
```

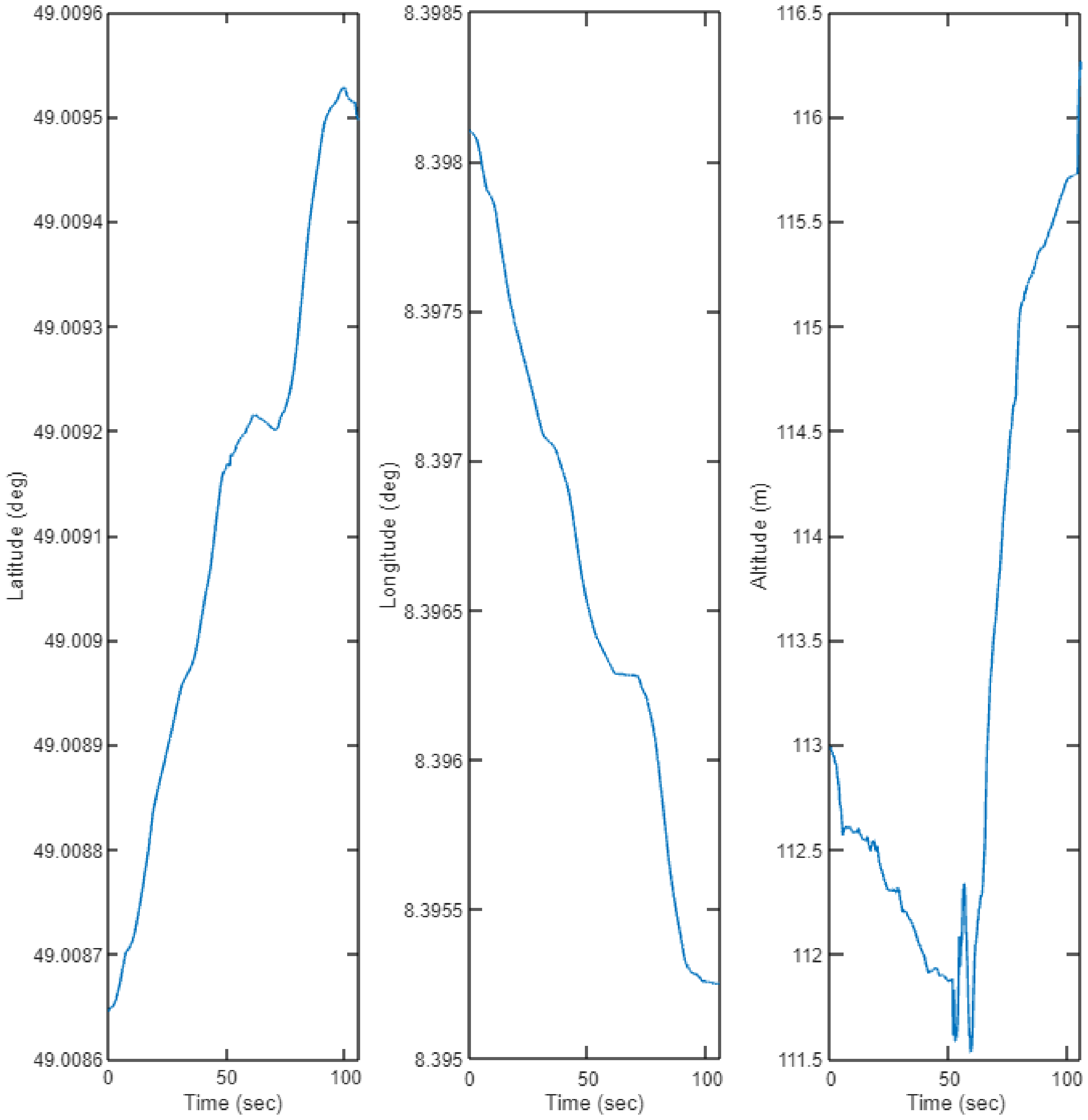
```
plot(timeVector, al);
xlabel('Time (sec)');
ylabel('Al (m/s^2)');
grid("on");

subplot(3,2,3);
plot(timeVector, au);
xlabel('Time (sec)');
ylabel('Au (m/s^2)');
grid("on");
subplot(3,2,4);
plot(timeVector, wf);
xlabel('Time (sec)');
ylabel('Wf (rad/s)');
grid("on");

subplot(3,2,5);
plot(timeVector, wl);
xlabel('Time (sec)');
ylabel('Wl (rad/s)');
grid("on");

subplot(3,2,6);
plot(timeVector, wu);
xlabel('Time (sec)');
ylabel('Wu (rad/s)');
grid("on");
```



```
%Now we plot the route using GPS data on a global map
webmap('Open Street Map');
wmmarker(latitude(1), longitude(1), 'FeatureName', 'Start point');
wmline(latitude(2:end-1), longitude(2:end-1));
wmmarker(latitude(end), longitude(end), 'FeatureName', 'End point');
```

```
%Filtering input data, if needed uncomment below section
%{
Fs = 10; %sampling frequency
%cutoff frequency
cutoff_frequency = 1; % Specify the cutoff frequency for filtering high-
frequency noise
%low-pass filter
[b, a] = butter(4, cutoff_frequency / (Fs / 2), 'low'); %4th-order Butterworth
filter

% Apply the low-pass filter to the data
af = filtfilt(b, a, af);
al = filtfilt(b, a, al);
wu = filtfilt(b, a, wu);
vn = filtfilt(b, a, vn);
ve = filtfilt(b, a, ve);
%}
```

```
%Creating subplots to visualize GPS geodatic frame data
figure;
set(gcf, 'Color', 'white');
figure('Position', [50, 50, 2000, 2000]); % [left bottom width height]

subplot(1,3,1);
plot(timeVector, latitude);
xlabel('Time (sec)');
ylabel('Latitude (deg)');

subplot(1,3,2);
plot(timeVector, longitude);
xlabel('Time (sec)');
ylabel('Longitude (deg)');

subplot(1,3,3);
plot(timeVector, altitude);
xlabel('Time (sec)');
ylabel('Altitude (m)');
```



Loading Unsync Data.

```
%Reading GPS/IMU data from Unsynchronized OXTS folder
cd(unsyncOxtsFolderPath);
UNSYNCOXTS = zeros(framesNum,30);
j = 1;
for i = 1:length(unsyncOxtsFiles)
    filename = unsyncOxtsFiles(i).name;
    if(length(filename) > 5)
        UNSYNCOXTS(j,:) = importdata(filename);
    end
    j = j +1;
```

```
end
%Go back to where the live script located to be used in further processing
%for GPS data (Where LLA_to_Local function script exists)
cd(mainDirectory);
```

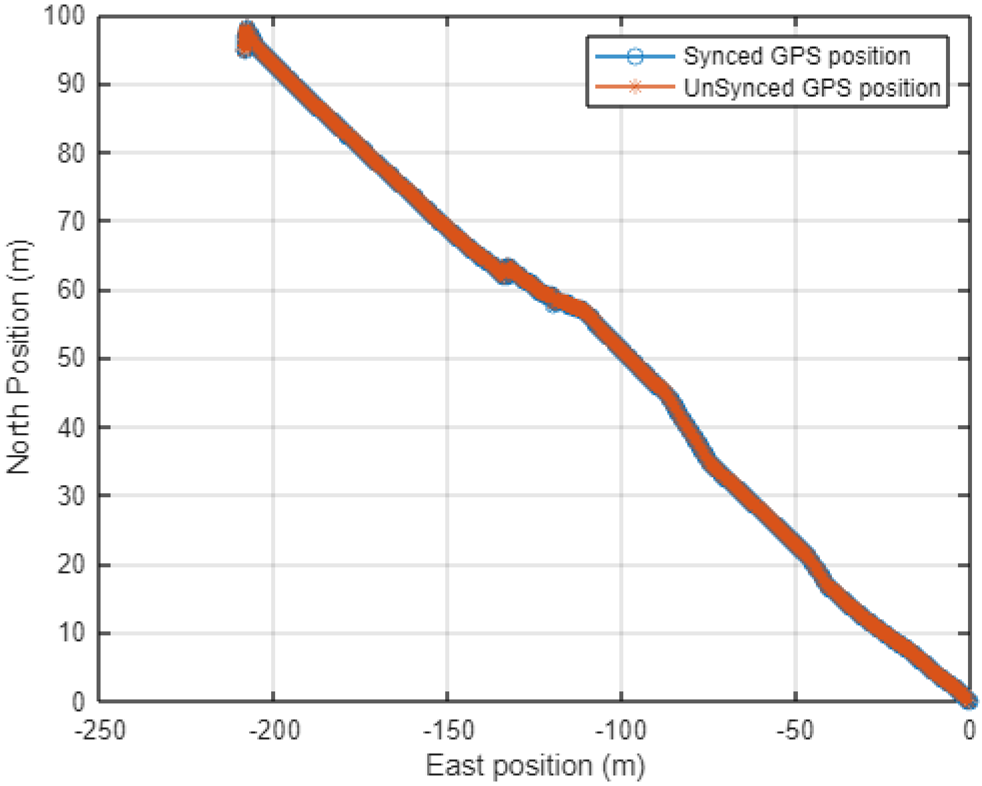
```
%Seperating OXTS folder to Data vectors needed for further processing
%To Get GPS-Based Position(Ground Truth Position)that will be converted to local
frame:
unsyncLatitude = UNSYNCOXTS(:,1);
unsyncLongitude = UNSYNCOXTS(:,2);
unsyncAltitude = UNSYNCOXTS(:,3);

%To Get (To evaluate integration model and difference):
unsyncRoll = UNSYNCOXTS(:,4);
unsynchPitch = UNSYNCOXTS(:,5);
unsyncYaw = UNSYNCOXTS(:,6);

%To get velocity of vehcile (To evaluate integration model and difference):
unsyncVn = UNSYNCOXTS(:,7);
unsyncVe = UNSYNCOXTS(:,8);

%IMU Readings (To obtain Pose estimation based on IMU data only):
    %Accelerometer reading:
unsyncAf = UNSYNCOXTS(:,15);
unsyncAl = UNSYNCOXTS(:,16);
unsyncAu = UNSYNCOXTS(:,17);
    %Groscope reading:
unsyncWf = UNSYNCOXTS(:,21);
unsyncWl = UNSYNCOXTS(:,22);
unsyncWu = UNSYNCOXTS(:,23);

%Loading GPS accuracy and numbers of satellites
unsyncPosAcc = UNSYNCOXTS(:,24);
unsyncNumSats = UNSYNCOXTS(:,27);

%Creating time frame starting from Second 0 (Assuming Ts is const at 0.01s)
unsyncTimeVector = 0:0.01:(unsyncFramesNum-1)*0.01;

%Creating timeSeries from timestamps text file
uOxtsTsPath = strcat(unSyncDataset_path, '\oxts\', 'timestamps.txt');
fid = fopen(uOxtsTsPath, 'r');
timestamps_str = textscan(fid, '%s', 'Delimiter', '\n');
fclose(fid);
timestamps = datetime(timestamps_str{1}, 'InputFormat', 'yyyy-MM-dd
HH:mm:ss.SSSSSSSSS', 'Format', 'yyyy-MM-dd HH:mm:ss.SSSSSSSSS');
time_diff = diff(timestamps);
time_diff_seconds = seconds(time_diff);
uOxtsTs = zeros(1, unsyncFramesNum);
uOxtsTs(1) = 0.01;
uOxtsTs(2:end) = time_diff_seconds;
usOxtsTsRef = zeros(1, length(uOxtsTs)); %For a vector containing the time
difference in second
for i = 2:length(uOxtsTs)
```

```
    usOxtsTsRef(i) = usOxtsTsRef(i-1) + uOxtsTs(i);
end
```

GPS data conversion (Geodatic to local) and Visualization.

```
%Converting LLA cordinate frame position to Local frame position using GPS
%data obtained
GPSn = zeros(framesNum, 1);
GPSe = zeros(framesNum, 1);
unsyncGPSn = zeros(unsyncFramesNum, 1);
unsyncGPSe = zeros(unsyncFramesNum, 1);
%Refrencing motion to first frame readings
for i= 1:framesNum
    [deltaE, deltaN, ~] = lla_to_enu(latitude(1), longitude(1), altitude(1),
latitude(i), longitude(i), altitude(i));
    GPSe(i) = deltaE;
    GPSn(i) = deltaN;
end
for i= 1:unsyncFramesNum
    [deltaE, deltaN, ~] = lla_to_enu(unsyncLatitude(1), unsyncLongitude(1),
unsyncAltitude(1), unsyncLatitude(i), unsyncLongitude(i), unsyncAltitude(i));
    unsyncGPSe(i) = deltaE;
    unsyncGPSn(i) = deltaN;
end
```

```
%Graph GPS based position
figure;

plot(GPSe, GPSn, '-o');
hold on;
plot(unsyncGPSe, unsyncGPSn, '-*');

xlabel('East position (m)');
ylabel('North Position (m)');
legend('Synced GPS position', 'UnSynced GPS position');
grid on;
```



IMU Based Localization

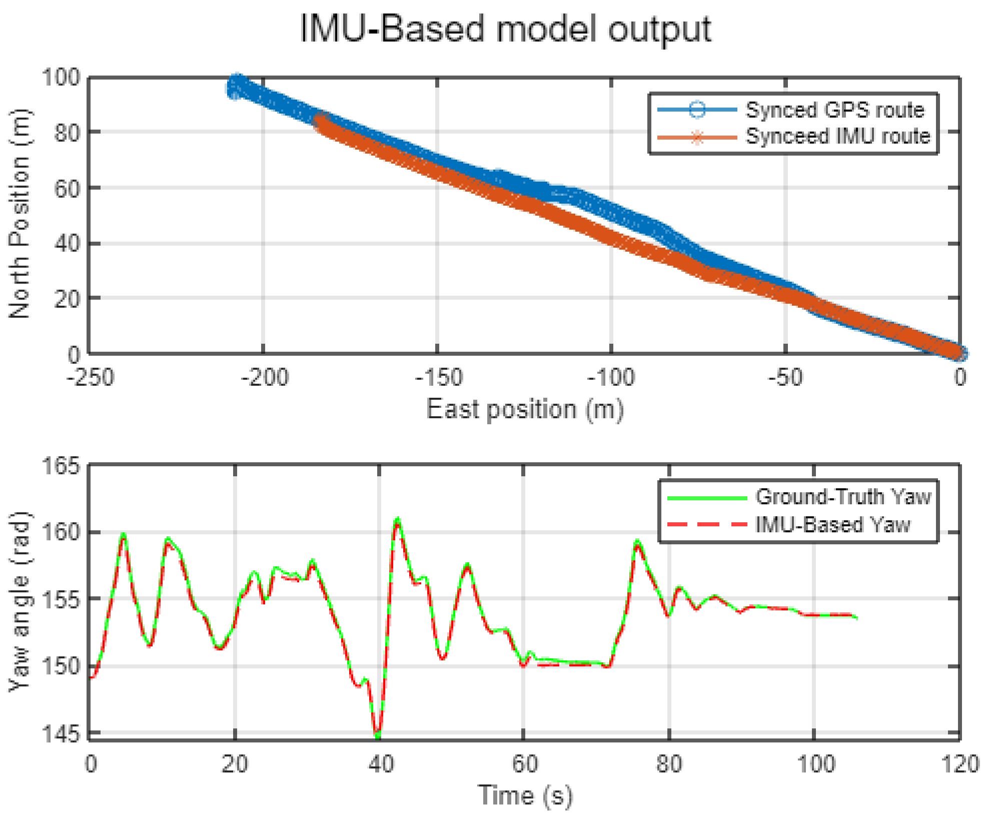
Synced IMU-Based Localization model, evaluation, and Stored data visualization.

```
%Convert Acceleration from sensor frame (Vehicle frame) to Global ENU Frame
Avehicle = [af,al];
Aenu = zeros(framesNum,2);
for i= 1:framesNum
    Aenu(i,1) = (cos(yaw(i)) * af(i)) -(sin(yaw(i)) * al(i));
    Aenu(i,2) = (sin(yaw(i)) * af(i)) +(cos(yaw(i)) * al(i));
end
Ae = Aenu(:,1);
An = Aenu(:,2);
```

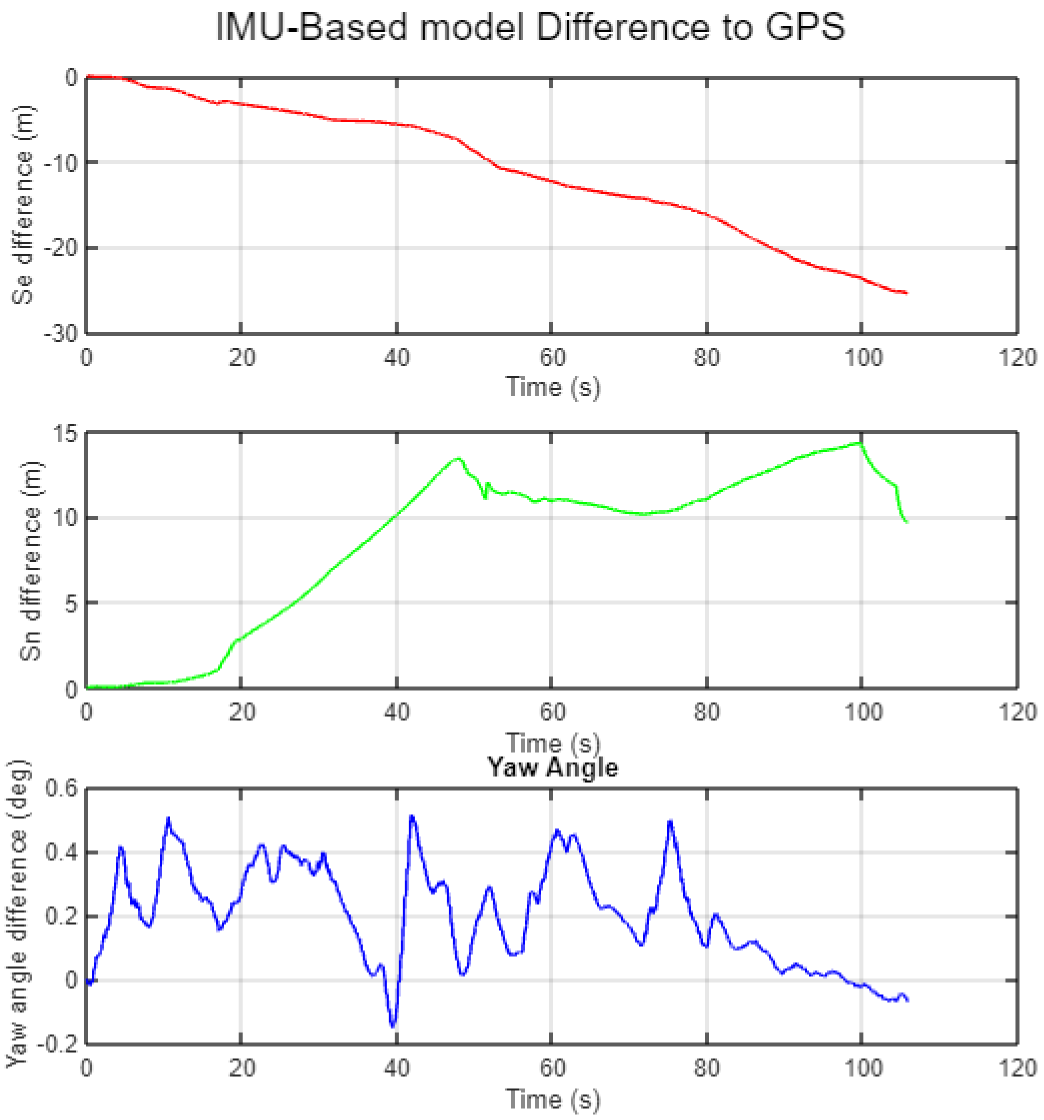
```
%To get IMU-Based Pose:
IMUYaw = zeros(framesNum, 1);
IMUn= zeros(framesNum,1);
IMUe= zeros(framesNum,1);
IMUVn = zeros(framesNum,1);
IMUVe = zeros(framesNum,1);

%Setting initial data
IMUYaw(1) = yaw(1);
IMUVn(1) = vn(1);
IMUVe(1) = ve(1);

%Assuming zero initial pose.
```

```
for i = 2:(framesNum)
    %Using double integration to get position from acceleration and single
    %step integration to get o
    % rientation from angular velocity
    IMUVn(i) = IMUVn(i-1) + (An(i) * Ts); %Velociy from integration (north
direction)
    IMUVe(i) = IMUVe(i-1) + (Ae(i) * Ts); %Velociy from integration (east
direction)

    IMUn(i) = IMUn(i-1) + (IMUVn(i) * Ts) + (0.5 * (Ts^2) * An(i)); %Position
from integration (north direction)
    IMUe(i) = IMUe(i-1) + (IMUVe(i) * Ts) + (0.5 * (Ts^2) * Ae(i)); %Position
from integration (east direction)

    IMUYaw(i) = IMUYaw(i-1) + (wu(i) * Ts); %orientation from integration (Yaw
angle)
end
```

```
%Evaluating IMU-Based Position based on Ground truth data
figure;

subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
hold on;
plot(IMUe, IMUn, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('Synced GPS route', 'Synceed IMU route');
grid on;

subplot(2, 1, 2);
plot(timeVector, rad2deg(yaw), 'g');
hold on;
plot(timeVector, rad2deg(IMUYaw), 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'IMU-Based Yaw');
grid on;
sgtitle('IMU-Based model output');
```



```
%Calculating Error (Difference between IMU and GPS data)
SeDiff = GPSe - IMUe;
SnDiff = GPSn- IMUn;
yawDiff = yaw- IMUYaw;

%Graphing error
figure;
figure('Position', [50, 50, 600, 600]); % [left bottom width height]

subplot(3, 1, 1);
plot(timeVector, SeDiff, 'r');
xlabel('Time (s)');
ylabel('Se difference (m)');
grid on;
subplot(3, 1, 2);
plot(timeVector, SnDiff, 'g');
xlabel('Time (s)');
ylabel('Sn difference (m)');
grid on;
subplot(3, 1, 3);
plot(timeVector, rad2deg(yawDiff), 'b');
xlabel('Time (s)');
ylabel('Yaw angle difference (deg)');
title('Yaw Angle')
grid on;

sgtitle('IMU-Based model Difference to GPS');
```



[Unsynchronized] IMU-Based Localization model, evaluation, and Stored data visualization.

```
%Convert Acceleration from sensor frame (Vehicle frame) to Global ENU Frame
unsyncAvehicle = [unsyncAf,unsyncAl];
unsyncAenu = zeros(unsyncFramesNum,2);
for i= 1:unsyncFramesNum
    unsyncAenu(i,1) = (cos(unsyncYaw(i)) * unsyncAf(i)) -(sin(unsyncYaw(i)) *
unsyncAl(i));
    unsyncAenu(i,2) = (sin(unsyncYaw(i)) * unsyncAf(i)) +(cos(unsyncYaw(i)) *
unsyncAl(i));
end
unsyncAe = unsyncAenu(:,1);
unsyncAn = unsyncAenu(:,2);
```

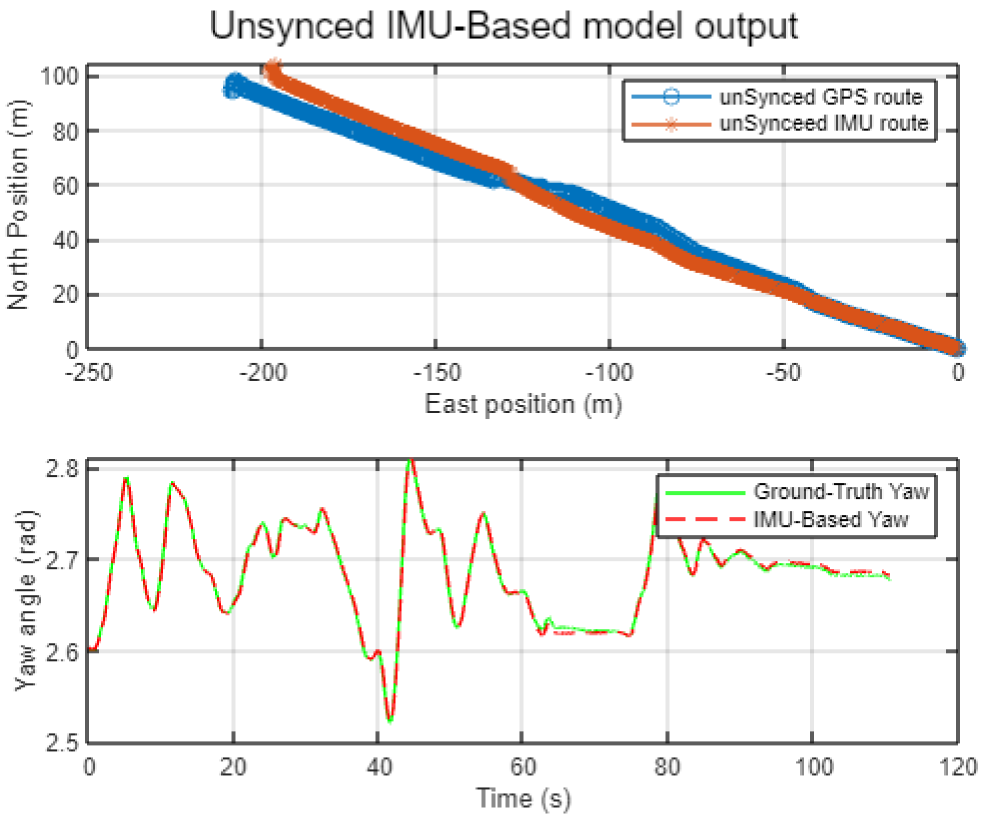
```
%To get Unsync IMU-Based Pose:
unsyncIMUYaw = zeros(unsyncFramesNum, 1);
unsyncIMUn= zeros(unsyncFramesNum,1);
```

```
unsyncIMUe= zeros(unsyncFramesNum,1);
unsyncIMUVn = zeros(unsyncFramesNum,1);
unsyncIMUVe = zeros(unsyncFramesNum,1);

%Setting initial data
unsyncIMUYaw(1) = unsyncYaw(1);
unsyncIMUVn(1) = unsyncVn(1);
unsyncIMUVe(1) = unsyncVe(1);

%Assuming zero initial pose.
for i = 2:(unsyncFramesNum)
    %Using double integration to get position from acceleration and single
    %step integration to get o
    % rientation from angular velocity
    unsyncIMUVn(i) = unsyncIMUVn(i-1) + (unsyncAn(i) * unsyncIMUTs); %Velociy
from integration (north direction)
    unsyncIMUVe(i) = unsyncIMUVe(i-1) + (unsyncAe(i) * unsyncIMUTs); %Velociy
from integration (east direction)

    unsyncIMUn(i) = unsyncIMUn(i-1) + (unsyncIMUVn(i) * unsyncIMUTs); %Position
from integration (north direction)
    unsyncIMUe(i) = unsyncIMUe(i-1) + (unsyncIMUVe(i) * unsyncIMUTs); %Position
from integration (east direction)

    unsyncIMUYaw(i) = unsyncIMUYaw(i-1) + (unsyncWu(i) * unsyncIMUTs);
%orientation from integration (Yaw angle)
end
```

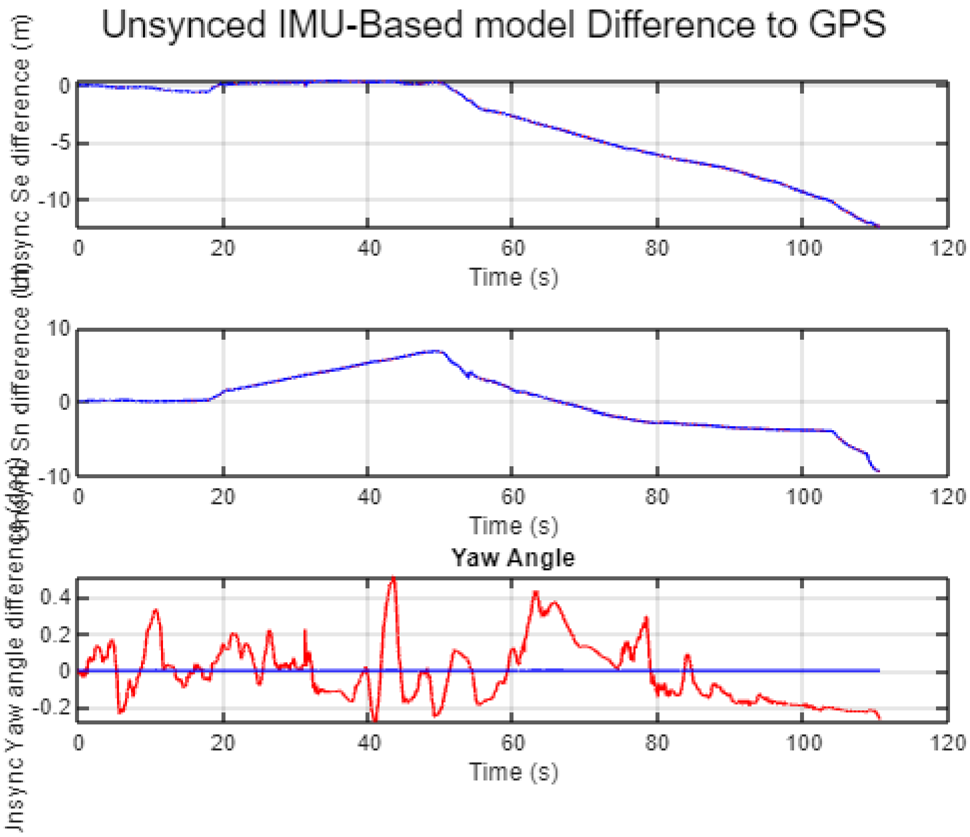
```
%now using timestamps difference in time to evaluate
%Setting initial data
unsyncIMUYawT = zeros(unsyncFramesNum, 1);
unsyncIMUnT = zeros(unsyncFramesNum,1);
unsyncIMUeT = zeros(unsyncFramesNum,1);
unsyncIMUVnT = zeros(unsyncFramesNum,1);
unsyncIMUVeT = zeros(unsyncFramesNum,1);

unsyncIMUYawT(1) = unsyncYaw(1);
unsyncIMUVnT(1) = unsyncVn(1);
unsyncIMUVeT(1) = unsyncVe(1);

%Assuming zero initial pose.
for i = 2:(unsyncFramesNum)
    %Using double integration to get position from acceleration and single
    %step integration to get o
    % rientation from angular velocity
    unsyncIMUVnT(i) = unsyncIMUVnT(i-1) + (unsyncAn(i) * uOxtsTs(i)); %Velociy
from integration (north direction)
    unsyncIMUVeT(i) = unsyncIMUVeT(i-1) + (unsyncAe(i) * uOxtsTs(i)); %Velociy
from integration (east direction)

    unsyncIMUnT(i) = unsyncIMUnT(i-1) + (unsyncIMUVnT(i) * uOxtsTs(i));
%Position from integration (north direction)
```

```
    unsyncIMUeT(i) = unsyncIMUeT(i-1) + (unsyncIMUVeT(i) * uOxtsTs(i));
%Position from integration (east direction)

    unsyncIMUYawT(i) = unsyncIMUYawT(i-1) + (unsyncWu(i) * uOxtsTs(i));
%orientation from integration (Yaw angle)
end
```

```
%Evaluating IMU-Based Position based on Ground truth data
figure;

subplot(2, 1, 1);
plot(unsyncGPSe, unsyncGPSn, '-o');
hold on;
plot(unsyncIMUe, unsyncIMUn, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('unSynced GPS route', 'unSynceed IMU route');
grid on;

subplot(2, 1, 2);
plot(unsyncTimeVector, unsyncYaw, 'g');
hold on;
plot(unsyncTimeVector, unsyncIMUYaw, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'IMU-Based Yaw');
grid on;
sgtitle('Unsynced IMU-Based model output');
```



```
%Calculating Error (Difference between Unsync IMU and GPS data)
unsyncSeDiff = unsyncGPSe - unsyncIMUe;
unsyncSnDiff = unsyncGPSn - unsyncIMUn;
unsyncYawDiff = unsyncYaw - unsyncIMUYaw;
unsyncSeDiffT = unsyncGPSe - unsyncIMUe;
unsyncSnDiffT = unsyncGPSn - unsyncIMUn;
unsyncYawDiffT = unsyncYaw - unsyncIMUYaw;

%Graphing error
figure;
subplot(3, 1, 1);
plot(unsyncTimeVector, unsyncSeDiff, 'r');
hold on;
plot(usOxtsTsRef, unsyncSeDiffT, 'b');
xlabel('Time (s)');
ylabel('Unsync Se difference (m)');
grid on;
subplot(3, 1, 2);
plot(unsyncTimeVector, unsyncSnDiff, 'r');
hold on;
plot(usOxtsTsRef, unsyncSnDiffT, 'b');
xlabel('Time (s)');
ylabel('Unsync Sn difference (m)');
grid on;
subplot(3, 1, 3);
plot(unsyncTimeVector, rad2deg(unsyncYawDiff), 'r');
hold on;
plot(usOxtsTsRef, deg2rad(unsyncYawDiffT), 'b');
xlabel('Time (s)');
ylabel('Unsync Yaw angle difference (deg)');
title('Yaw Angle')
grid on;

sgtitle('Unsynced IMU-Based model Difference to GPS');
```



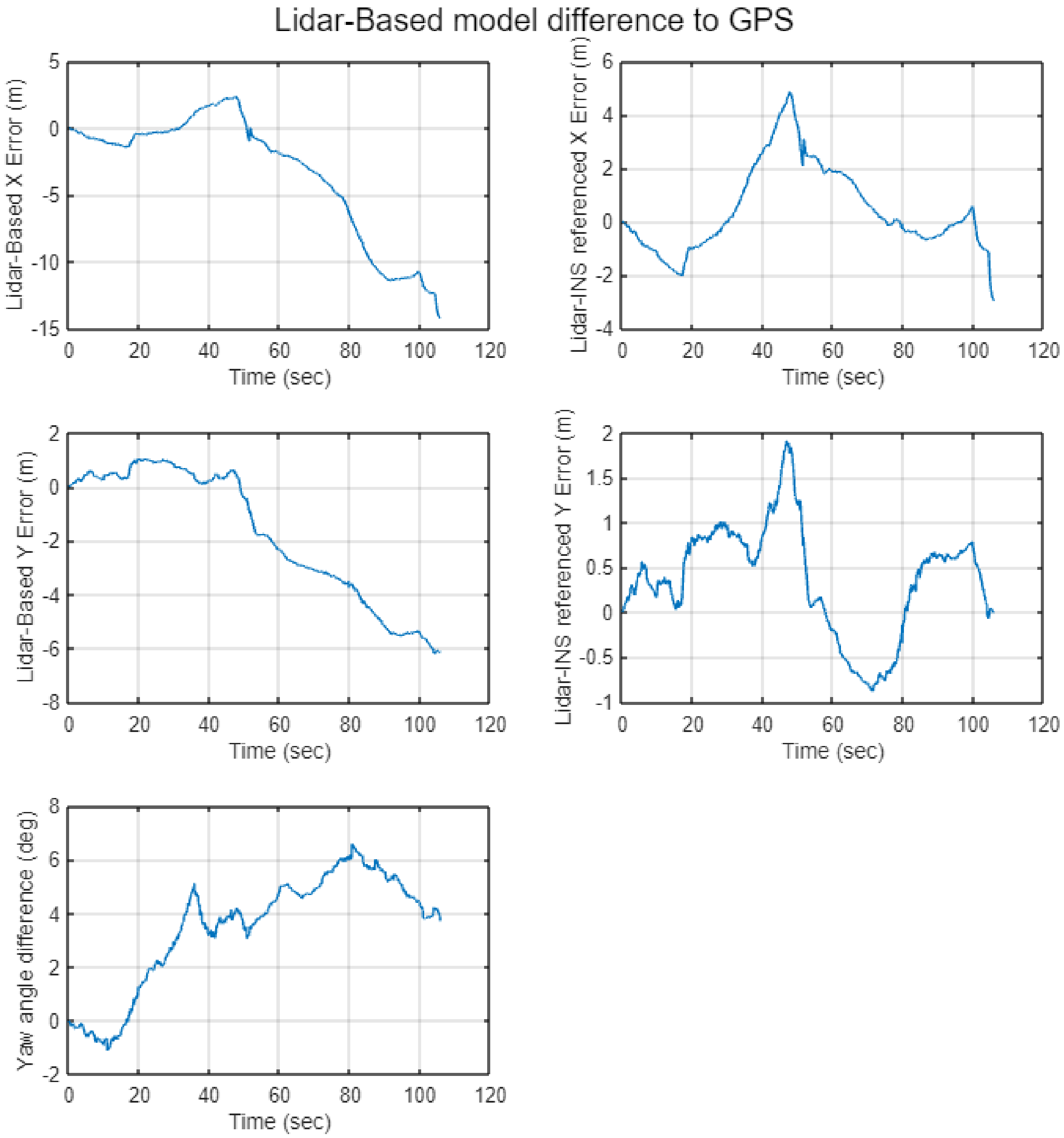
Lidar-Based Localization model and evaluation.

```
lidarX = zeros(1, framesNum);
lidarY = zeros(1, framesNum);
lidarXBar = zeros(1, framesNum);
lidarYBar = zeros(1, framesNum);
lidarYaw = zeros(1, framesNum);
lidarYaw(1) = rad2deg(yaw(1)); %Setting initial starting angle
lidarSampleNumber = framesNum-1;
for i = 1:lidarSampleNumber %for more accurate (full trajectory results we need
to change from a limited number to total number of frames)
    % Check if each point cloud has at least three unique points
    ptCloudOne= pointCloudObjects{i};
    ptCloudTwo = pointCloudObjects{i+1};
    numptCloudOne = size(ptCloudOne.Location, 1);
    numptCloudTwo = size(ptCloudTwo.Location, 1);
    if numptCloudOne < 3 || numptCloudTwo < 3
        lidarX(i+1) = lidarX(i);
        lidarY(i+1) = lidarY(i);
        lidarXBar(i+1) = lidarXBar(i);
        lidarYBar(i+1) = lidarYBar(i);
        lidarYaw(i+1) = lidarYaw(i);
    else
        [tform, ~, ~] = pcregistericp(ptCloudTwo, ptCloudOne,
Metric="pointToPlane");
        % Extract rotation matrix and translation vector from transformation
matrix
        R = tform.T(1:3, 1:3);
        eulerAngles = -rotm2eul(R, 'XYZ');
        deltaYaw_vehicle_deg = double(rad2deg(eulerAngles(3)));
        t = tform.T(4, 1:3)';
        deltaY_vehicle_m =  (t(1) * sin(deg2rad(lidarYaw(i)))) - (t(2) *
cos(deg2rad(lidarYaw(i)))); %for only lidar data
        deltaX_vehicle_m = - (t(2) * sin(deg2rad(lidarYaw(i)))) + (t(1) *
cos(deg2rad(lidarYaw(i)))); %for only lidar data
        deltaY_vehicle_mBar =  (t(1) * sin(IMUYaw(i))) - (t(2) *
cos(IMUYaw(i))); %for Lidar-INS referenced
        deltaX_vehicle_mBar = - (t(2) * sin(IMUYaw(i))) + (t(1) *
cos(IMUYaw(i))); %for Lidar-INS referenced
        lidarY(i+1) = lidarY(i) + deltaY_vehicle_m;
        lidarX(i+1) = lidarX(i) + deltaX_vehicle_m;
        lidarYBar(i+1) = lidarYBar(i) + deltaY_vehicle_mBar;
        lidarXBar(i+1) = lidarXBar(i) + deltaX_vehicle_mBar;
        lidarYaw(i+1) = lidarYaw(i) + deltaYaw_vehicle_deg;
    end
    %Display number of iteration to see current progress
    if(i==1)
        fprintf('Out of %d frames, Processing point cloud matching on frame
No.',framesNum);
    end
    fprintf('\b\b\b\b\b%d', i+1);
end
```

```
Out of 1059 frames, Processing point cloud matching on frame No.
1059
```

```
%Evaluating Lidar-Based Position based on Ground truth data
figure;

subplot(2, 1, 1);
plot(unsyncGPSe, unsyncGPSn, '-o');
hold on;
plot(lidarX, lidarY, '-*');
plot(lidarXBar, lidarYBar, '-s');

xlabel('East position (m)');
ylabel('North Position (m)');
legend('Synced GPS route', 'Lidar route', 'Lidar INS referenced route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, deg2rad(lidarYaw), 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'IMU-Based Yaw');
grid on;
sgtitle('Unsynced IMU-Based model output');

sgtitle('Lidar-Based model output');
```

```
%Calculating Error (Difference between Lidar and GPS data)
LidarYDiff = GPSe - (lidarX)';
LidarXDiff = GPSn - (lidarY)';
LidarYBarDiff = GPSe - (lidarXBar)';
LidarXBarDiff = GPSn - (lidarYBar)';
LidaryawDiff = rad2deg(yaw) - (lidarYaw)';

%Graphing error
figure;
figure('Position', [0, 0, 1250, 1250]);

subplot(3,2,1);
plot(timeVector, LidarXDiff);
xlabel('Time (sec)');
ylabel('Lidar-Based X Error (m)');
grid("on");

subplot(3,2,2);
plot(timeVector, LidarXBarDiff);
xlabel('Time (sec)');
ylabel('Lidar-INS referenced X Error (m)');
grid("on");

subplot(3,2,3);
plot(timeVector, LidarYDiff);
xlabel('Time (sec)');
ylabel('Lidar-Based Y Error (m)');
grid("on");

subplot(3,2,4);
plot(timeVector, LidarYBarDiff);
xlabel('Time (sec)');
ylabel('Lidar-INS referenced Y Error (m)');
grid("on");

subplot(3,2,5);
plot(timeVector,  LidaryawDiff);
xlabel('Time (sec)');
ylabel('Yaw angle difference (deg)');
grid("on");
sgtitle('Lidar-Based model difference to GPS');
```



Lidar-Based model difference to GPS

Camera-Based Localization model and evaluation.

```
%Creating cameraParams object
%See cam_to_cam_calib file to obtain these values
focalLength = [984 980];
principalPoint = [690 233];
cameraParams = cameraIntrinsics(focalLength, principalPoint, size(grayVector{1}
(:,:,1)));
```

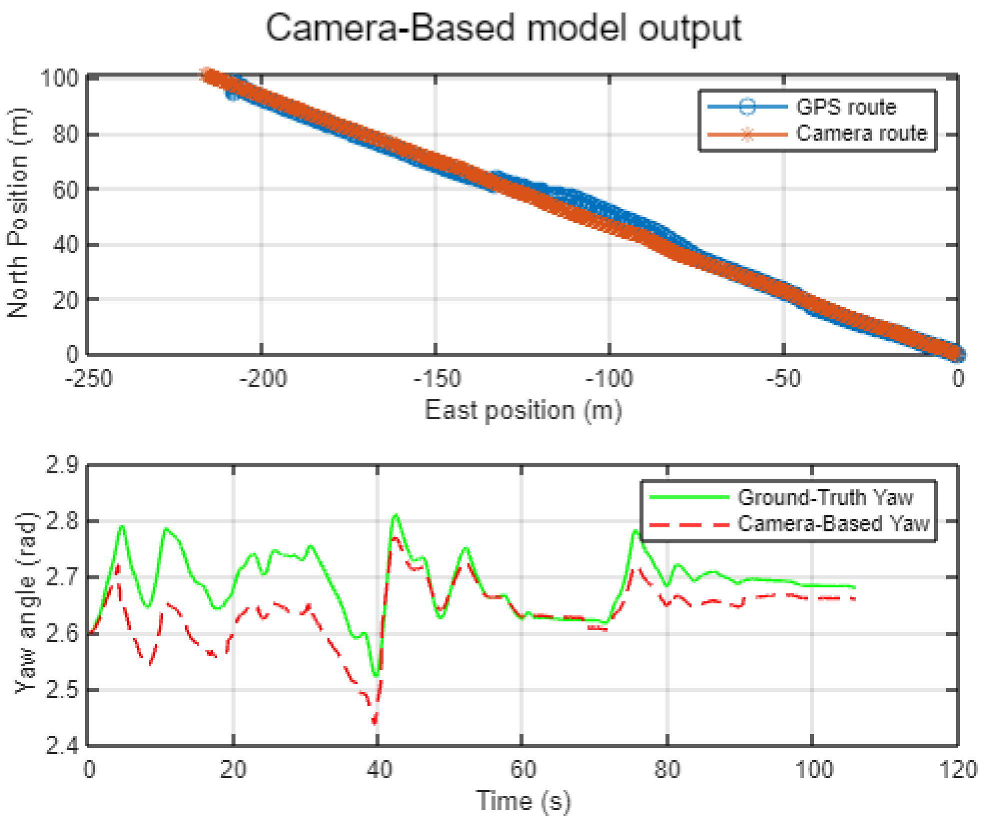
```
%Loop for saving camera estimates
camX = zeros(1,numel(pngFiles));
```

```
camY = zeros(1,numel(pngFiles));
camYaw = zeros(1,numel(pngFiles));
camYaw(1) = yaw(1);
figure;
for i = 1:numel(pngFiles) - 1

    grayFrame1 = grayVector{i};
    grayFrame2 = grayVector{i+1};

    %Detect and match features
    %For limited number of features
    %points1 = selectStrongest(detectKAZEFeatures(grayFrame1), 500);
    %points2 = selectStrongest(detectKAZEFeatures(grayFrame2), 500);

    %For maximum number of features
    points1 = detectKAZEFeatures(grayFrame1);
    points2 = detectKAZEFeatures(grayFrame2);

    [features1, points1] = extractFeatures(grayFrame1, points1);
    [features2, points2] = extractFeatures(grayFrame2, points2);

    indexPairs = matchFeatures(features1, features2);
    matchedPoints1 = points1(indexPairs(:, 1), :);
    matchedPoints2 = points2(indexPairs(:, 2), :);

    % Estimate Fundamental/Essential matrix
    [eMatrix, inliers] = estimateEssentialMatrix(matchedPoints1, matchedPoints2,
cameraParams);

    % Select inlier points
    inlierPoints1 = matchedPoints1(inliers);
    inlierPoints2 = matchedPoints2(inliers);

    %Estimate relative camera pose
    relPose = estrelpose(eMatrix, cameraParams, inlierPoints1, inlierPoints2);

    Rot = relPose.R;
    t = relPose.Translation;

    eulerAngles = rotm2eul(Rot, 'XYZ');
    camYaw(i+1) = camYaw(i) - eulerAngles(2);
    camX(i+1) = camX(i) + t(3)*cos(yaw(i))*scaleFactor(i) - t(1)*sin((pi/2)-
yaw(i))*scaleFactor(i);
    camY(i+1) = camY(i) + t(3)*sin(yaw(i))*scaleFactor(i) - t(1)*cos((pi/2)-
yaw(i))*scaleFactor(i);

    %Visualize matched features
    %showMatchedFeatures(grayFrame1, grayFrame2, inlierPoints1, inlierPoints2,
'montage');
    if(i==1)
        fprintf('Out of %d frames, Processing point cloud matching on frame
No.',framesNum);
    end
    fprintf('\b\b\b\b\b%d', i+1);
```

```
end
```

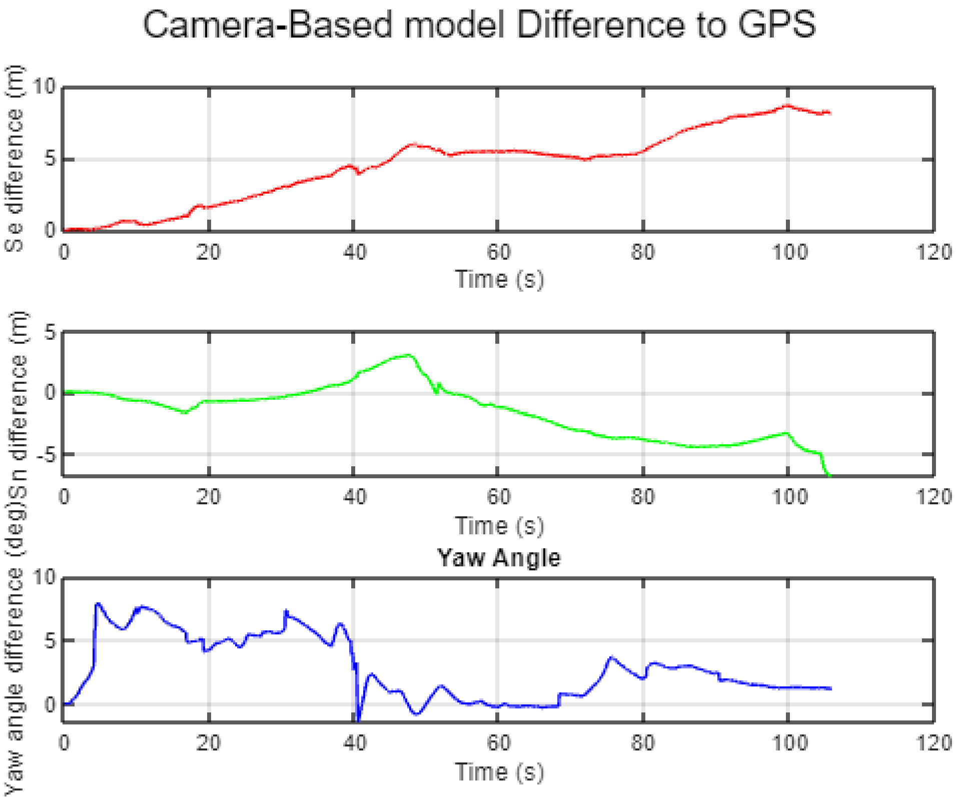
```
Out of 1059 frames, Processing point cloud matching on frame No.
1059
```

```
figure;
subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
hold on;
plot(camX, camY, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('GPS route', 'Camera route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, camYaw, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Camera-Based Yaw');
grid on;
sgtitle('Camera-Based model output');
```



```
%camera based error evaluation
%Calculating Error (Difference between Camera and GPS data)
SeDiffCam = GPSe' - camX;
SnDiffCam = GPSn'- camY;
```

```
yawDiffCam = yaw' - camYaw;

%Graphing error
figure;
subplot(3, 1, 1);
plot(timeVector, SeDiffCam, 'r');
xlabel('Time (s)');
ylabel('Se difference (m)');
grid on;
subplot(3, 1, 2);
plot(timeVector, SnDiffCam, 'g');
xlabel('Time (s)');
ylabel('Sn difference (m)');
grid on;
subplot(3, 1, 3);
plot(timeVector, rad2deg(yawDiffCam), 'b');
xlabel('Time (s)');
ylabel('Yaw angle difference (deg)');
title('Yaw Angle')
grid on;

sgtitle('Camera-Based model Difference to GPS');
```



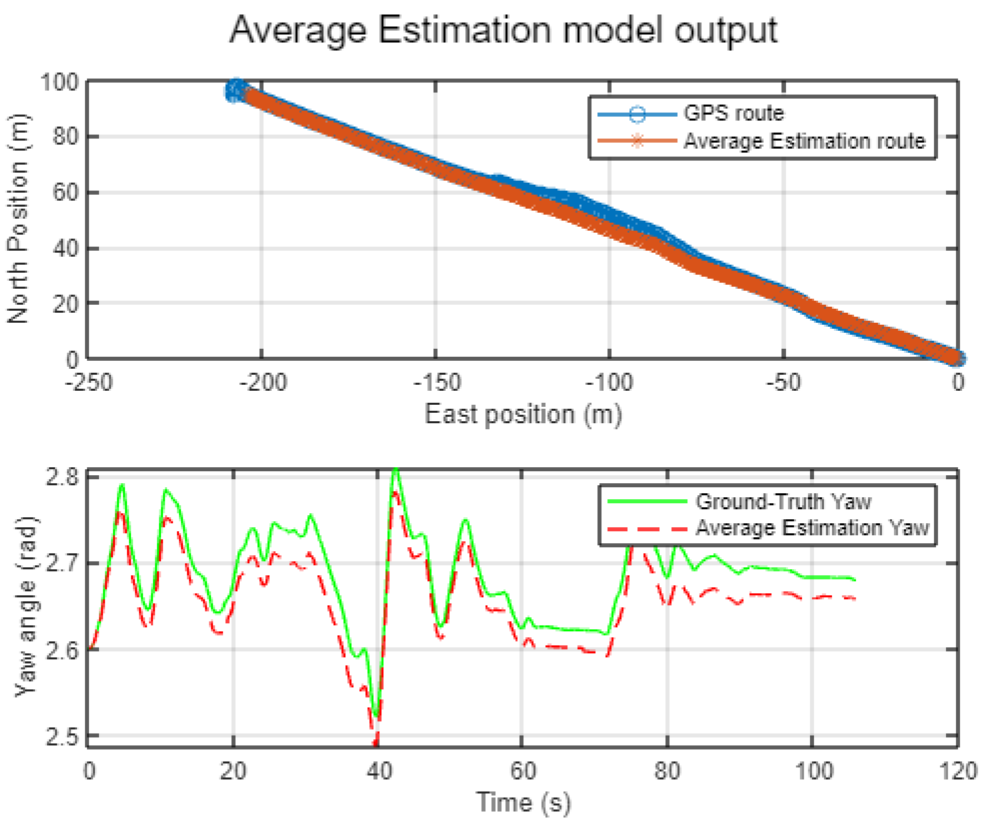
Sensory Data Fusion

Average Estimation Model

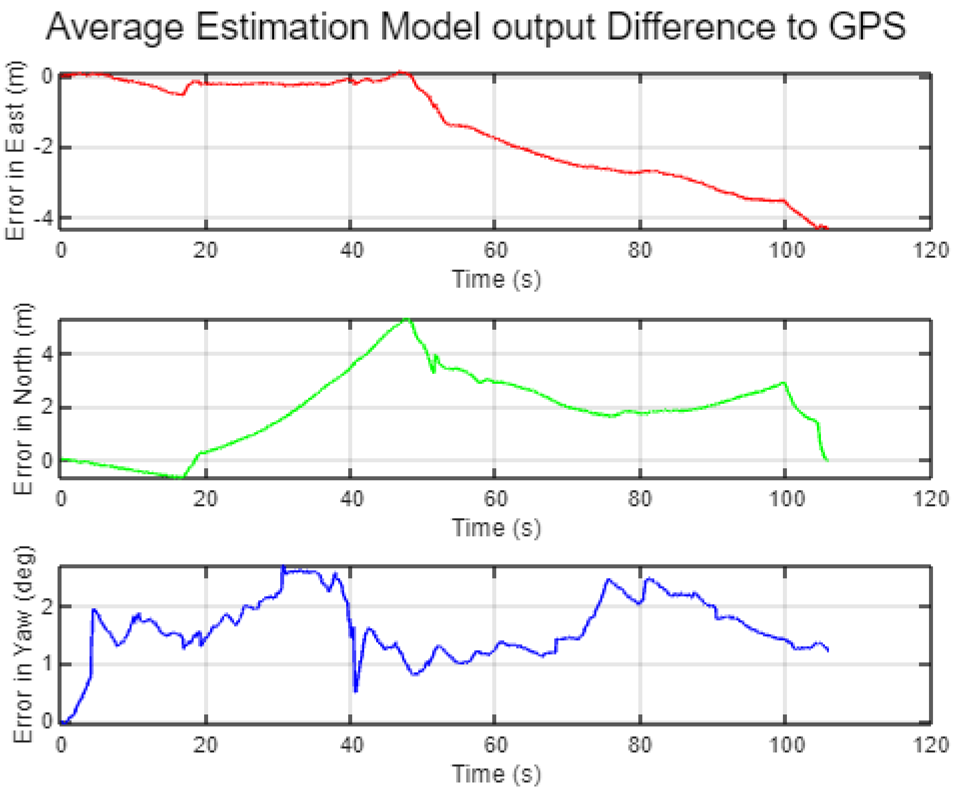
```
XAvg = zeros(framesNum, 1);
```

```
YAvg = zeros(framesNum, 1);
YawAvg = zeros(framesNum, 1);

for i= 1:framesNum
    XAvg(i) = (camX(:,i) + lidarXBar(:,i) + GPSe(i,:) + IMUe(i,:)) / 4;
    YAvg(i) = (camY(:,i) + lidarYBar(:,i) + GPSn(i,:) + IMUn(i,:)) / 4;
    YawAvg(i) = (camYaw(:,i) + deg2rad(lidarYaw(:,i)) + yaw(i,:) +
IMUYaw(i,:)) / 4;
end
```

```
%Graphing Average Estimation output in comparison with GPS data as the ground
truth
figure;

subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
hold on;
plot(XAvg, YAvg, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('GPS route', 'Average Estimation route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, YawAvg, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Average Estimation Yaw');
grid on;
sgtitle('Average Estimation model output');
```



```
%AV Using synced data evaluation
AEDeltaE = GPSe - XAvg;
AEDeltaN = GPSn - YAvg;
AEDeltaYaw = yaw - YawAvg;

figure;

subplot(3, 1, 1);
plot(timeVector, AEDeltaE, 'r');
xlabel('Time (s)');
ylabel('Error in East (m)');
grid on;

subplot(3, 1, 2);
plot(timeVector, AEDeltaN, 'g');
xlabel('Time (s)');
ylabel('KF_North/GPS North (m)');
ylabel('Error in North (m)');
grid on;

subplot(3, 1, 3);
plot(timeVector, rad2deg(AEDeltaYaw), 'b');
xlabel('Time (s)');
ylabel('Error in Yaw (deg)');
grid on;
sgtitle('Average Estimation Model output Difference to GPS');
```

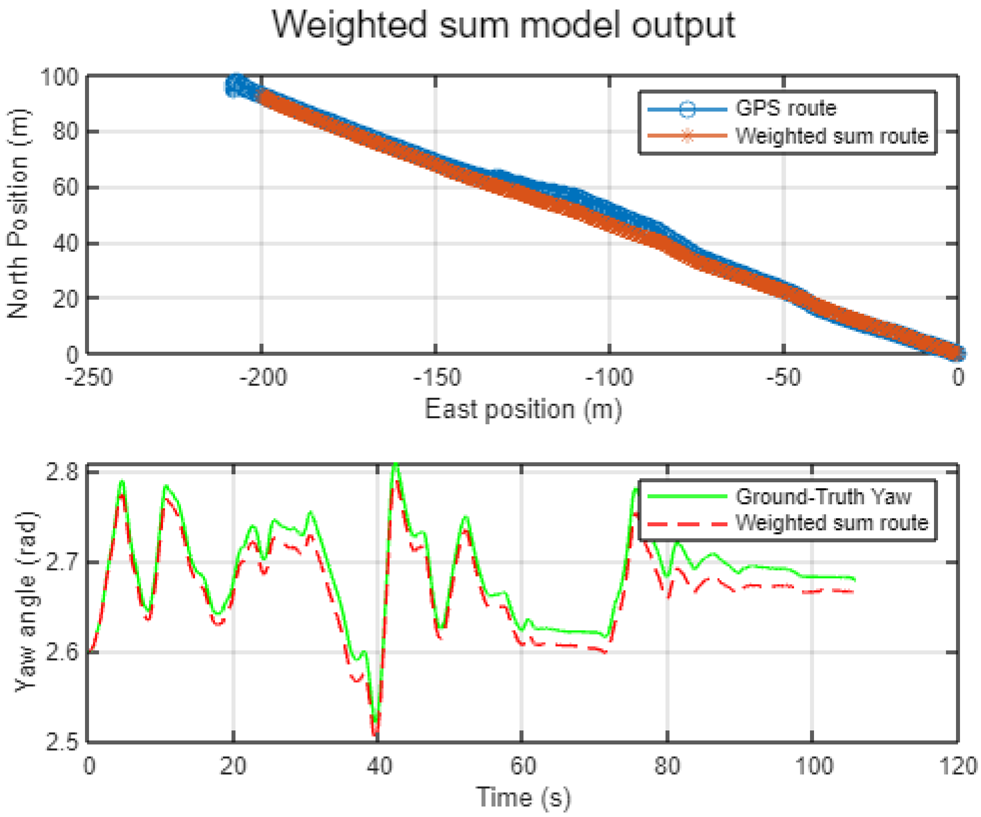


Weighted Sum Estimation

```
XGWs = zeros(framesNum, 1);
YGWs = zeros(framesNum, 1);
YawGWs = zeros(framesNum, 1);
X = [camX', lidarXBar', GPSe, IMUe];
Y = [camY', lidarYBar', GPSn, IMUn];
Yaw = [camYaw', deg2rad(lidarYaw)', yaw, IMUYaw];
WeigthGXY = [5, 10, 20, 20];
WeigthGYaw = [5, 8, 20, 10];

for i= 1:framesNum
    XGWs(i,:) = sum(WeigthGXY .* X(i,:)) / sum(WeigthGXY);
    YGWs(i,:) = sum(WeigthGXY .* Y(i,:)) / sum(WeigthGXY);
    YawGWs(i,:) = sum(WeigthGYaw .* Yaw(i,:)) / sum(WeigthGYaw);
end
```

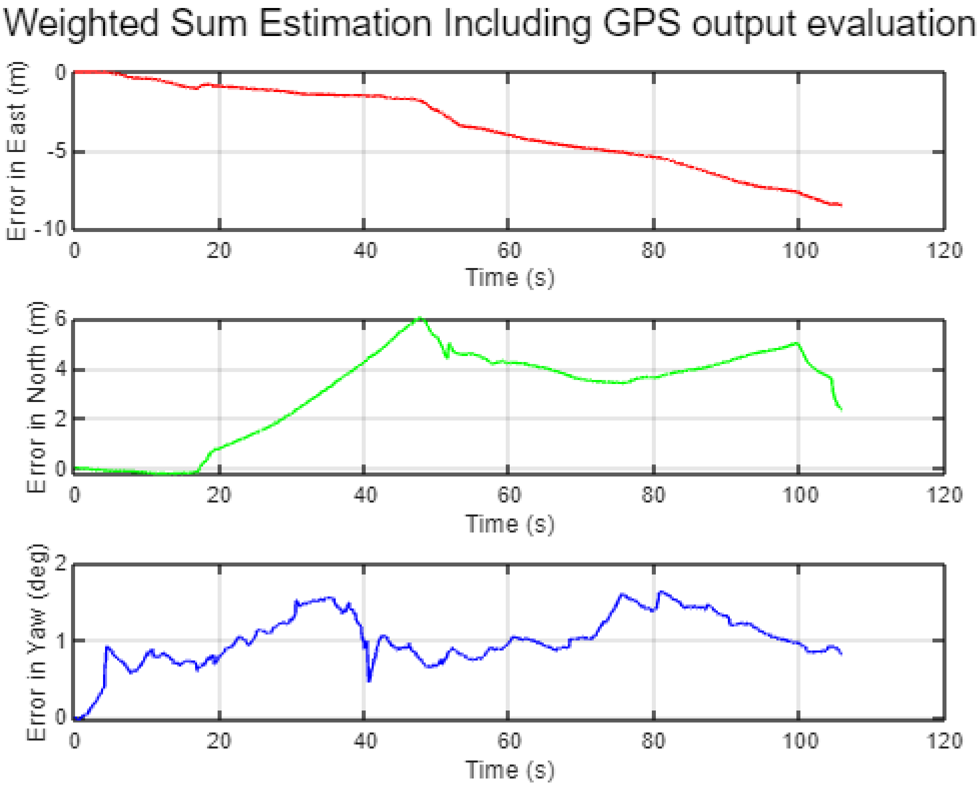
```
%Graphing Weighted Sum Estimation Including GPS output in comparison with GPS
data as the ground truth
figure;

subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
hold on;
plot(XGWs, YGWs, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
```

```
legend('GPS route', 'Weighted sum route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, YawGWs, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Weighted sum route');
grid on;
sgtitle('Weighted sum model output');
```



```
%GWS data difference
GWSDeltaE = GPSe - XGWs;
GWSDeltaN = GPSn - YGWs;
GWSDeltaYaw = yaw - YawGWs;

figure;

subplot(3, 1, 1);
plot(timeVector, GWSDeltaE, 'r');
xlabel('Time (s)');
ylabel('Error in East (m)');
grid on;

subplot(3, 1, 2);
plot(timeVector, GWSDeltaN, 'g');
xlabel('Time (s)');
```

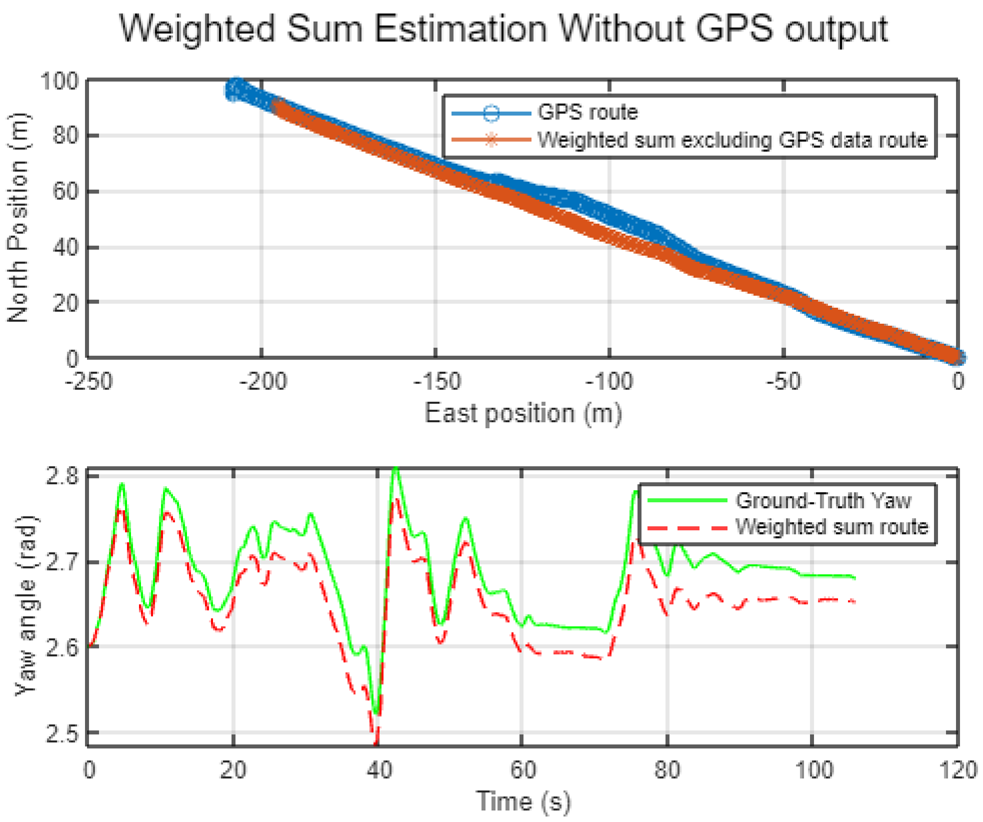
```
ylabel('Error in North (m)');
grid on;

subplot(3, 1, 3);
plot(timeVector, rad2deg(GWSDeltaYaw), 'b');
xlabel('Time (s)');
ylabel('Error in Yaw (deg)');
grid on;
sgtitle('Weighted Sum Estimation Including GPS output evaluation');
```



```
XWs = zeros(framesNum, 1);
YWs = zeros(framesNum, 1);
YawWs = zeros(framesNum, 1);
WeigthXY = [5, 10, 0, 20];
WeigthYaw = [5, 8, 0, 10];

for i= 1:framesNum
    XWs(i,:) = sum(WeigthXY .* X(i,:)) / sum(WeigthXY);
    YWs(i,:) = sum(WeigthXY .* Y(i,:)) / sum(WeigthXY);
    YawWs(i,:) = sum(WeigthYaw .* Yaw(i,:)) / sum(WeigthYaw);
end
```

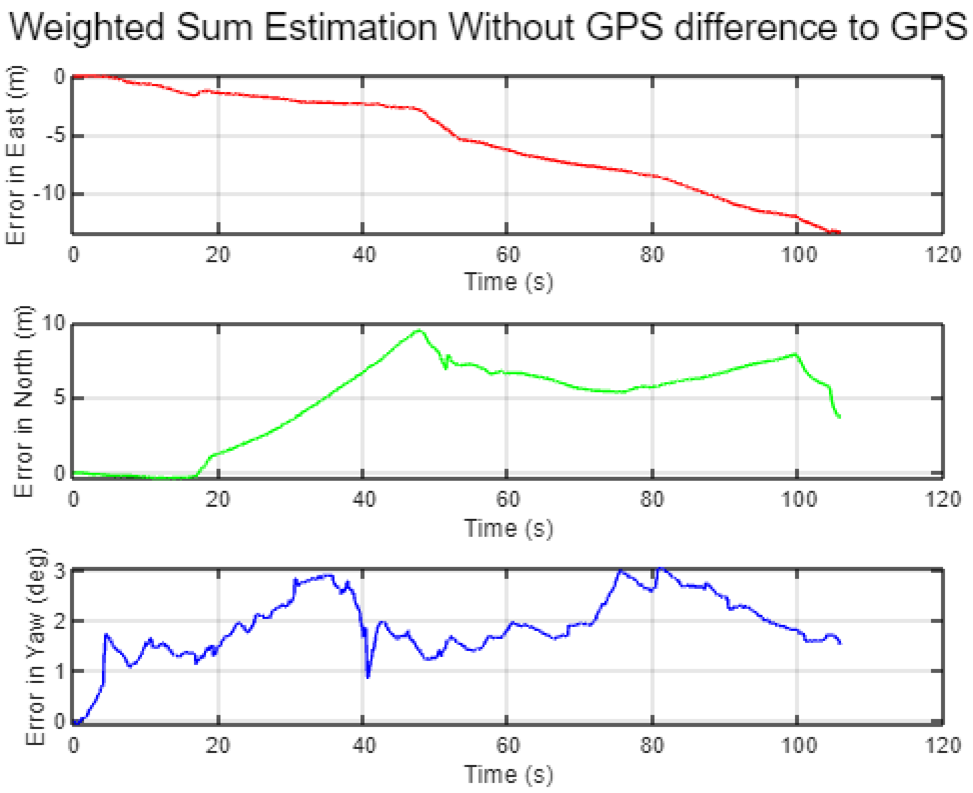
```
%Graphing Weighted Sum Estimation Without GPS output in comparison with GPS data
as the ground truth
figure;

subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
```

```
hold on;
plot(XWs, YWs, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('GPS route', 'Weighted sum excluding GPS data route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, YawWs, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Weighted sum route');
grid on;

sgtitle('Weighted Sum Estimation Without GPS output');
```



```
%WS data difference
WSDeltaE = GPSe - XWs;
WSDeltaN = GPSn - YWs;
WSDeltaYaw = yaw - YawWs;

figure;

subplot(3, 1, 1);
plot(timeVector, WSDeltaE, 'r');
xlabel('Time (s)');
ylabel('Error in East (m)');
```

```
grid on;

subplot(3, 1, 2);
plot(timeVector, WSDeltaN, 'g');
xlabel('Time (s)');
ylabel('Error in North (m)');
grid on;

subplot(3, 1, 3);
plot(timeVector, rad2deg(WSDeltaYaw), 'b');
xlabel('Time (s)');
ylabel('Error in Yaw (deg)');
grid on;
sgtitle('Weighted Sum Estimation Without GPS difference to GPS');
```



Standard Kalman Filter

Synced data Kalman Filter.

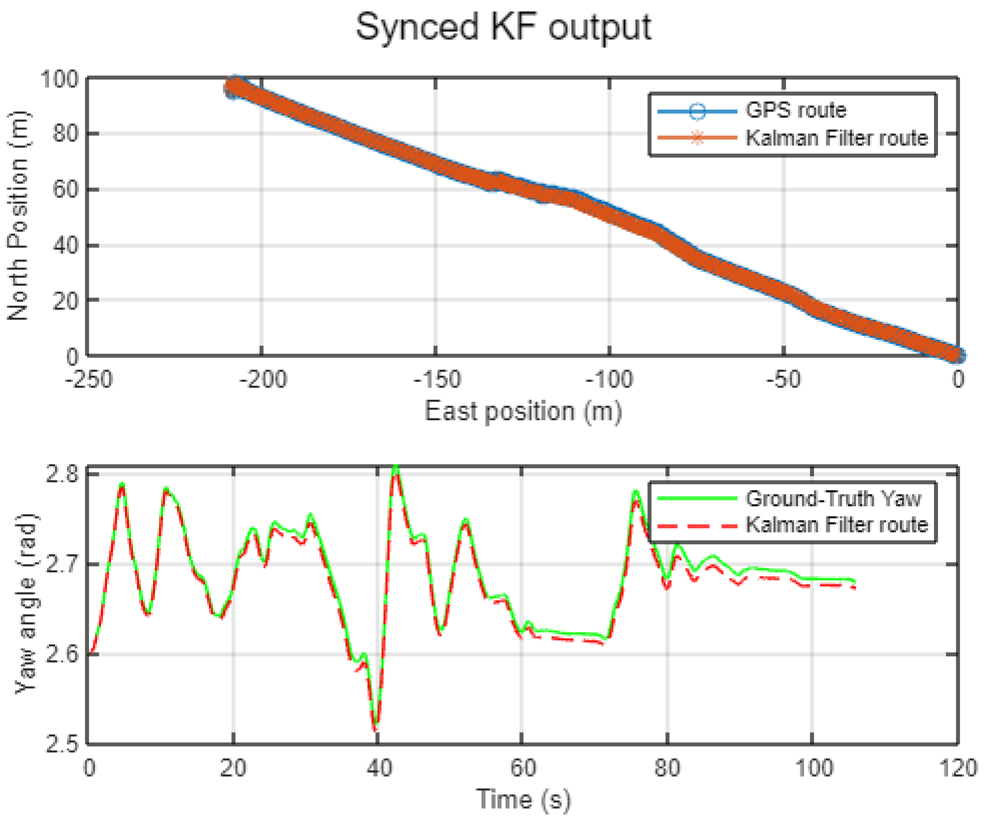
```
%Now with all data stored and set to be used in evaluating different filters
estimates.
%Using Kalman Filter as follows (Initialzing Parameters and matrices (dt, F, G,
H, Q, R) -> Setting Initial estimates -> Main Loop (Prediction -> update))

%1- Initialzing Parameters and Matrices (Synced data)
dt = 0.1; %Time step for used synced data approximately.
%Initializing State Transition matrix (F)
F = [1, 0, dt, 0, 0;
```

```
     0, 1, 0, dt, 0;
     0, 0, 1, 0, 0;
     0, 0, 0, 1, 0;
     0, 0, 0, 0, 1];
%Initializing Control Matrix (G)
G = [(dt^2)/2, 0, 0;
     0, (dt^2)/2, 0;
     dt, 0, 0;
     0, dt, 0;
     0, 0, dt];
%Initializing Measurements matrix (H)
H = [1, 0, 0, 0, 0;
     0, 1, 0, 0, 0;
     0, 0, 0, 0, 1;
     1, 0, 0, 0, 0;
     0, 1, 0, 0, 0;
     0, 0, 0, 0, 1;
     1, 0, 0, 0, 0;
     0, 1, 0, 0, 0;
     0, 0, 0, 0, 1];
%Initializing Process noise covariance matrix (Q)
Q = diag([0.1, 0.1, 0.01, 0.01, 0.1]);
%Initializing Measurement noise covariance matrix (R) for every sensor
R = diag([0.2, 0.2, 0.2, 0.1, 0.1, 0.1, 0.01, 0.01, 0.01]); %CAMERA -> LIDAR ->
GPS
%2-Setting initial estimates
%Initializing variables vector to hold xCheck, xHat, pCheck, pHat
xCheck = zeros(framesNum+1,5,1)';
pCheck = zeros(framesNum+1,5,5);
xHat = zeros(framesNum+1,5,1)'; % (+1) for inital estimates -> xHat(0)
pHat = zeros(framesNum+1,5,5); % (+1) for inital estimates -> pHat(0)
K = zeros(framesNum+1,5,9);
%Initializing state estimates xHat(k-1) -> first prediction iteration
xHat(:,1) = zeros(5,1); %[GPSe(0); GPSn(0); ve(0); vn(0); yaw(0);]; -> are all
assumed to be zero
xHat(5,1) = yaw(1);
%Initializing error covariance estimates pHat(k-1) -> first prediction iteration
pHat(1,:,:) = eye(5);
%Input matrix
u = [Ae An wu]';
%Measurement Matrix y
y = zeros(9, framesNum+1);
y(:,2:end) = [camX' camY' camYaw' lidarXBar' lidarYBar' deg2rad(lidarYaw') GPSe
GPSn yaw]'; %to store input with size with size 9*numFrames
```

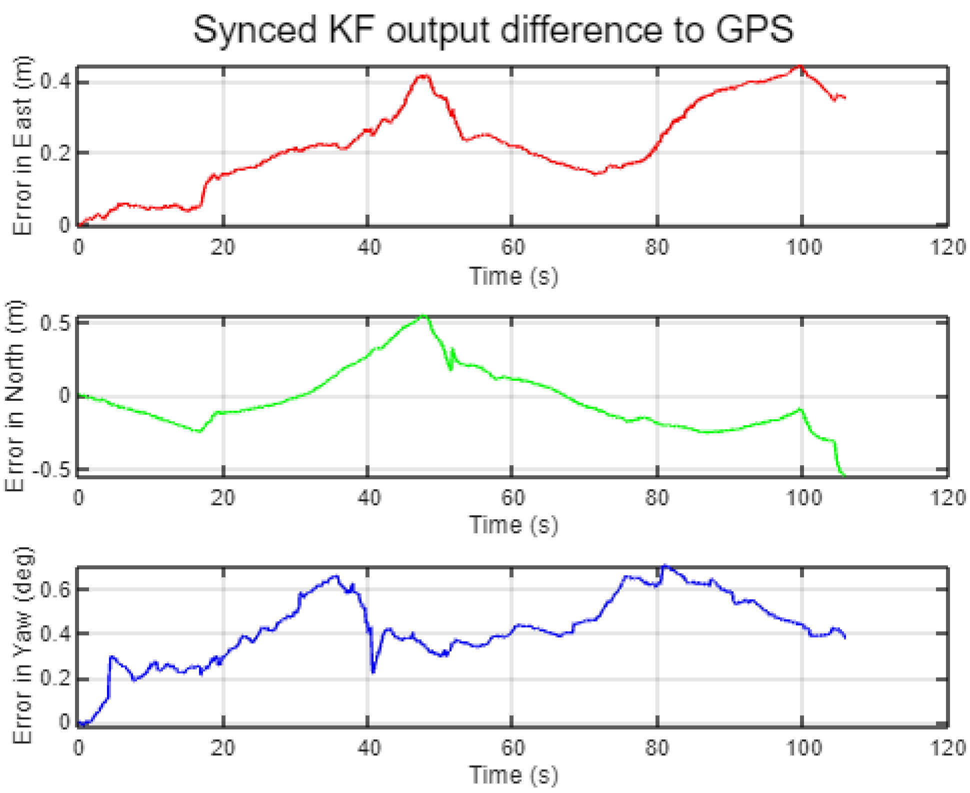
```
%3.0-Main filter loop
for i = 2:framesNum +1
%Prediction step
xCheck(:,i) = (F * xHat(:,i-1)) + (G * u(:,i-1));
pCheck(i,:,:) = (F * reshape(pHat(i-1,:,:), 5, 5) * F') + Q;
%Update step -> proceeed update step in 3 stages ->
K(i,:,:) = (reshape(pCheck(i,:,:), 5, 5) * H') * (inv(((H
*reshape(pCheck(i,:,:), 5, 5) * H') + R)));
```

```
xHat(:,i) = xCheck(:,i) + reshape(K(i,:,:), 5, 9)*(y(:,i) - (H * xCheck(:,i)));
pHat(i,:,:) = (eye(5) - (reshape(K(i,:,:), 5, 9) * H)) *
reshape(pCheck(i,:,:),5, 5);
end
```

```
%Seperating 2D Pose from states for visualization
kfEast = xHat(1, 2:end);
kfNorth = xHat(2, 2:end);
kfYaw = xHat(5, 2:end);
%Graphing Filter output in comparison with GPS data as the ground truth
figure;

subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
hold on;
plot(kfEast, kfNorth, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('GPS route', 'Kalman Filter route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, kfYaw, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Kalman Filter route');
grid on;

sgtitle('Synced KF output');
```



```
%KF Using synced data difference
kfDeltaE = GPSe - kfEast';
kfDeltaN = GPSn - kfNorth';
kfDeltaYaw = yaw - kfYaw';

figure;

subplot(3, 1, 1);
plot(timeVector, kfDeltaE, 'r');
xlabel('Time (s)');
ylabel('Error in East (m)');
grid on;

subplot(3, 1, 2);
plot(timeVector, kfDeltaN, 'g');
xlabel('Time (s)');
ylabel('Error in North (m)');
grid on;

subplot(3, 1, 3);
plot(timeVector, rad2deg(kfDeltaYaw), 'b');
xlabel('Time (s)');
ylabel('Error in Yaw (deg)');
grid on;
sgtitle('Synced KF output difference to GPS');
```



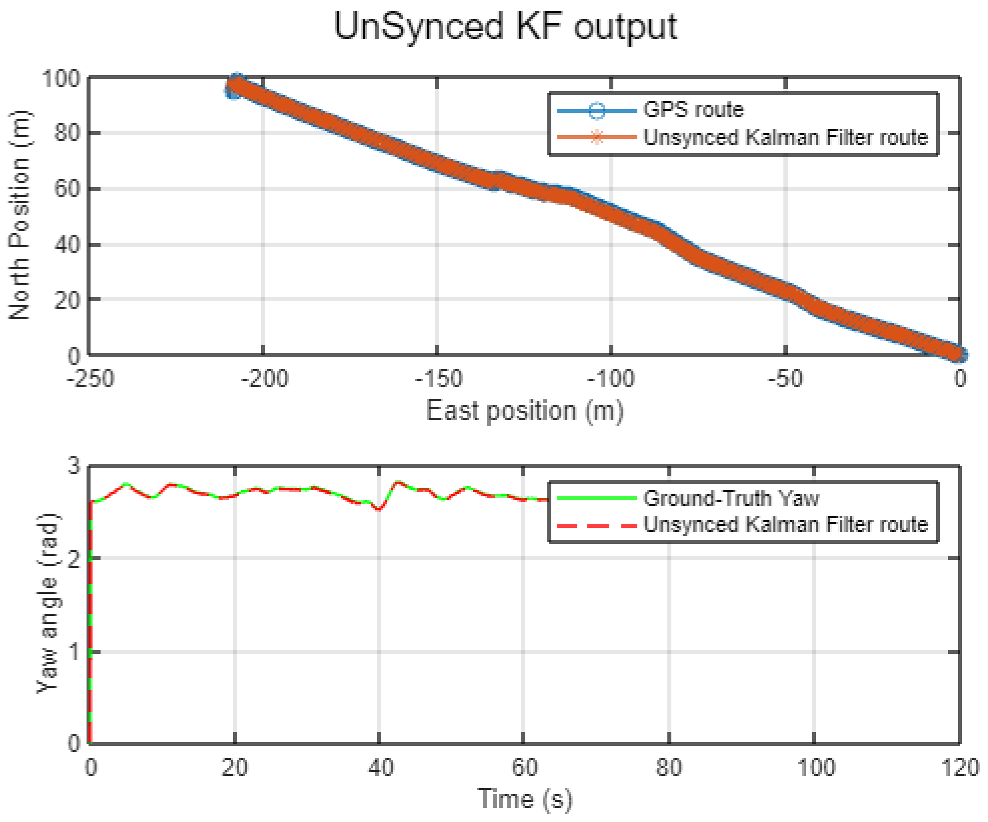
Unsynced data Kalman Filter.

```
%1- Initialzing Parameters and Matrices (UnSynced data)
dtU = 0.01; %Time step for used synced data approximately.
%Initializing State Transition matrix (F)
FU = [1,     0,      dtU,     0,      0;
      0,     1,      0,      dtU,     0;
      0,     0,      1,      0,      0;
      0,     0,      0,      1,      0;
      0,     0,      0,      0,      1];
%Initializing Control Matrix (G)
GU = [(dtU^2)/2,      0,                  0;
      0,             (dtU^2)/2,           0;
      dtU,            0,                  0;
      0,             dtU,                 0;
      0,             0,                  dtU];

%Initializing Measurements matrix (H) -> Including only GPS
HUGPS = [1,     0,      0,      0,      0;
         0,     1,      0,      0,      0;
         0,     0,      0,      0,      1];
%Initializing Process noise covariance matrix (Q)
QU = diag([0.1, 0.1, 0.1, 0.1, 0.1]);
%Initializing Measurement noise covariance matrix (R) for every sensor
RUGPS = diag([0.1, 0.1, 0.1]); %GPS

%1-Setting variables and initial estimates for filter saving the estimates after
cam & lidar update
```

```
%Initializing variables vector to hold xCheck, xHat, pCheck, pHat
xHatU = zeros(framesNum,5,1)'; % (+1) for inital estimates -> xHat(0)
pHatU = zeros(framesNum,5,5); % (+1) for inital estimates -> pHat(0)
%2-Setting variables and initial estimates for filter not including GPS
%Initializing variables vector to hold xCheck, xHat, pCheck, pHat
xCheckUG = zeros(unsyncFramesNum+1,5,1)';
pCheckUG = zeros(unsyncFramesNum+1,5,5);
xHatUG = zeros(unsyncFramesNum+1,5,1)'; % (+1) for inital estimates -> xHat(0)
pHatUG = zeros(unsyncFramesNum+1,5,5); % (+1) for inital estimates -> pHat(0)
%Initializing state estimates xHat(k-1) -> first prediction iteration
xHatUG(5,1) = unsyncYaw(1); %[GPSe(0); GPSn(0); ve(0); vn(0); yaw(0);]; -> are
all assumed to be zero not including yaw
%Initializing error covariance estimates pHat(k-1) -> first prediction iteration
pHatUG(1,:,:) = eye(5);
%Input matrix
uU = [unsyncAe unsyncAn unsyncWu];
```

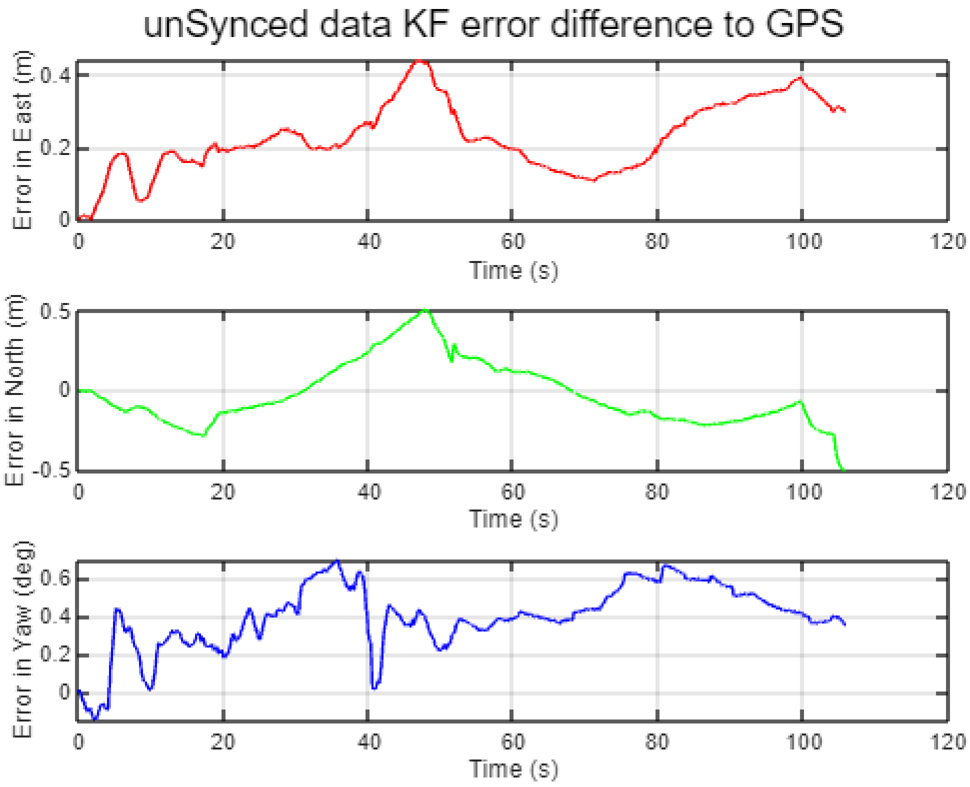
```
%3-Main filter loop for unsynced data
gpsF = zeros(framesNum, 3); %Corelated frames of synced data in unsynced data
%Providing start point as initial condition
gpsF(1,1) = unsyncGPSe(1);
gpsF(1,2) = unsyncGPSn(1);
gpsF(1,3) = yaw(1);
filterRatio = unsyncFramesNum/framesNum;
for i = 2:unsyncFramesNum
    %Prediction step
    xCheckUG(:,i) = (FU * xHatUG(:,i-1)) + (GU * uU(i-1,:)');
    pCheckUG(i,:,:) = (FU * reshape(pHatUG(i-1,:,:), 5, 5) * FU') + QU;

    %Update step
    %When Camera and lidar data are taken into consideration
    if(floor(mod(i, filterRatio)) == 1)
        frameIndex = ceil(i / filterRatio);
        %Now Set R, H, and Y --> to suit Lidar, Camera, GPS
        Y = [camX(frameIndex) camY(frameIndex) camYaw(frameIndex)
lidarXBar(frameIndex) lidarYBar(frameIndex) deg2rad(lidarYaw(frameIndex))
unsyncGPSe(i-1) unsyncGPSn(i-1) unsyncYaw(i-1)]';
        K = (reshape(pCheckUG(i,:,:), 5, 5) * H') * (inv(((H *
reshape(pCheckUG(i,:,:), 5, 5) * H') + R)));
        xHatUG(:,i) = xCheckUG(:,i) + K*(Y - (H * xCheckUG(:,i)));
        pHatUG(i,:,:) = (eye(5) - K * H) * reshape(pCheckUG(i,:,:), 5, 5);
        xHatU(:,frameIndex+1) = xHatUG(:,i);
        pHatU(frameIndex+1,:,:) = pHatUG(i,:,:);
        gpsF(frameIndex+1, :) = [unsyncGPSe(i-1) unsyncGPSn(i-1)
unsyncYaw(i-1)]';
    else
        Y = [unsyncGPSe(i-1) unsyncGPSn(i-1) unsyncYaw(i-1)]';
        K = (reshape(pCheckUG(i,:,:), 5, 5) * HUGPS') * (inv(((HUGPS *
reshape(pCheckUG(i,:,:), 5, 5) * HUGPS') + RUGPS)));
        xHatUG(:,i) = xCheckUG(:,i) + K*(Y - (HUGPS * xCheckUG(:,i)));
        pHatUG(i,:,:) = (eye(5) - K * HUGPS) * reshape(pCheckUG(i,:,:), 5, 5);
    end
end
```

```
%Seperating 2D Pose from states for visualization
kfEastU = xHatU(1,2:end);
kfNorthU = xHatU(2,2:end);
kfYawU = xHatU(5,2:end);
%Graphing Filter output in comparison with GPS data as the ground truth
figure;
subplot(2, 1, 1);
plot(gpsF(:,1), gpsF(:,2), '-o');
hold on;
plot(kfEastU, kfNorthU, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('GPS route', 'Unsynced Kalman Filter route');
grid on;

subplot(2, 1, 2);
plot(timeVector', gpsF(2:end,3), 'g');
hold on;
plot(timeVector, kfYawU, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Unsynced Kalman Filter route');
grid on;

sgtitle('UnSynced KF output');
```



```
figure;
%KF Using unsynced data
```

```
kfDeltaEU = gpsF(2:end,1) - kfEastU';
kfDeltaNU = gpsF(2:end,2) - kfNorthU';
kfDeltaYawU = gpsF(2:end,3) - kfYawU';

figure;

subplot(3, 1, 1);
plot(timeVector, kfDeltaEU, 'r');
xlabel('Time (s)');
ylabel('Error in East (m)');
grid on;

subplot(3, 1, 2);
plot(timeVector, kfDeltaNU, 'g');
xlabel('Time (s)');
ylabel('KF_North/GPS North (m)');
ylabel('Error in North (m)');
grid on;

subplot(3, 1, 3);
plot(timeVector, rad2deg(kfDeltaYawU), 'b');
xlabel('Time (s)');
ylabel('Error in Yaw (deg)');
grid on;
sgtitle('unSynced data KF error difference to GPS');
```

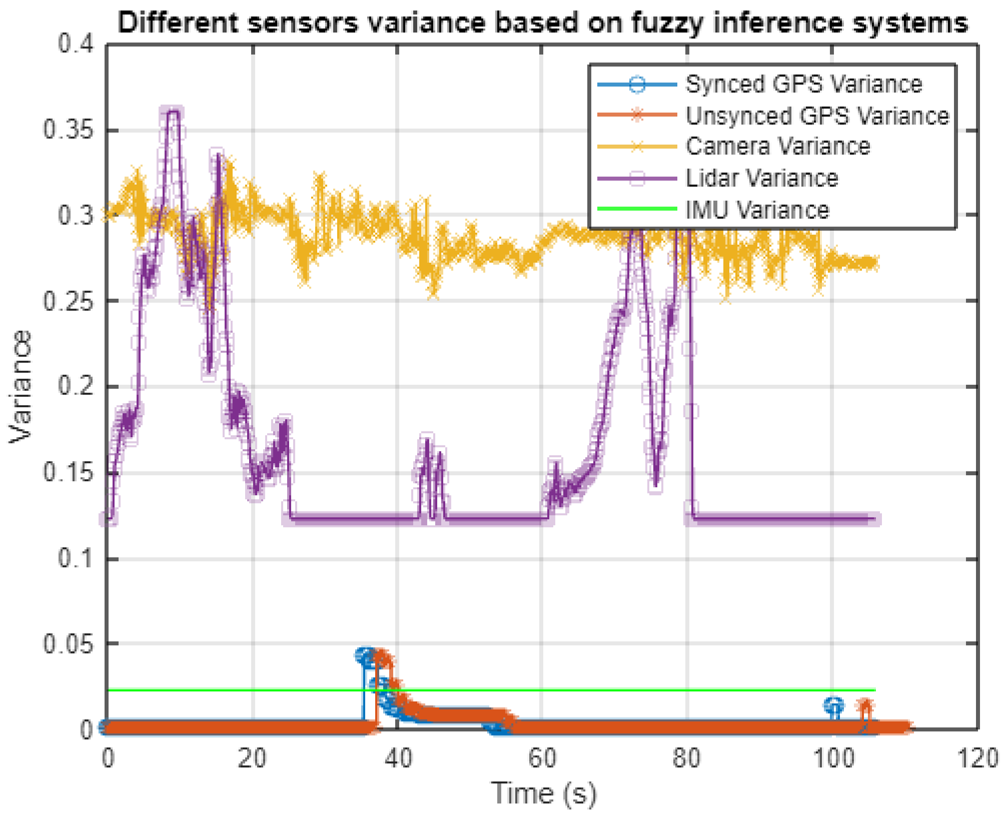


Extracting Weights for adaptive filters.

```
%First extracting Synced data weights for camera, lidar, and gps
```

```
gpsVar = (gpsWeights_FIS([posAcc numSats])).^2;
unsyncGpsVar = (gpsWeights_FIS([unsyncPosAcc unsyncNumSats])).^2;
camVar = (camWeights_FIS(camAvI)).^2;
lidarVar = (lidarWeights_FIS(pcdR)).^2;
imuVar = (0.15 * ones(framesNum, 1)).^2;%as imu weight and it is constant
```

```
%Plotting Weights for adaptive filters
figure;
plot(timeVector, gpsVar, '-o');
hold on;
plot(unsyncTimeVector, unsyncGpsVar, '-*');
plot(timeVector, camVar, '-x');
plot(timeVector, lidarVar, '-s');
plot(timeVector, imuVar, '-g');
legend('Synced GPS Variance', 'Unsynced GPS Variance', 'Camera Variance', 'Lidar
Variance', 'IMU Variance');
title('Different sensors variance based on fuzzy inference systems');
xlabel('Time (s)');
ylabel('Variance');
grid on;
hold off;
```



Adaptive filters (Weighted Average - KF - unsynced KF).

Adaptive Weighted Average Model

```
XAGWs = zeros(framesNum, 1);
```

```
YAGWs = zeros(framesNum, 1);
YawAGWs = zeros(framesNum, 1);
X = [camX', lidarXBar', GPSe, IMUe];
Y = [camY', lidarYBar', GPSn, IMUn];
Yaw = [camYaw', deg2rad(lidarYaw)', yaw, IMUYaw];
WeigthsAvModel = [(1 ./ camVar) (1 ./ lidarVar) (1 ./ gpsVar) (1 ./ imuVar)];

for i= 1:framesNum
    XAGWs(i,:) = sum(WeigthsAvModel(i,:) .* X(i,:)) / sum(WeigthsAvModel(i,:));
    YAGWs(i,:) = sum(WeigthsAvModel(i,:) .* Y(i,:)) / sum(WeigthsAvModel(i,:));
    YawAGWs(i,:) = sum(WeigthsAvModel(i,:) .* Yaw(i,:)) /
sum(WeigthsAvModel(i,:));
end
```

Adaptive Kalman Filter

```
%Storing R values
AR = ones(9,9,framesNum);
imuVariance = imuVar(1);
for i = 1:framesNum
    AR(:,:,i) = diag([camVar(i), camVar(i), camVar(i), lidarVar(i), lidarVar(i),
lidarVar(i), gpsVar(i), gpsVar(i), gpsVar(i)]); %Camera - lidar - gps
end
%Initializing parameters.
AQ = diag([imuVariance, imuVariance, imuVariance^0.5, imuVariance^0.5,
imuVariance]);
AxCheck = zeros(framesNum+1,5,1)';
ApCheck = zeros(framesNum+1,5,5);
AxHat = zeros(framesNum+1,5,1)'; % (+1) for inital estimates -> xHat(0)
ApHat = zeros(framesNum+1,5,5); % (+1) for inital estimates -> pHat(0)
AK = zeros(framesNum+1,5,9);
%Initializing state estimates xHat(k-1) -> first prediction iteration
AxHat(:,1) = zeros(5,1); %[GPSe(0); GPSn(0); ve(0); vn(0); yaw(0);]; -> are all
assumed to be zero
AxHat(5,1) = yaw(1);
%Initializing error covariance estimates pHat(k-1) -> first prediction iteration
ApHat(1,:,:) = eye(5);
%applying same Kalman main loop but with adaptive weights
for i = 2:framesNum +1
    %Prediction step
    AxCheck(:,i) = (F * AxHat(:,i-1)) + (G * u(:,i-1));
    ApCheck(i,:,:) = (F * reshape(ApHat(i-1,:,:), 5, 5) * F') + AQ;
    %Update step -> proceeed update step in 3 stages ->
    AK(i,:,:) = (reshape(ApCheck(i,:,:), 5, 5) * H') * (inv(((H
*reshape(ApCheck(i,:,:), 5, 5) * H') + reshape(AR(:,:,i-1), 9,9))));
    AxHat(:,i) = AxCheck(:,i) + reshape(AK(i,:,:), 5, 9)*(y(:,i) - (H *
AxCheck(:,i)));
    ApHat(i,:,:) = (eye(5) - (reshape(AK(i,:,:), 5, 9) * H)) *
reshape(ApCheck(i,:,:),5, 5);
end
AkfEast = AxHat(1, 2:end);
AkfNorth = AxHat(2, 2:end);
```

```
AkfYaw = AxHat(5, 2:end);
```

Adaptive Kalman Filter for Unsynced data

```
%Initializing Process noise covariance matrix (Q)
AQU = diag([imuVariance, imuVariance, imuVariance^0.5, imuVariance^0.5,
imuVariance]);
%Initializing Measurement noise covariance matrix (R) for every sensor
ARUGPS = ones(3,3,unsyncFramesNum);
for i = 1:unsyncFramesNum
    ARUGPS(:,:,i) = diag([unsyncGpsVar(i), unsyncGpsVar(i), unsyncGpsVar(i)]);
%Camera - lidar - gps
end
%Setting variables and initial estimates for filter saving the estimates after
cam & lidar update
%Initializing variables vector to hold xCheck, xHat, pCheck, pHat
AxHatU = zeros(framesNum,5,1)'; % (+1) for inital estimates -> xHat(0)
ApHatU = zeros(framesNum,5,5); % (+1) for inital estimates -> pHat(0)
%2-Setting variables and initial estimates for filter not including GPS
%Initializing variables vector to hold xCheck, xHat, pCheck, pHat
AxCheckUG = zeros(unsyncFramesNum+1,5,1)';
ApCheckUG = zeros(unsyncFramesNum+1,5,5);
AxHatUG = zeros(unsyncFramesNum+1,5,1)'; % (+1) for inital estimates -> xHat(0)
ApHatUG = zeros(unsyncFramesNum+1,5,5); % (+1) for inital estimates -> pHat(0)
%Initializing state estimates xHat(k-1) -> first prediction iteration
AxHatUG(5,1) = unsyncYaw(1); %[GPSe(0); GPSn(0); ve(0); vn(0); yaw(0);]; -> are
all assumed to be zero not including yaw
%Initializing error covariance estimates pHat(k-1) -> first prediction iteration
ApHatUG(1,:,:) = eye(5);
%Main filter loop for unsynced data
AgpsF = zeros(framesNum, 3); %Corelated frames of synced data in unsynced data
AgpsF(1,3) = yaw(1);
filterRatio = unsyncFramesNum/framesNum;


for i = 2:unsyncFramesNum
    %Prediction step
    AxCheckUG(:,i) = (FU * AxHatUG(:,i-1)) + (GU * uU(i-1,:)');
    ApCheckUG(i,:,:) = (FU * reshape(ApHatUG(i-1,:,:), 5, 5) * FU') + AQU;

    %Update step
    %When Camera and lidar data are taken into consideration
    if(floor(mod(i, filterRatio)) == 1)
        frameIndex = ceil(i / filterRatio);
        %Now Set R, H, and Y --> to suit Lidar, Camera, GPS
        Y = [camX(frameIndex) camY(frameIndex) camYaw(frameIndex)
lidarXBar(frameIndex) lidarYBar(frameIndex) deg2rad(lidarYaw(frameIndex))
unsyncGPSe(i-1) unsyncGPSn(i-1) unsyncYaw(i-1)]';
        RAfilter = diag([camVar(frameIndex) camVar(frameIndex)
camVar(frameIndex) lidarVar(frameIndex) lidarVar(frameIndex)
lidarVar(frameIndex) unsyncGpsVar(i-1) unsyncGpsVar(i-1) unsyncGpsVar(i-1)]);
```

```
        K = (reshape(ApCheckUG(i,:,:), 5, 5) * H') * (inv(((H *
reshape(ApCheckUG(i,:,:), 5, 5) * H') + RAfilter)));
        AxHatUG(:,i) = AxCheckUG(:,i) + K*(Y - (H * AxCheckUG(:,i)));
        ApHatUG(i,:,:) = (eye(5) - K * H) * reshape(ApCheckUG(i,:,:), 5, 5);
        AxHatU(:,frameIndex) = AxHatUG(:,i);
        ApHatU(frameIndex,:,:) = ApHatUG(i,:,:);
        AgpsF(frameIndex, :) = [unsyncGPSe(i-1) unsyncGPSn(i-1) unsyncYaw(i-1)]';
    else
        Y = [unsyncGPSe(i-1) unsyncGPSn(i-1) unsyncYaw(i-1)]';
        K = (reshape(ApCheckUG(i,:,:), 5, 5) * HUGPS') * (inv(((HUGPS *
reshape(ApCheckUG(i,:,:), 5, 5) * HUGPS') + reshape(ARUGPS(:,:,i-1), 3,3))));
        AxHatUG(:,i) = AxCheckUG(:,i) + K*(Y - (HUGPS * AxCheckUG(:,i)));
        ApHatUG(i,:,:) = (eye(5) - K * HUGPS) * reshape(ApCheckUG(i,:,:), 5, 5);
    end

end
AkfEastU = AxHatU(1,1:end);
AkfNorthU = AxHatU(2,1:end);
AkfYawU = AxHatU(5,1:end);
```

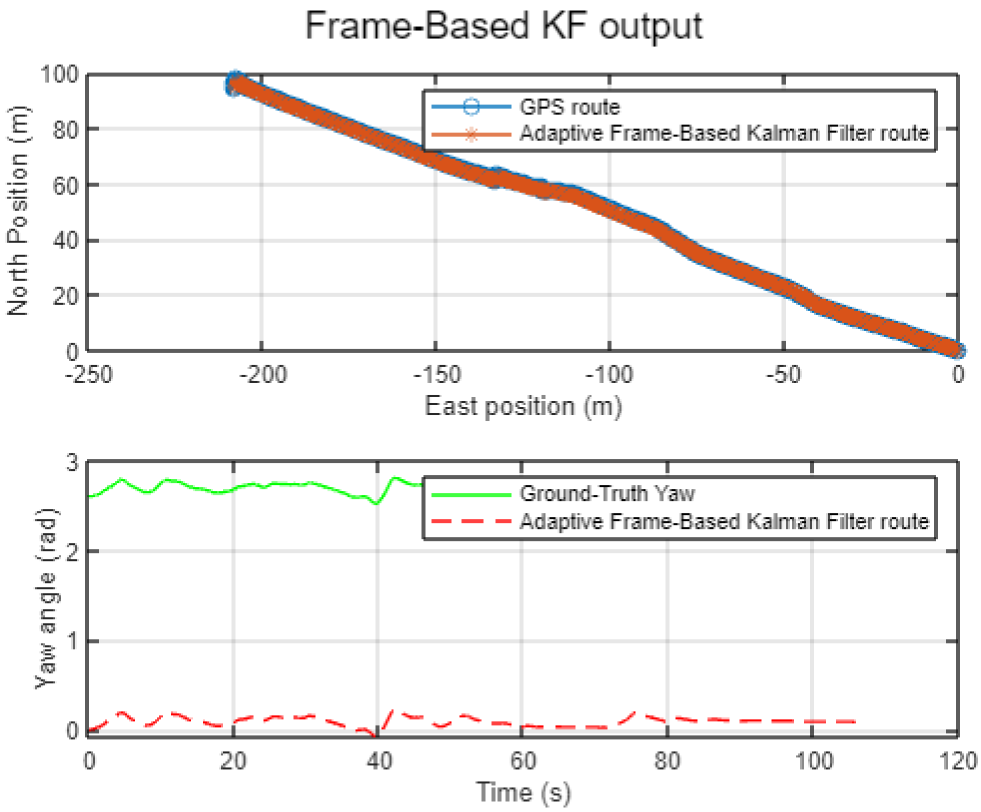
Frame-Based KF

```
%Trying Variations of KF with absolute position different for each frame on its
own.
%Separating Absolute Estimates from each Sensor
AbsIMUX = diff(IMUe);
AbsIMUY = diff(IMUn);
AbsIMUYaw = diff(IMUYaw);
AbsGPSX = diff(GPSe);
AbsGPSY = diff(GPSn);
AbsGPSYaw = diff(yaw);
AbsCamX = diff(camX);
AbsCamY = diff(camY);
AbsCamYaw = diff(camYaw);
AbsLidarX = diff(lidarXBar);
AbsLidarY = diff(lidarYBar);
AbsLidarYaw = diff(lidarYaw);

%Kalman filter
xCheckFrames = zeros(framesNum+1,5,1)';
pCheckFrames = zeros(framesNum+1,5,5);
xHatFrames = zeros(framesNum+1,5,1)'; % (+1) for inital estimates -> xHat(0)
pHatFrames = zeros(framesNum+1,5,5); % (+1) for inital estimates -> pHat(0)
KFrames = zeros(framesNum+1,5,9);
%Initializing state estimates xHat(k-1) -> first prediction iteration
xHatFrames(:,1) = zeros(5,1); %[GPSe(0); GPSn(0); ve(0); vn(0); yaw(0);]; -> are
all assumed to be zero
xHatFrames(5,1) = yaw(1);
%Initializing error covariance estimates pHat(k-1) -> first prediction iteration
pHatFrames(1,:,:) = eye(5);
%Measurement Matrix y
yFrames = zeros(9, framesNum);
```

```
yFrames(:,2:end) = [AbsCamX; AbsCamY; AbsCamYaw; AbsLidarX; AbsLidarY;
deg2rad(AbsLidarYaw); AbsGPSX'; AbsGPSY'; AbsGPSYaw']; %to store input with size
with size 9*numFrames
```

```
for i = 2:framesNum +1
%Prediction step
xCheckFrames(:,i) = (F * zeros(5,1)) + (G * u(:,i-1)); %Replacing initial
estimates with zeros and pInitial with identity matrix due to absolute
referencing
pCheckFrames(i,:,:) = (F * eye(5) * F') + AQ;
%Update step -> proceeed update step in 3 stages ->
KFrames(i,:,:) = (reshape(pCheckFrames(i,:,:), 5, 5) * H') * (inv(((H
*reshape(pCheckFrames(i,:,:), 5, 5) * H') + reshape(AR(:,:,i-1), 9,9))));
xHatFrames(:,i) = xCheckFrames(:,i) + reshape(KFrames(i,:,:), 5,
9)*(yFrames(:,i-1) - (H * xCheckFrames(:,i)));
pHatFrames(i,:,:) = (eye(5) - (reshape(KFrames(i,:,:), 5, 9) * H)) *
reshape(pCheckFrames(i,:,:),5, 5);
end
kfXFrames = cumsum(xHatFrames(1,2:end));
kfYFrames = cumsum(xHatFrames(2,2:end));
kfYawFrames = cumsum(xHatFrames(5,2:end));%Plotting
```

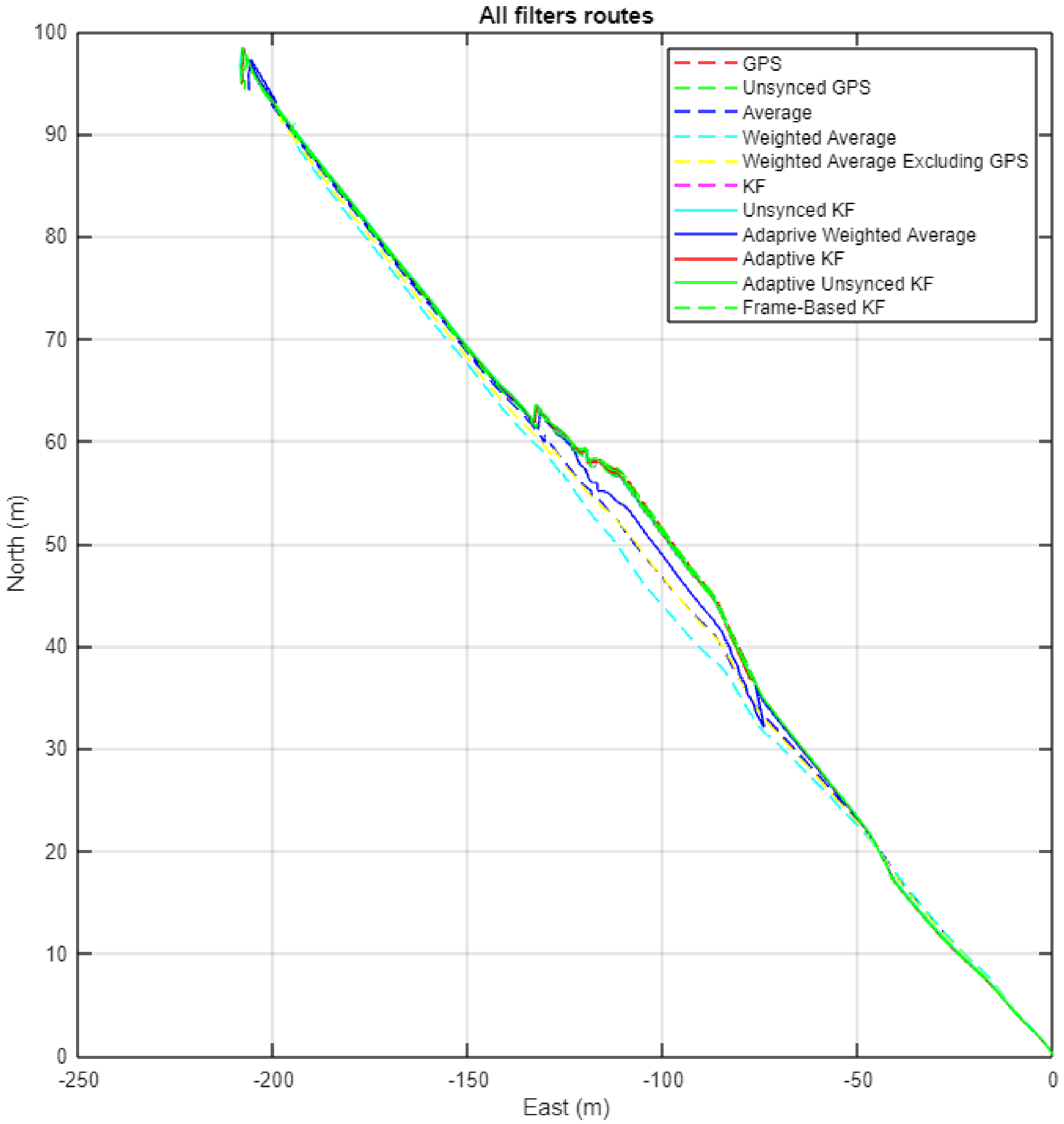
```
figure;
subplot(2, 1, 1);
plot(GPSe, GPSn, '-o');
hold on;
plot(kfXFrames, kfYFrames, '-*');
xlabel('East position (m)');
ylabel('North Position (m)');
legend('GPS route', 'Adaptive Frame-Based Kalman Filter route');
grid on;

subplot(2, 1, 2);
plot(timeVector, yaw, 'g');
hold on;
plot(timeVector, kfYawFrames, 'r--');
xlabel('Time (s)');
ylabel('Yaw angle (rad)');
legend('Ground-Truth Yaw', 'Adaptive Frame-Based Kalman Filter route');
grid on;
sgtitle('Frame-Based KF output');
```



Evaluating Fusion Techniques on world map using Latitude/Longitude Coordinates.

```
LL_Av = zeros(framesNum, 2); %for average estimation
LL_WEG = zeros(framesNum, 2); %for weighted estimation With GPS
LL_WE = zeros(framesNum, 2); %for weighted estimation Without GPS
LL_KFS = zeros(framesNum, 2); %for KF using synced data
LL_KFUS = zeros(framesNum, 2); %for KF using unsynced data
%For adaptive filters
ALL_WEG = zeros(framesNum, 2); %for weighted estimation adaptive
ALL_KFS = zeros(framesNum, 2); %for KF using synced data adaptive
ALL_KFUS = zeros(framesNum, 2); %for KF using unsynced data adaptive
%frame based
LL_KFFrame = zeros(framesNum, 2); %for frame-based kalman filter

for i = 1:framesNum
    LL_Av(i,:) = en_to_ll([XAvg(i), YAvg(i)] , [latitude(1), longitude(1),
altitude(1)]);
    LL_WE(i,:) = en_to_ll([XWs(i), YWs(i)] , [latitude(1), longitude(1),
altitude(1)]);
    LL_WEG(i,:) = en_to_ll([XGWs(i), YGWs(i)] , [latitude(1), longitude(1),
altitude(1)]);
    LL_KFS(i,:) = en_to_ll([kfEast(i), kfNorth(i)] , [latitude(1), longitude(1),
altitude(1)]);
    LL_KFUS(i,:) = en_to_ll([kfEastU(i), kfNorthU(i)] , [unsyncLatitude(1),
unsyncLongitude(1), unsyncAltitude(1)]);
    %For adaptive filters
    ALL_WEG(i,:) = en_to_ll([XAGWs(i), YAGWs(i)] , [latitude(1), longitude(1),
altitude(1)]);
    ALL_KFS(i,:) = en_to_ll([AkfEast(i), AkfNorth(i)] , [latitude(1),
longitude(1), altitude(1)]);
    ALL_KFUS(i,:) = en_to_ll([AkfEastU(i), AkfNorthU(i)] , [unsyncLatitude(1),
unsyncLongitude(1), unsyncAltitude(1)]);
    %For sensor-based frames kalma
    LL_KFFrame(i,:) = en_to_ll([kfXFrames(i), kfYFrames(i)] ,
[unsyncLatitude(1), unsyncLongitude(1), unsyncAltitude(1)]);
end
```

```
%Plotting East & North Positions of all filters
figure;
figure('Position', [0, 0, 2000, 2000]);

plot(GPSe, GPSn, 'r--');
hold on;
plot(unsyncGPSe, unsyncGPSn, 'g--');
plot(XAvg, YAvg, 'b--');
plot(XWs, YWs, 'c--');
plot(XGWs, YGWs, 'y--');
plot(kfEast, kfNorth, 'm--');
plot(kfEastU, kfNorthU, '-c');
plot(XAGWs, YAGWs, '-b');
plot(AkfEast, AkfNorth, '-r');
plot(AkfEastU, AkfNorthU, '-g');
plot(kfXFrames, kfYFrames, 'g--');

legend('GPS', 'Unsynced GPS', 'Average', 'Weighted Average', 'Weighted Average
Excluding GPS', 'KF', 'Unsynced KF', 'Adaprive Weighted Average', ...
    'Adaptive KF', "Adaptive Unsynced KF", "Frame-Based KF");
title('All filters routes');
xlabel('East (m)');
ylabel('North (m)');
grid on;
hold off;
```



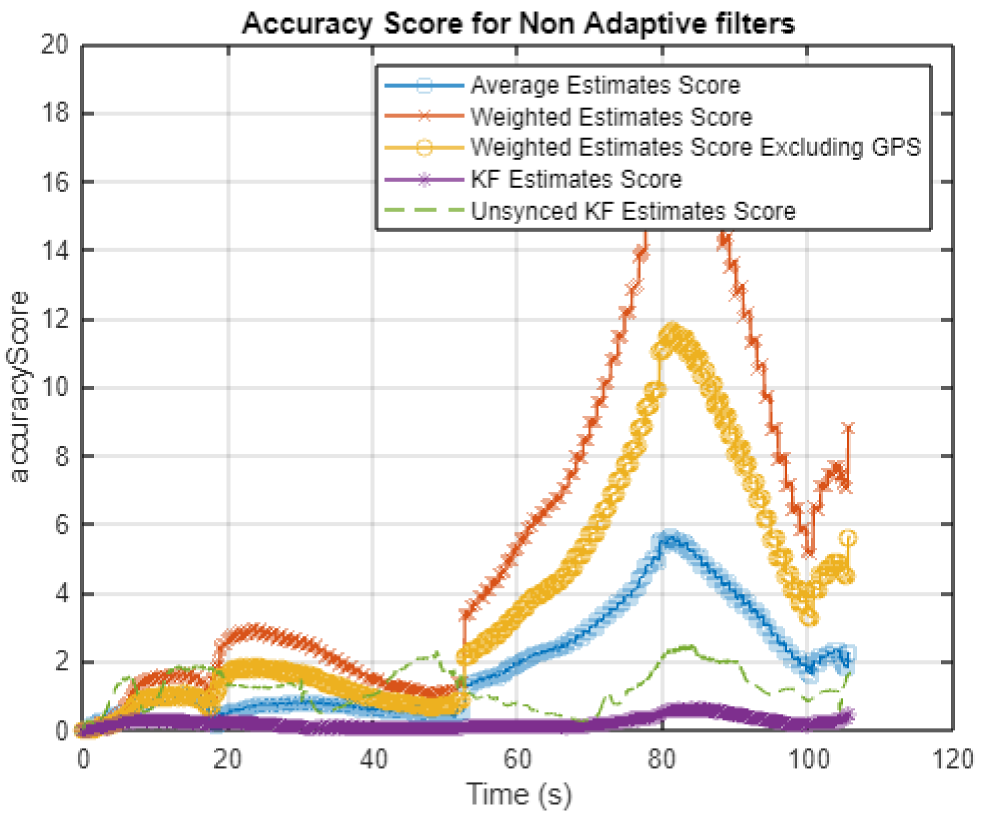
```
%Now we plot the route using GPS data on a global map
webmap('Open Street Map');
wmmarker(latitude(1), longitude(1), 'FeatureName', 'Start point actual');
wmline(latitude(2:end-1), longitude(2:end-1), "Color", 'black');
wmmarker(latitude(end), longitude(end), 'FeatureName', 'End point actual');

wmline(LL_Av(2:end-1, 1), LL_Av(2:end-1, 2), "Color", "yellow", "OverlayName",
'Average Estimates path');
wmmarker(LL_Av(end, 1), LL_Av(end, 2), 'FeatureName', 'End point Average
Estimates');
```

```
wmline(LL_WE(2:end-1, 1), LL_WE(2:end-1, 2), "Color", "magenta", "OverlayName",
'Weighted Estimates Including GPS path');
wmmarker(LL_WE(end, 1), LL_WE(end, 2), 'FeatureName', 'End point Weighted
Estimates Excluding GPS');

wmline(LL_WEG(2:end-1, 1), LL_WEG(2:end-1 ,2), "Color", "cyan", "OverlayName",
'Weighted Estimates Excluding GPS path');
wmmarker(LL_WEG(end, 1), LL_WEG(end, 2), 'FeatureName', 'End point Weighted
Estimates Including GPS');

wmline(LL_KFS(2:end-1, 1), LL_KFS(2:end-1, 2), "Color", "blue", "OverlayName",
'KF Estimates path');
wmmarker(LL_KFS(end, 1), LL_KFS(end, 2), 'FeatureName', 'End point KF Estimates
using Synced data');

wmline(LL_KFUS(2:end-1, 1), LL_KFUS(2:end-1, 2), "Color", "green",
"OverlayName", 'Unsynced KF path');
wmmarker(LL_KFUS(end, 1), LL_KFUS(end, 2), 'FeatureName', 'End point Unsynced KF
Estimates');

wmline(ALL_WEG(2:end-1, 1), ALL_WEG(2:end-1, 2), "Color", "red", "OverlayName",
'adaptive weighted average estimates path');
wmmarker(ALL_WEG(end, 1), ALL_WEG(end, 2), 'FeatureName', 'End point adaptive
weighted average Estimates');

wmline(ALL_KFS(2:end-1, 1), ALL_KFS(2:end-1, 2), "Color", "yellow",
"OverlayName", 'adaptive KF path');
wmmarker(ALL_KFS(end, 1), ALL_KFS(end, 2), 'FeatureName', 'End point adaptive KF
Estimates');

wmline(ALL_KFUS(2:end-1, 1), ALL_KFUS(2:end-1, 2), "Color", "white",
"OverlayName", 'adaptive Unsynced KF path');
wmmarker(ALL_KFUS(end, 1), ALL_KFUS(end, 2), 'FeatureName', 'End point adaptive
Unsynced KF Estimates');

wmline(LL_KFFrame(2:end-1, 1), LL_KFFrame(2:end-1, 2), "Color", "cyan",
"OverlayName", 'Frame-Based KF path');
wmmarker(LL_KFFrame(end, 1), LL_KFFrame(end, 2), 'FeatureName', 'End point Frame-
Based KF Estimates');
```

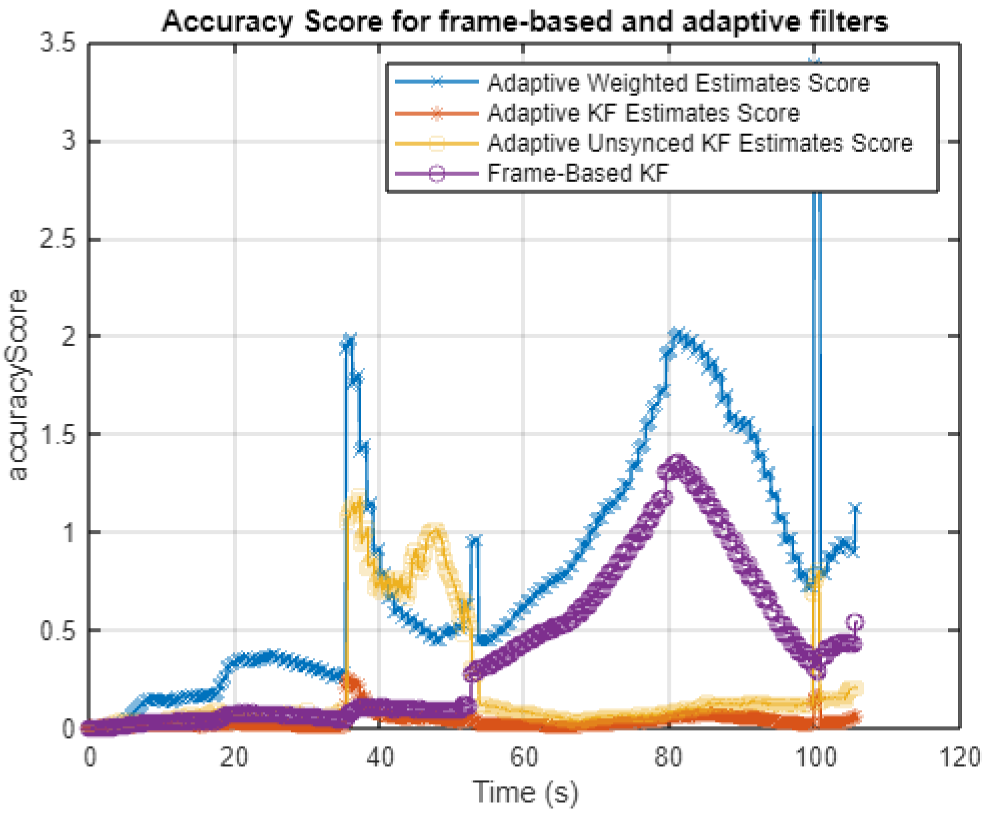
```
%Now we evaluate each filter using gps normalized accuracy score measure
AVAccScore = zeros(framesNum,1);
WEAccScore = zeros(framesNum,1);
WEGAccScore = zeros(framesNum,1);
KFSAccScore = zeros(framesNum,1);
KFUSAccScore = zeros(framesNum,1);
AWEGAccScore = zeros(framesNum,1);
AKFSAccScore = zeros(framesNum,1);
AKFUSAccScore = zeros(framesNum,1);
FBKFAccScore = zeros(framesNum,1);

for i= 1:framesNum
```

```
    [AVAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i), XAvg(i),
YAvg(i));
    [WEAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i), XWs(i),
YWs(i));
    [WEGAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i), XGWs(i),
YGWs(i));
    [KFSAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i),
kfEast(i), kfNorth(i));
    [KFUSAccScore(i), ~, ~] = accuracyScore(gpsF(i,1), gpsF(i,2),
unsyncPosAcc(ceil(i*(1/filterRatio))), kfEastU(i), kfNorthU(i));
    [AWEGAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i),
XAGWs(i), YAGWs(i));
    [AKFSAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i),
AkfEast(i), AkfNorth(i));
    [AKFUSAccScore(i), ~, ~] = accuracyScore(AgpsF(i,1), AgpsF(i,2),
unsyncPosAcc(ceil(i*(1/filterRatio))), AkfEastU(i), AkfNorthU(i));
    [FBKFAccScore(i), ~, ~] = accuracyScore(GPSe(i), GPSn(i), posAcc(i),
kfXFrames(i), kfYFrames(i));
end
```

```
%Now we plot change in accuracy measure for different approaches (Low accuracy
filters)
figure;

plot(timeVector, AVAccScore, '-s');
hold on;
plot(timeVector, WEAccScore, '-x');
plot(timeVector, WEGAccScore, '-o');
plot(timeVector, KFSAccScore, '-*');
plot(timeVector, KFUSAccScore, '--');

legend('Average Estimates Score', 'Weighted Estimates Score', 'Weighted
Estimates Score Excluding GPS', 'KF Estimates Score', 'Unsynced KF Estimates
Score');
title('Accuracy Score for Non Adaptive filters');
xlabel('Time (s)');
ylabel('accuracyScore');
grid on;
hold off;
```



```
%Now we plot change in accuracy measure for different approaches (High accuracy
filters)
figure;

plot(timeVector, AWEGAccScore, '-x');
hold on;
plot(timeVector, AKFSAccScore, '-*');
plot(timeVector, AKFUSAccScore, '-s');
plot(timeVector, FBKFAccScore, '-o');

legend('Adaptive Weighted Estimates Score','Adaptive KF Estimates Score',
'Adaptive Unsynced KF Estimates Score', 'Frame-Based KF');
title('Accuracy Score for frame-based and adaptive filters');
xlabel('Time (s)');
ylabel('accuracyScore');
grid on;
hold off;
```



```
%To obtain total distance of travel
totalDist = 0;
for i= 2:framesNum
    deltaEast = GPSe(i) - GPSe(i-1);
    deltaNorth = GPSn(i) - GPSn(i-1);
    dist = sqrt(deltaEast^2 + deltaNorth^2);
    totalDist = totalDist + dist;
end
%Displaying Average accuracy score per path
fprintf(['For a route with length = %f (m)
\n________________________________________\n\n' ...
    'Average Estimates Average accuracyScore = %f\n\nWeighted Estimates Average
accuracyScore = %f\n\n' ...
    'Weighted Estimates Excluding GPS Average accuracyScore = %f\n\nSynced KF
Estimates Average accuracyScore = %f\n\n' ...
    'Adaptive Weighted Estimates Excluding GPS Average accuracyScore = %f\n\n'
...
    'Unsynced KF Estimates Average accuracyScore = %f\n\nAdaptive KF Estimates
Average accuracyScore = %f\n\n' ...
    'Adaptive Unsynced KF Estimates Average accuracyScore = %f\n\nFrame-Based KF
Average AccuracyScore = %f'], totalDist,mean(AVAccScore), ...
    mean(WEAccScore), mean(WEGAccScore),mean(KFSAccScore), mean(AWEGAccScore),
mean(KFUSAccScore), mean(AKFSAccScore), mean(AKFUSAccScore), mean(FBKFAccScore));
```

```
For a route with length = 237.832732 (m)
________________________________________

Average Estimates Average accuracyScore = 1.876649

Weighted Estimates Average accuracyScore = 5.740868
Weighted Estimates Excluding GPS Average accuracyScore = 3.653279

Synced KF Estimates Average accuracyScore = 0.221358

Adaptive Weighted Estimates Excluding GPS Average accuracyScore = 0.799923

Unsynced KF Estimates Average accuracyScore = 1.212436

Adaptive KF Estimates Average accuracyScore = 0.039406

Adaptive Unsynced KF Estimates Average accuracyScore = 0.209377

Frame-Based KF Average AccuracyScore = 0.382453
```