Next Generation Vehicle Positioning Techniques for GPS-Degraded Environments to Support Vehicle Safety and Automation Systems

FHWA BAA DTFH61-09-R-00004

EXPLORATORY ADVANCED RESEARCH PROGRAM

Auburn University
SRI (formerly Sarnoff) Corporation
The Pennsylvania State University
Kapsch TrafficCom Inc.
NAVTEQ North America LLC

Quarterly Report 6

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1. Scope

In an open environment, GPS provides a good estimation of vehicle position. Numerous improvements over the basic GPS framework have provided accuracies in the centimeter range. However, blockages of the GPS signal create significant problems for the positioning solution. In so-called “urban canyons”, GPS signals are blocked by the presence of tall buildings. Similarly, heavy foliage in forests can block line-of-sight to the satellites. Because of these problems, a broader approach is needed that does not rely exclusively on GPS. This project takes into account three key technology areas which have each been individually shown to improve positioning solutions where GPS is not available or is hampered in a shadowed environment. First, terrain-based localization can be readily used to find the vehicle’s absolute longitudinal position within a pre-mapped highway segment – compensating for drift which occurs in dead-reckoning system in long longitudinal stretches of road. Secondly, visual odometry keys upon visual landmarks at a detailed level to correlate position to a (visually) premapped road segment to find vehicle position along the roadway. Both of these preceding techniques rely on foreknowledge of road features – in essence, a feature-enhanced version of a digital map. This becomes feasible in the “connected vehicle” future, in which tomorrow’s vehicles have access to quantities of data orders of magnitude greater than today’s cars, as well as the ability to share data at high data rates. The third technology approach relies on radio frequency (RF) ranging based on DSRC radio technology. In addition to pure RF ranging with no GPS signals, information from RF ranging can be combined with GPS range measurements (which may be inadequate on their own) to generate a useful position. Based on testing and characterization of these technologies individually in a test track environment, Auburn will define a combined Integrated Positioning System (IPS) for degraded GPS environments, which will also incorporate ongoing FHWA EAR work at Auburn in fusion of GPS and on-board sensors. This integrated approach will blend the strengths of each technique for greater robustness and precision overall. This research is expected to be a major step forward towards exceptionally precise and reliable positioning by taking advantage of long-term trends in on-board computing, connected vehicles, and data sharing.

1.1 SRI Sarnoff Contribution

The scope of SRI Sarnoff’s work under Year One of this project is the evaluation of their Visual Aided Navigation System for providing highly accurate positioning for vehicles. As such there are 3 major tasks:

(1) Evaluate and provide a survey of Sarnoff’s existing Visual Navigation results

(2) Integrate Visual Navigation system on Auburn Engineering’s G35 vehicle test platform and collect test data using the integrated system.

(3) Process and analyze the data from the tests and evaluate the performance and recommend any improvements and optimizations.

1.2 The Pennsylvania State University Contribution

For sake of clarity and coherence, the scope of Penn State's contribution to the project, as discussed in previous quarterly reports, is reproduced here. The primary objectives under Penn State's purview are:

(1) Developing the proven particle filter approach so that it can be used for localization with commercial-grade sensors, rather than defense-grade sensors,
(2) Modifying and optimizing the particle filter algorithm, and exploring alternative approaches, so that localization can take place online (in real-time) rather than offline, and
(3) Modifying and optimizing the algorithms as well as terrain map representation, so that the localization algorithms work over a large network of roads, rather than a small section of a single road alone.

1.3 Kapsch TrafficCom Inc. Contribution

Kapsch will investigate the accuracy of close proximity calculations available from the 5.9 GHz DSRC communications channel. A great deal of information related to positioning can be inferred from the DSRC communications channel. Basic calculations may provide a location region achieved through the channel ranging calculations to more precise lane based proximity determinations through advanced analysis of the communications channel. Kapsch will research a combination of both approaches through available data defined in the IEEE 802.11p standard for 5.9 GHz communication and through scientific Radio Frequency (RF) analysis.

Kapsch will support Auburn for the characterization of the ability to utilize the 5.9 GHz DSRC communication channel for next generation non-GPS localization services. The Received Signal Strength Indication (RSSI) in-conjunction with other aspects of the DSRC communications channel will be analyzed and a method developed for signal ranging. Kapsch does not believe RSSI ranging techniques will fully meet the desired localization needs. Year 2 will yield more advanced algorithms and DSRC equipment capable of providing lane level localization from the DSRC communications channel. This task includes the following sub-tasks:

(1) System Engineering and Deployment of DSRC Infrastructure at the Auburn Test Track
(2) Lab testing of DSRC signal ranging solution
(3) On-site testing of DSRC signal ranging solution
(4) Analysis of DSRC signal ranging test results

2. Current Progress

2.1 SRI Progress

2.1.1 Visual Navigation Sensor Package and Data Collection

The sensor package for visual navigation consists of cameras and IMU mounted on the vehicle roof rack, described in a previous report.

The front camera box was rebuilt and returned to Auburn on 02/15/2011, with new cabling, network hub, and cameras installed. The configured laptop was also sent to Auburn at that time. The cameras were mounted on the vehicle and calibrated by Chris Rose at Auburn. Data was collected on the test track at varying speeds and lighting conditions and raw video, IMU, and groundtruth GPS data was collected.

The figure below shows the camera system hardware, including the front camera enclosure with two cameras and an IMU, the breakout box with the gigbit hub and trigger, and the laptop.

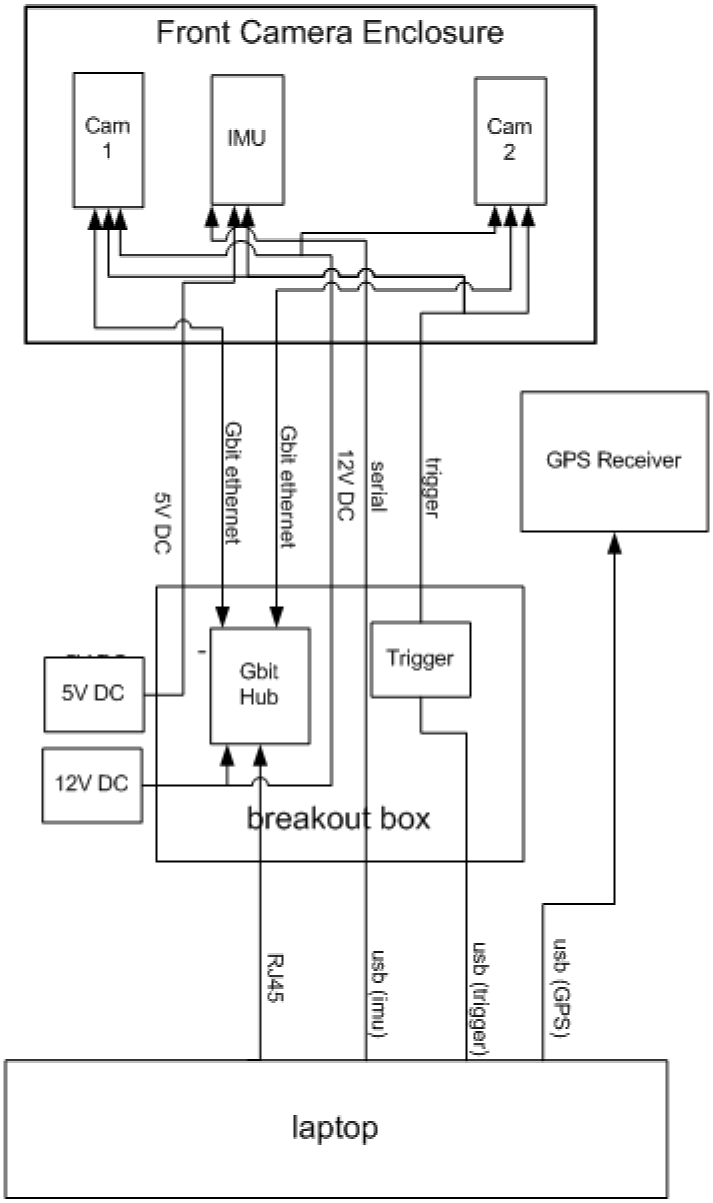


Figure 1: Wiring diagram for the front-only camera system

2.1.2 Visual Navigation System and Software

Visual landmarking gives absolute 3D positioning from landmark databases recorded and augmented on the fly.

- **Landmark image**: a constellation of HOG features, each associated with a 3D point (from stereo)
- **Landmark database**: a collection of automatically selected landmark images, referenced by the 6DOF viewing pose.
- **Landmark matching**: retrieving and recognizing a landmark image (uses vocabulary tree and spatial caching for speed), then estimating new viewing pose.

SRI Sarnoff is currently integrating the Visual Landmarking system with the GPS alignment system.

The figure below shows two slightly different scenes of an open field surrounded by forest. One scene is labeled as Dynamic Landmark Database, while the other scene is labeled Inspection Run. An arrow points from the inspection run scene ot the dynamic landmark database scene. Two additional arrows point down from both scenes to two additional scenes of two trees in a grassy field, which are labeled Landmark Based Retrieval of Reference Image.

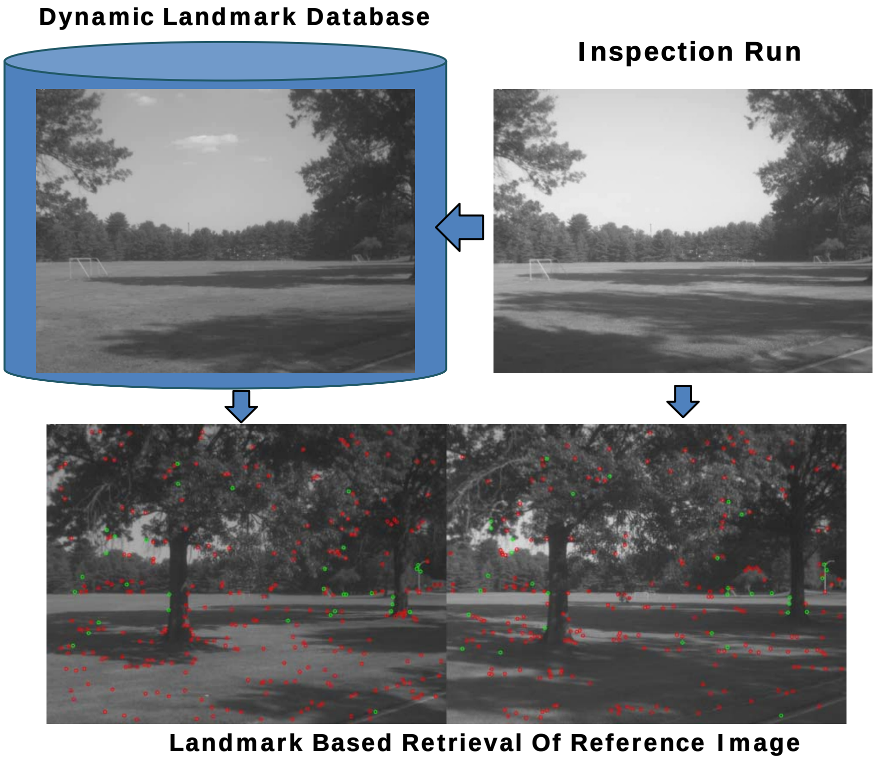


Figure 2: A landmark database is built automatically from 2D features and 3D features and view-based 6DOF poses. Once the landmark database is built, absolute positioning can be done by matching the current view to a reference image in the database and inferring

2.1.3 Visual Navigation Data Analysis

The data collected by Auburn Univ on 4/18 was taken for 2 purposes. One, to assess various synchronization and configuration issues using data that includes quick starts and stops and swerves. Rapid acceleration, deceleration, and roll and pitch changes are used to locate synchronization problems between the cameras, the IMU, and the GPS data.

The remainder of the data collected on 4/18 was used to assess the accuracy of visual odometry over different speeds and different lighting conditions. Artificial degradation of the ground truth

GPS data was done by adding uniform translations of 2m, 4m, and 6m, and reducing the data rate to 1Hz (from 10Hz). Visual odometry alone was also considered. Drift rates were computed for each case by comparing position of the visual odometry at each frame with ground truth position.

The figure below shows a graph of total drift over different GPS data. The 1Hz, 6m data stays below 2 meter drift over the 10 mph, 30mph, 50mph and low lighting data. The 1Hz, 4m data remains slightly above 2 meters for the 30mph, 50 mph, and low lighting. The 1Hz, 2m data is at 4m for the 10 mph run, 2m for the 30mph run, 10m for the 50 mph run, and 7m for the low lighting run. Finally, for the 1 min GPS outage, the data is at 4m for the 10mph run, 3m for the 30 mph run, 6m for the 50 mph run, and 7m for the low lighting run.

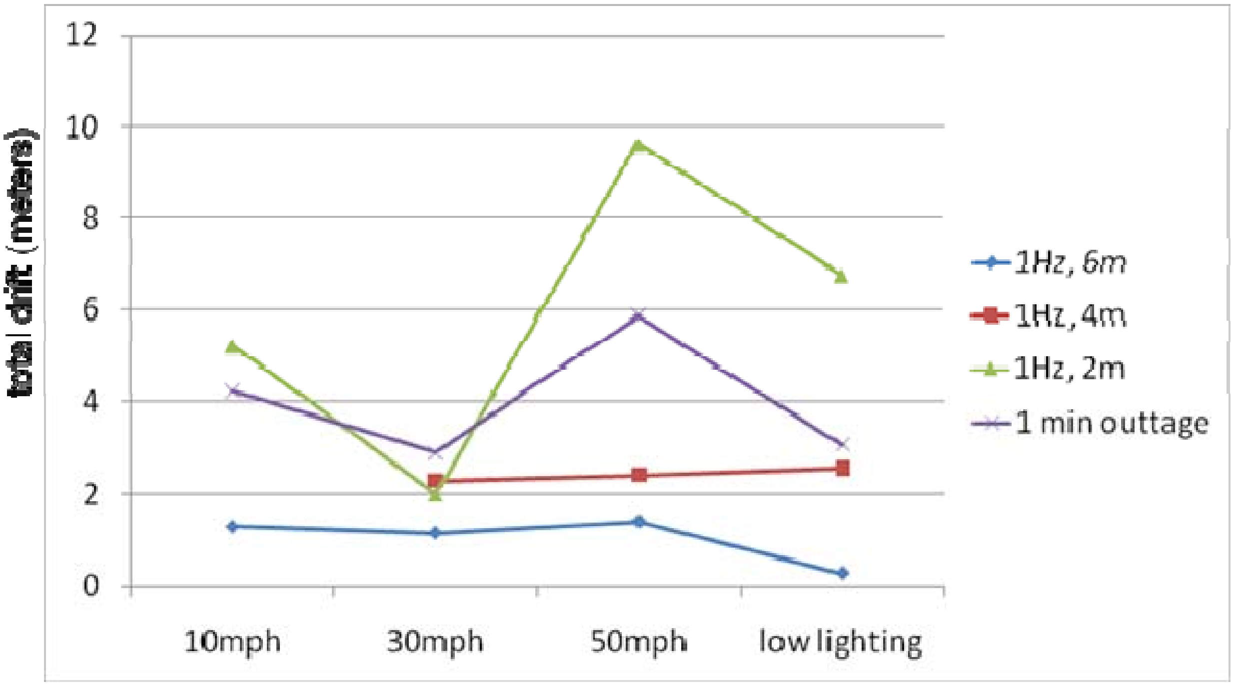
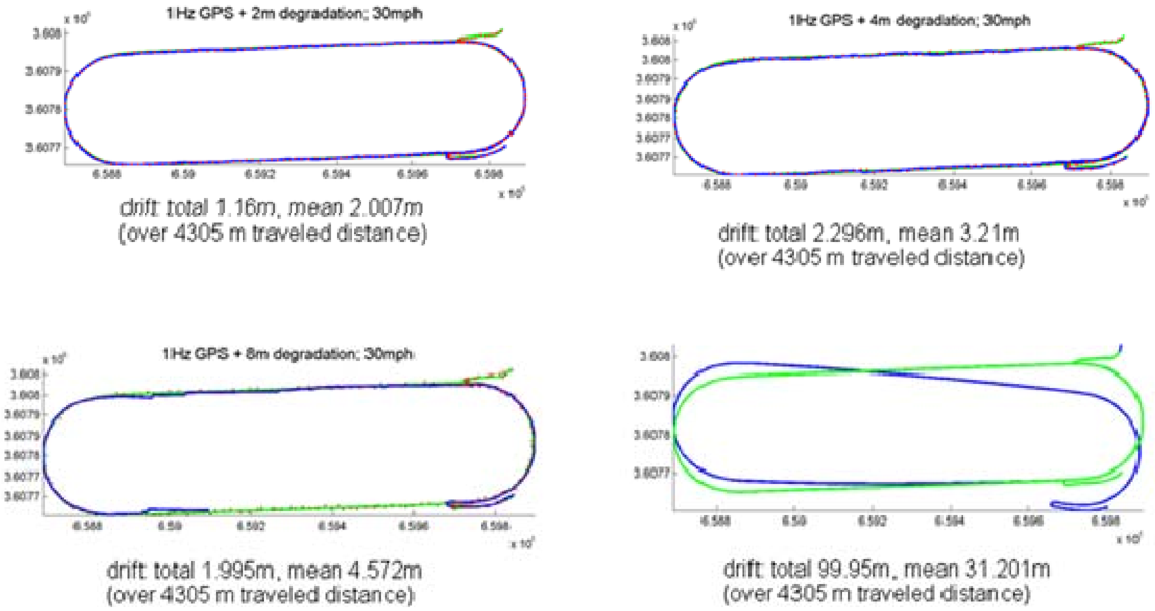


Figure 3: Comparison of drift over multiple data sequences with different GPS noise levels

Four plots are shown below which show a bird's eye view of the test track when visodo has degraded GPS at 30mph. The top left plot shows little drift for low noise. The top right plot shows similar results for the 4m degradation. More drift can be seen in the 8m degradation in the lower left plot, and finally significant drift is seen in the lower right plot for no GPS.



drift total 1.16m, mean 2.007m
(over 4305 m traveled distance)

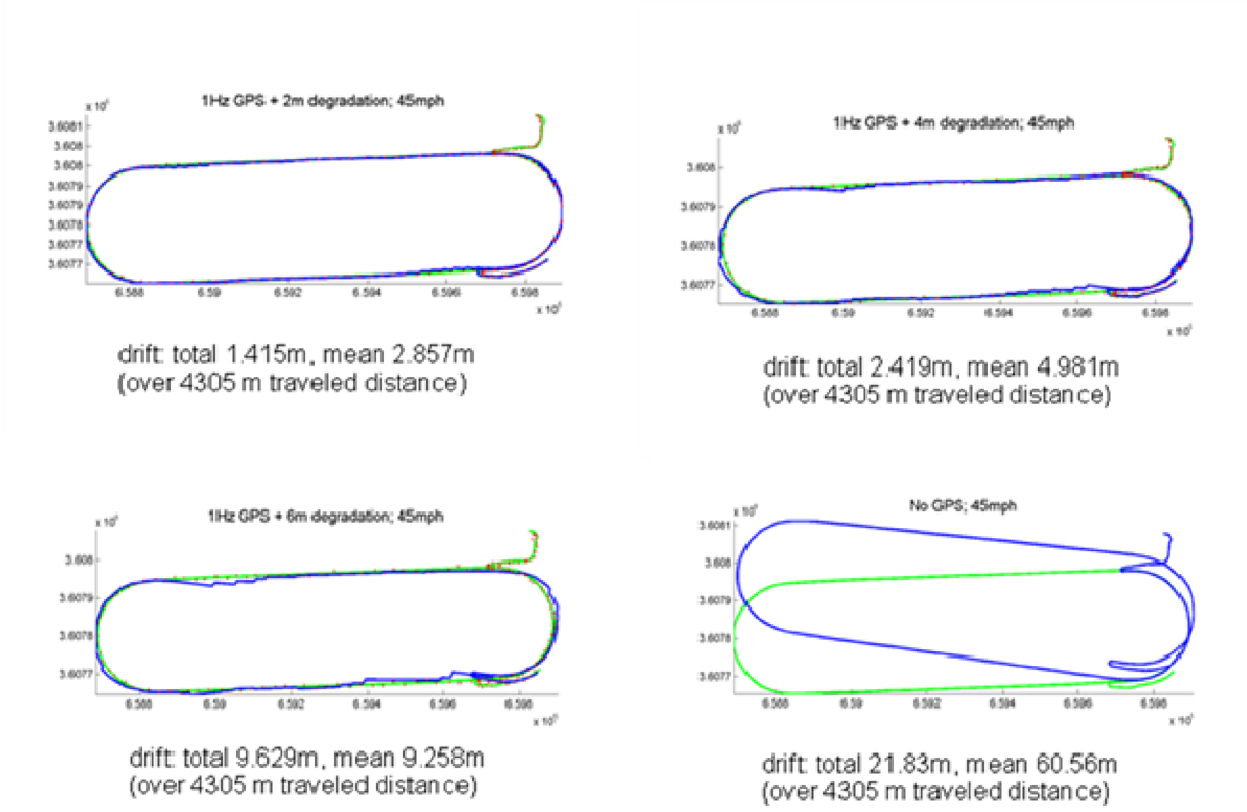
drift total 2.296m, mean 3.21m
(over 4305 m traveled distance)

drift total 1.995m, mean 4.572m
(over 4305 m traveled distance)

drift total 99.95m, mean 31.201m
(over 4305 m traveled distance)

Figure 4: Results of visodo plus degraded GPS at 30mph.

Four plots are shown below which show a bird's eye view of the test track when visodo has degraded GPS at 50mph. The top left plot shows little drift for low noise. The top right plot shows similar results for the 4m degradation. More drift can be seen in the 6m degradation in the lower left plot, and finally significant drift is seen in the lower right plot for no GPS.



1Hz GPS + 2m degradation; 45mph

drift: total 1.415m, mean 2.857m
(over 4305 m traveled distance)

1Hz GPS + 4m degradation; 45mph

drift: total 2.419m, mean 4.981m
(over 4305 m traveled distance)

1Hz GPS + 6m degradation; 45mph

drift: total 9.629m, mean 9.258m
(over 4305 m traveled distance)

No GPS; 45mph

drift: total 21.83m, mean 60.56m
(over 4305 m traveled distance)

Figure 5: Results of visodo plus degraded GPS at 50mph.

2.2 Penn State Progress

Following up from previous quarterly reports, as part of Task (2), Penn State has successfully conducted additional field tests to analyze the efficacy of the real-time implementation of the terrain-based localization algorithm at Penn State. The test results revealed that accurate tire radius estimates will be needed to ensure that the vehicle tracking is performed adequately using odometry measurements in the time period between algorithm measurement update steps using terrain data. This requirement has been conveyed to our colleagues at Auburn. Additionally, work is underway on Task (3) and terrain database management strategies, such as creating an ad-hoc on-board server, are being studied. The details of the progress since the previous quarterly report and current and upcoming work are included in the following sections.

2.2.1 Real Time Implementation

Task (2) entails the development of a real-time implementation of the localization algorithm. Following up from initial field tests, additional functionalities such as on-the-fly initialization of the algorithm using GPS coordinates and options for Integrated Position System (IPS)-based activation of the algorithm were included in the Simulink model. Further, the Simulink model was modified so as to return the current position estimate in ECEF coordinates to the Integrated Positioning System (IPS) layer. Field tests were performed in two scenarios: First, with no GPS data available and second, when GPS data was only intermittently available. Figures 6 and 7 show the vehicle position estimate, in terms of distance traveled along the road, and tracking error when no GPS is available, respectively. Figures 9 and 8 show the vehicle position estimate and tracking error when GPS is intermittently available, respectively. It is observed that the algorithm performs better when GPS is intermittently available as compared to when GPS is unavailable. Modifications to the algorithm parameters are currently being performed to obtain optimal performance.

Four plots are shown below. The top left plot shows the true position and estimated position over time based on distance traveled with no GPS. The top right plot shows the vehicle tracking error with no GPS, and the error hovers around the 10m mark with drops to 0m and peaks at 20m. The lower left plot shows the true position and estimated position once more but with intermittent GPS. The lower right plot shows the vehicle tracking error, where the error is reduced to 0 during the conditions where GPS is active.

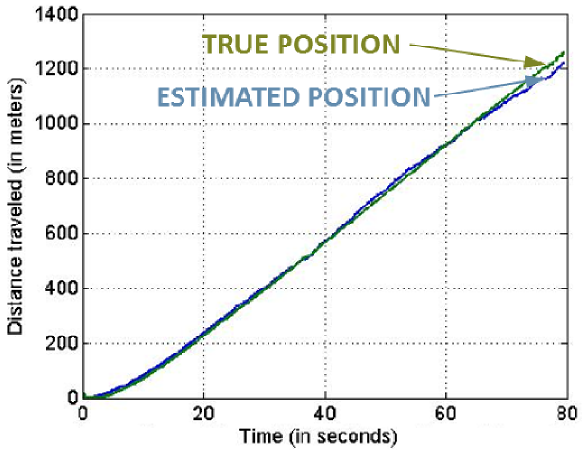


Figure 6: Vehicle tracking – Distance traveled – No GPS

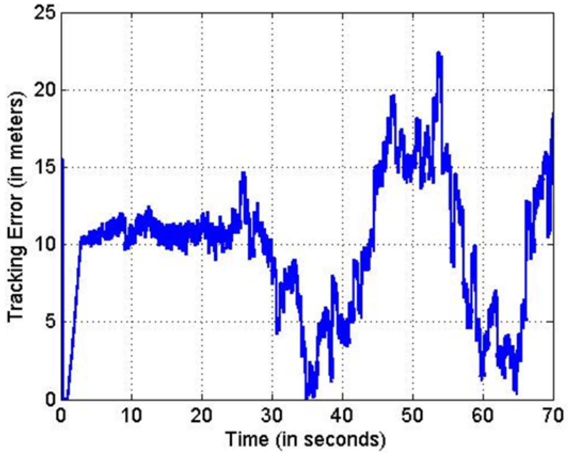


Figure 7: Vehicle tracking error – No GPS

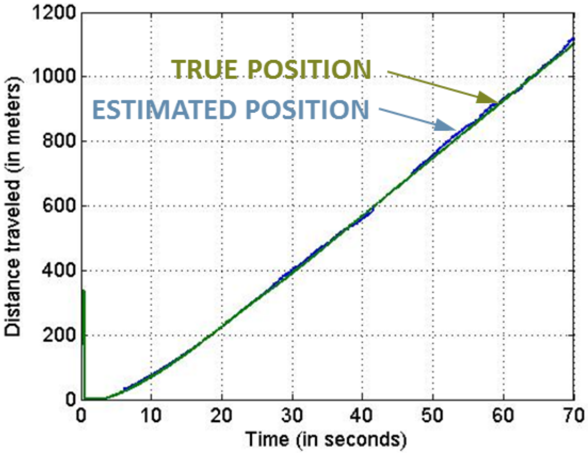


Figure 9: Vehicle tracking – Distance traveled – Intermittent GPS

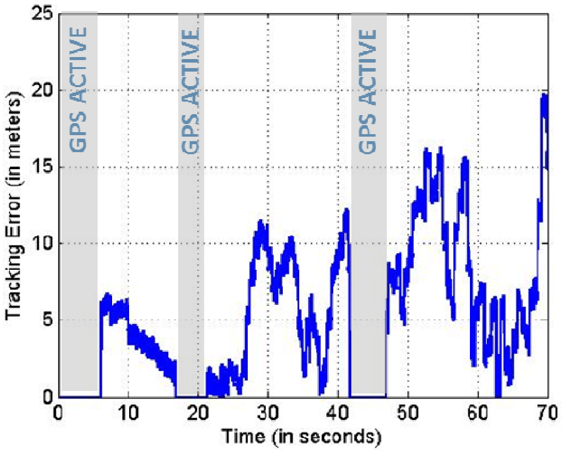


Figure 8: Vehicle tracking error – Intermittent GPS

2.3 Kapsch TrafficCom Inc. Progress

Kapsch implemented a modification to the 5.9 DSRC radio driver which allows to measure the turn-around time for a packet exchange between and RSE and OBU. The results indicate that the turn-around time is correlated to distances measured between vehicles.

The figure below shows two vehicles facing each other. The left vehicle is labeled as roaming, while the right vehicle is labeled as stationary.

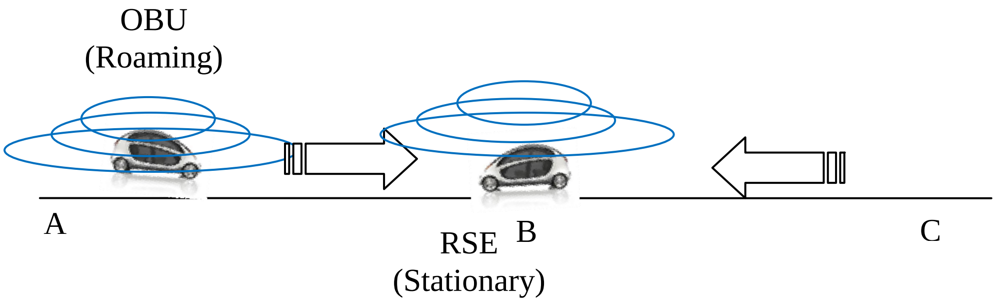


Figure 10: Field testing of the DSRC ranging

Kapsch conducted field testing of the DSRC ranging. The tests were conducted in order to verify functionality of the radio to detect and measure variations in distances between communicating radios.

2.3.1 Testing

A vehicle with an RSE MCNU R1500 was position in the middle of a street. The second vehicle had an MCU on-board unit (OBU). The new ranging software was installed on the MCU.

The second vehicle was traveling between two points A and B selected at the opposite ends of the street.

Ranging logs were recorded on the MCU OBU.

The range between vehicles was determined using laser range meter.

2.3.2 Results

Results for two tests are shown below.

In the first experiment, vehicles were initially positioned 105.3 meters apart. In the closes point, vehicles were separated by about 12 meters.

The chart shows measurements of times for packet roundtrip exchange between the OBU and RSE. The chart shows that the time changed in proportion to the distance between vehicles.

The figure below shows the measurements of times for packet exchange. At A, horizontal lines extend out around the 1573-1572 range. Further horizontal lines cascade down in a stairway-like pattern until B, where the horizontal lines are once more at 1562-1564 range. The lines build up once more in a stair-like pattern until a spike, which is followed by location C.

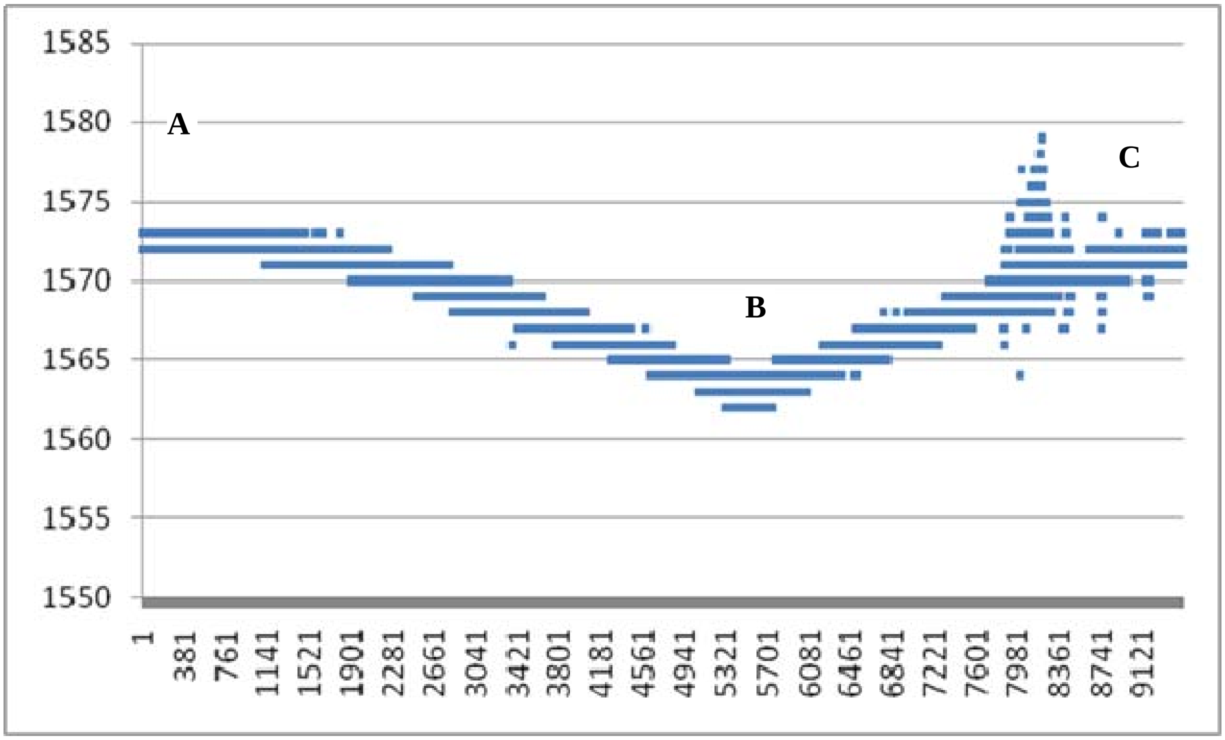


Figure 11: Measurements of times for packet roundtrip exchange

The second chart shows the second test. In this test, the initial position between the vehicles was 258 meters. The roaming vehicle travelled toward the stationary vehicle. The roaming vehicle stopped around point B and then proceeded to the point C. At point C the vehicle turned around and returned to the point B.

The figure below shows another test for measurements of times for packet roundtrip exchange. Once more there are locations labeled A, B, and C. However, in this plot the horizontal lines begin at A, drop down to B, increase to C, then drop down back to B.

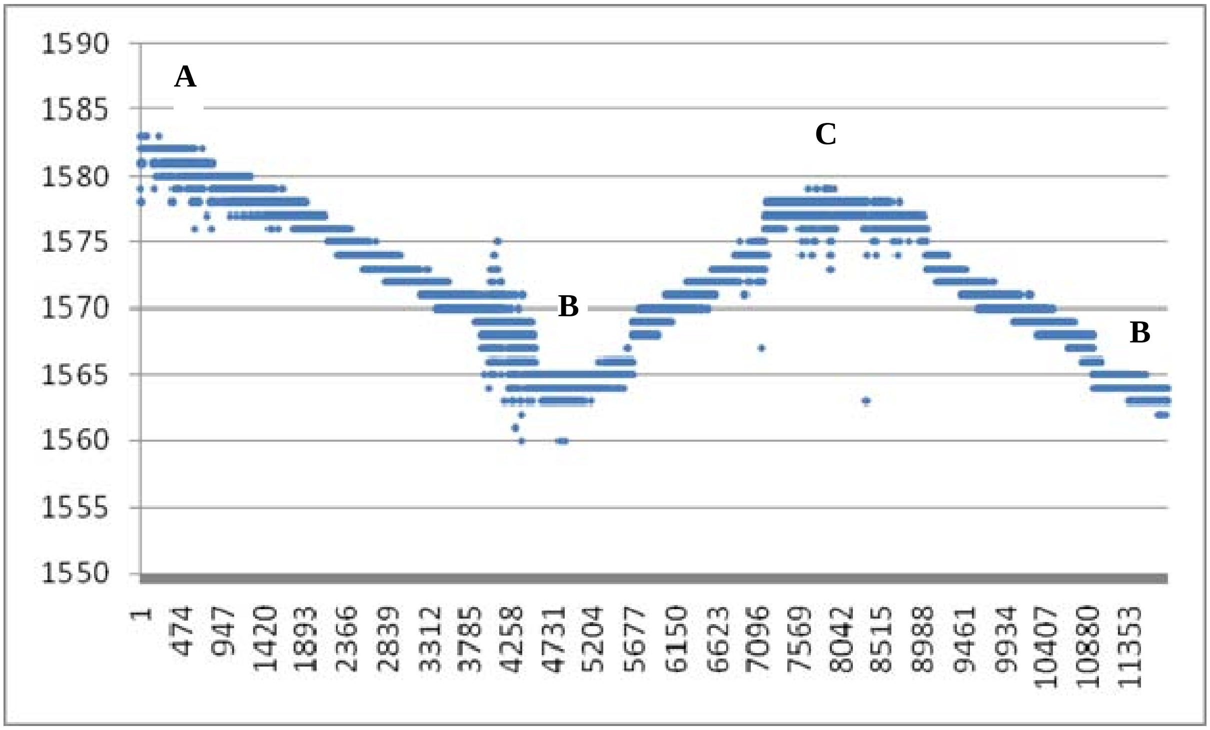


Figure 12: Second test of measurements of times for packet roundtrip exchange

2.4 Auburn University Progress

2.4.1 Project Update in D.C.

Team members from Auburn visited Turner-Fairbank Highway Research Center on March 29th to give an update on the current progress of the project.

2.4.2 Automotive Panel Webinar

Progress on the project was presented to the Automotive Panel through a webinar on April 29th by each team.

2.4.3 Interfacing

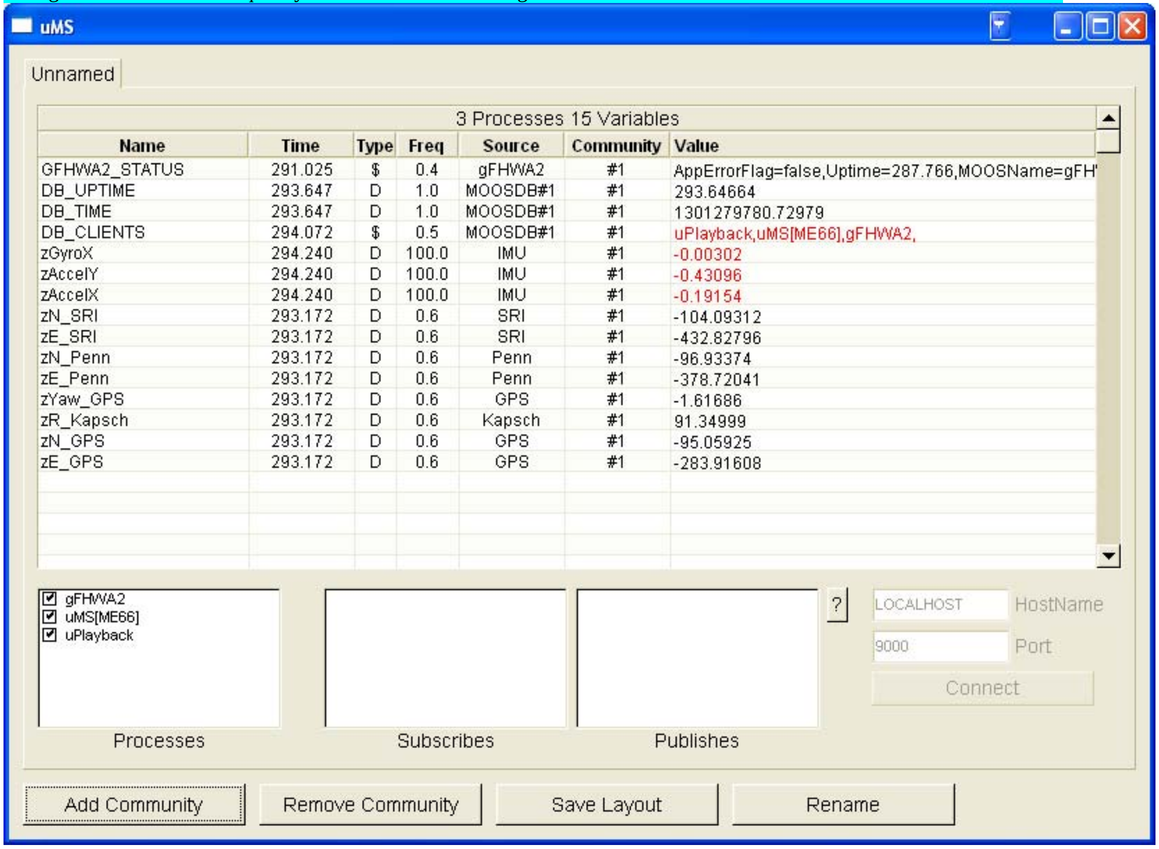
Interfacing the data from each subsystem is currently in progress. The interface with SRI Sarnoff is complete, and data is capable of being sent between Penn State's system and Auburn. The message structure still needs to be complete between Auburn and Penn State. Data can be received through the Kapsch system; however, the interface into the MOOS database still needs to be complete.

2.4.4 Integrated Positioning System

Work on the Integrated Positioning System(IPS) is ongoing. The IPS will use a form of the nonlinear Kalman filter -Unscented Kalman filter (UKF) or Extended Kalman filter (EKF)- for estimation. Current work has been leaning towards the EKF due to its ability to handle multiple measurements with varying update rates. Also, much of the literature has shown that in the case of a GPS/INS filter, the UKF fails to provide a significant improvement over the EKF to justify its increased computational cost.

Development of the system within MOOS has been completed. In addition, the full system has been simulated with the EKF to ensure the computational cost is sufficient for real time operation. Figure 13 shows a screenshot of the MOOS database at a moment of time during the simulated data run.

The figure below shows a window of the MOOS database. The top portion shows variables which are updated as data is streamed in through simulation. The frequency at which the data is being found as well as the value of the most recent data can be seen.



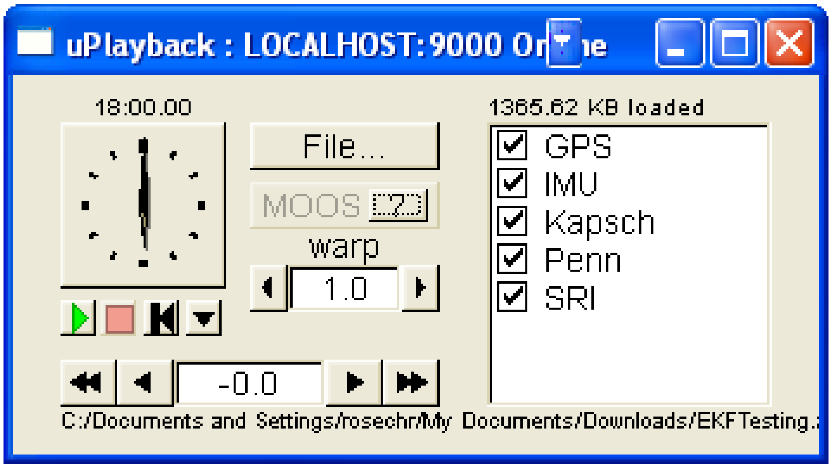
3 Processes 15 Variables

Name	Time	Type	Freq	Source	Community	Value
GFHWA2_STATUS	291.025	$	0.4	gFHWA2	#1	AppErrorFlag=false,Uptime=287.766,MOOSName=gFH'
DB_UPTIME	293.647	D	1.0	MOOSDB#1	#1	293.64664
DB_TIME	293.647	D	1.0	MOOSDB#1	#1	1301279780.72979
DB_CLIENTS	294.072	$	0.5	MOOSDB#1	#1	uPlayback,uMS[ME66],gFHWA2,
zGyroX	294.240	D	100.0	IMU	#1	-0.00302
zAccelY	294.240	D	100.0	IMU	#1	-0.43096
zAccelX	294.240	D	100.0	IMU	#1	-0.19154
zN_SRI	293.172	D	0.6	SRI	#1	-104.09312
zE_SRI	293.172	D	0.6	SRI	#1	-432.82796
zN_Penn	293.172	D	0.6	Penn	#1	-96.93374
zE_Penn	293.172	D	0.6	Penn	#1	-378.72041
zYaw_GPS	293.172	D	0.6	GPS	#1	-1.61686
zR_Kapsch	293.172	D	0.6	Kapsch	#1	91.34999
zN_GPS	293.172	D	0.6	GPS	#1	-95.05925
zE_GPS	293.172	D	0.6	GPS	#1	-283.91608

Figure 13: MOOS Database Representation at a moment of time

Figure 14 shows the MOOS playback GUI, which allows for quick and easy simulation of various sensor configurations. MOOS records data in a log file as data is streamed in from various sensors. MOOS playback can take the data from this log file and simulate data streaming into the database in real time. Using this simulation, algorithms can be easily tested for real time capability using actual data obtained from the subsystems. The playback functionality also allows for a "slow motion" time step, in which data is updated to the database at a slower rate than real time. For situations where extensive logging from the IPS system is desired which is incapable of running in real time, the slower timestep system allows for offline data processing using the same algorithms as the real time processing.

The figure below shows the MOOS playback GUI. Various buttons are shown for connecting to the MOOS database, varying time progress, and selection of sensors for processing.



☑ GPS
☑ IMU
☑ Kapsch
☑ Penn
☑ SRI

C:/Documents and Settings/rosechr/My Documents/Downloads/EKFTesting.

Figure 14: MOOS playback simulation

3. Future Work

3.1 SRI Future Work

3.1.1 Continued data analysis

- Adding Landmark matching to pose pipeline
- combining GPS and Landmarks in filter

3.1.2 Software development

- Output pose in NED instead of UTM coordinate frame
- Improvement of GPS alignment algorithms.

3.2 Penn State Future Work

3.2.1 Road Network Implementation

As mentioned in the previous quarterly report, a road network implementation for a vehicle will require creating multiple estimators to maintain tracking. Since it was found that a single computer with the real-time implementation algorithm running can handle only about 5 km of terrain data, Penn State is currently attempting to set up an ad-hoc on-board server to handle requests for terrain data. Once these terrain database management issues are resolved, multiple estimators will be set up to handle multiple position estimates as will be required in scenarios such as crossing an intersection. This will be followed by simulation tests to analyze the effectiveness of the road-network implementation.

3.2.2 Future Work

Penn State's plans for the near future involve handing over the finished real-time implementation of Penn State's algorithm to our colleagues at Auburn University. Additionally, as mentioned earlier, work is already underway to incorporate the possibility of road intersections and road networks into the algorithm's functionality. By the next quarterly report, it is expected that the ad-hoc on-board server for terrain database management will be set up, and the algorithm will be tested for a simulated intersection, with some progress on testing it in real environments.

3.3 Kapsch Future Work

Kapsch will continue to test and refine the DSRC ranging system.

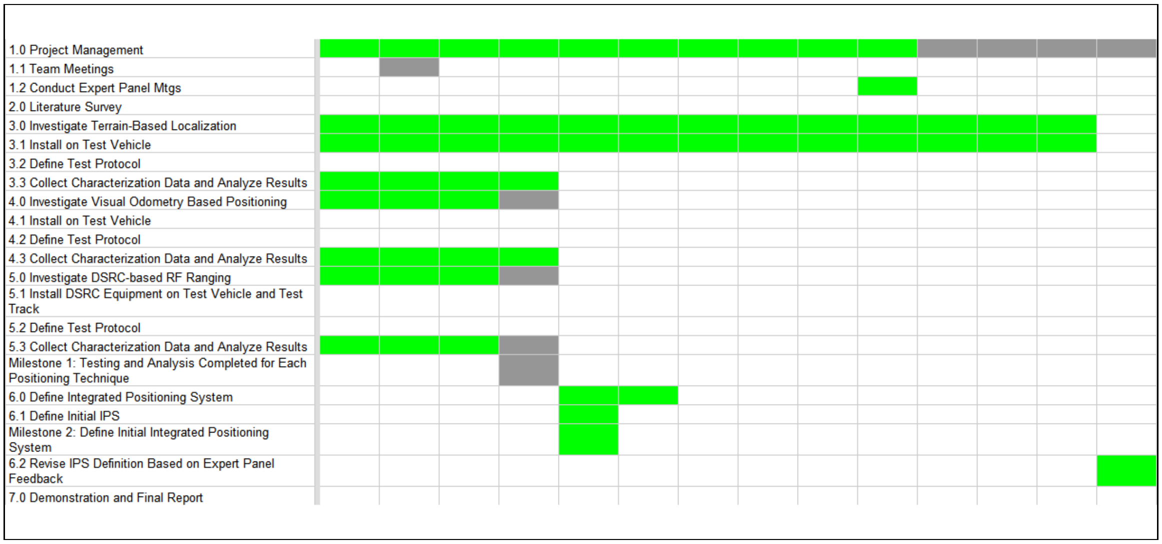
3.4 Auburn University Future Work

Auburn will continue to work with partners to interface and mount the sensors on the test vehicle. In addition, Auburn will provide data needed for any of the subsystems.

Since data from each sensor is unavailable for processing in the IPS, the data used for the simulation was based on the performance given in the previous quarterly reports. As such, much of the noise statistics will need to be refined as the actual systems become available. In addition, the current IPS system may be revised as needed – for instance, if the EKF fails to provide an adequate solution due to nonlinearities, the UKF may be chosen. Also, the decision to use a tightly coupled or a loosely coupled EKF is still unknown. Due to the inclusion of the DSRC ranges, the tightly coupled system is expected.

Gantt Chart

As indicated in the Schedule for Year 2, the Gantt chart has been refined to reflect realistic timetables, most notably the demonstration of the system in winter.



1.0 Project Management	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨
1.1 Team Meetings		▨												
1.2 Conduct Expert Panel Mtgs										🟩				
2.0 Literature Survey														
3.0 Investigate Terrain-Based Localization	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
3.1 Install on Test Vehicle	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
3.2 Define Test Protocol														
3.3 Collect Characterization Data and Analyze Results	🟩	🟩	🟩	🟩										
4.0 Investigate Visual Odometry Based Positioning	🟩	🟩	🟩	▨										
4.1 Install on Test Vehicle														
4.2 Define Test Protocol														
4.3 Collect Characterization Data and Analyze Results	🟩	🟩	🟩	🟩										
5.0 Investigate DSRC-based RF Ranging	🟩	🟩	🟩	▨										
5.1 Install DSRC Equipment on Test Vehicle and Test Track														
5.2 Define Test Protocol														
5.3 Collect Characterization Data and Analyze Results	🟩	🟩	🟩	▨										
Milestone 1: Testing and Analysis Completed for Each Positioning Technique				▨										
6.0 Define Integrated Positioning System					🟩	🟩								
6.1 Define Initial IPS					🟩									
Milestone 2: Define Initial Integrated Positioning System					🟩									
6.2 Revise IPS Definition Based on Expert Panel Feedback														🟩
7.0 Demonstration and Final Report														