Performance Evaluation of Sensor Combinations on Mobile Robots for Automated Platoon Control

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BIOGRAPHIES

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Dr. Elizabeth Cannon is Professor and Head of Geomatics Engineering at the University of Calgary. She has worked extensively in various GPS-related areas and on the integration of GPS and inertial navigation systems for precise aircraft positioning. Dr. Cannon is a Past President of the ION and the recipient of the 2001 Kepler Award.

ABSTRACT

Autonomous absolute navigation of vehicles is still a distant concept. However, autonomous relative navigation of vehicles is a much more feasible task. The concept of Collaborative Driving Systems (CDS) involves linking several vehicles together using in-vehicle positioning and control systems as well as inter-vehicle communication. Joining vehicles in a platoon will have many benefits, including increasing road capacity, improving safety, and reducing driver fatigue and stress. In the development of such a system, there are three levels of implementation. Firstly, software simulation may be used. Next, real sensors on low cost test beds such as robots can be used. Finally, real sensors on real vehicles can be used. This paper focuses on the second level. Various sensors are mounted on mobile robots. The lead robot is manually controlled, while another robot is left to autonomously follow. The sensors on the robots include GPS, a digital camera, and a laser scanner. The primary sensor is GPS, as this is likely to give the highest accuracy in carrier phase fixed-ambiguity mode. The other sensors are used primarily to augment GPS when GPS observations are unavailable, and to improve the ambiguity resolution process. All tests described here are performed post-mission, simulating real time processing. Results show that GPS gives very high accuracy relative positions, resulting in high accuracy distance measurements. However, local angle can not be consistently or accurately provided by a single antenna GPS system. The digital camera provides continuous distance and angle measurements, though the distance measurements are not as accurate as the GPS results. The laser scanner also provides distance and angle measurements that were high accuracy, except for the many occasions in which an incorrect target was identified. GPS combined with either auxiliary sensor resulted in superior performance, by reducing time to fixing ambiguities, and improving accuracy during GPS data outage and float ambiguity positioning.

INTRODUCTION

Collaborative driving involves several vehicles following the same route, while linked through knowledge of relative positions and velocities, and inter-vehicle communication. In the future, following vehicles will be automatically controlled based on the lead vehicle. This system is known as a Collaborative Driving System (CDS).

There are several advantages to a CDS. Firstly, performance of existing road infrastructure will be improved by allowing vehicles to travel more closely together without decreasing safety. This is achieved by eliminating the human decision-making perception and reaction process (US DOT, 2002). With near instantaneous automated perception and response, vehicles will not have traveled as far before corrective action is taken. Increasing the capacity of existing roadways is a major benefit.

Secondly, safety is improved. As mentioned, by removing the human component in the perception-response cycle, and adding direct communication with other vehicles, safety can be improved.

Thirdly, a CDS will result in a reduction in driver fatigue and stress. Many collisions occur because the driver is tired and not paying close attention to the surroundings, or not immediately capable of making the decisions and actions to correct a situation. A CDS will reduce this responsibility. Once a system is developed that is proven to be safe, the driver can relax more. Also, road rage should be greatly reduced, partly because the drivers are more relaxed, and partly because they will not be angry at other drivers' actions (Smart et al., 2004).

There are three major levels of testing that can be performed in the creation of a CDS. Firstly, software simulation can be performed. In this situation, sensors and roadway conditions would be simulated, and vehicle reactions can also be simulated. This is very useful to begin designing decision-making algorithms, especially for maneuvers such as merging into a platoon and leaving a platoon (Hallé et al., 2003). One of the main problems is the difficulty with which sensor data can accurately be simulated.

A second stage of testing involves using real sensors on low cost test beds, such as mobile robots. This way, the output of real sensors can be used, along with all real issues that those sensors encounter. Meanwhile, if errors in action take place, such as collisions, the results are not catastrophic. The main disadvantage with this level of testing is that it does not always represent the dynamics of real vehicles.

The final stage of testing is in essence the final product. Real vehicles with real sensors would be driven on roads, with navigation of following vehicles being completely autonomous. This is necessary as the final proving ground for the system before it can be released into public use. However, it is also a very expensive step, and can not be afforded until confidence has been built in the system through the first two steps.

This paper involves the second stage of testing. Mobile robots at the University of Sherbrooke were used with several sensors, to simulate autonomous following of a lead vehicle using post-mission analysis. Michaud et al. (2002) had the mobile robots navigate autonomously with respect to each other, using a digital camera. This research aims to add a laser scanner and GPS to the robots, to improve positioning reliability and accuracy. Each sensor has advantages and disadvantages, and therefore by combining the sensors, the disadvantages may be mitigated.

SENSORS

Primarily, three sensors are investigated: a digital camera, a laser scanner, and GPS. These will be examined individually and in combinations.

The digital camera has already been used on these robots at the University of Sherbrooke for relative navigation. The camera sees a colored cardboard tube placed on a lead robot, and based on the size and location of the colored tube in the image, distance and angle to the leader can be established. This sensor requires line-of-sight from the follower robot to the leader robot. Occasionally, the algorithm is confused by the presence of other similarly colored objects in the field of vision. The accuracy of the camera is moderate, as will be shown in the results. Figure 1 shows an image from the camera.

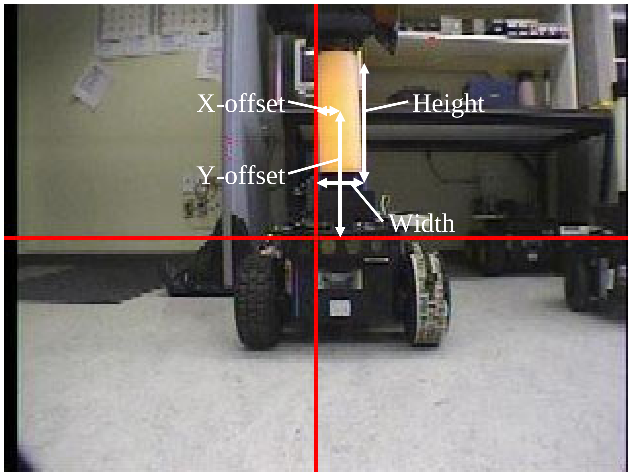

Figure 1: Image from Camera

The laser scanner takes distance measurements at many angular increments across the field of view. The accuracy of these distance and angle measurements should be quite high. Line-of-sight is required from the follower robot to the lead robot. The main problem lies in identifying which measurement is to the lead robot. As shown in Figure 2, the lead robot did have a distinguished shape that could often be identified, however other obstacles could have a similar shape in some cases.

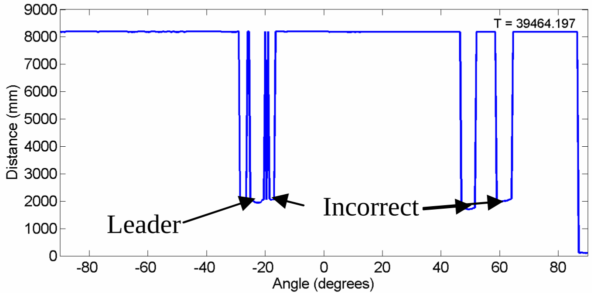

Figure 2: Laser Profile

GPS must be used in differential carrier phase mode to give accuracies that would be required for inter-vehicle positioning for navigation purposes. Differencing will take place between the follower robot and the lead robot, to avoid the need for a fixed GPS reference station. While float ambiguities may give reasonable accuracy, in general fixed ambiguities will be required. Resolution of ambiguities often takes some time, and has to re-occur if any signal blockages take place. GPS requires line-of sight to satellites from both the follower and the lead robot. GPS should give very high accuracy distance measurements, as well as azimuth measurements between the robots. However, the local angle between the robots is of primary interest. In order to obtain this, heading of the follower robot is required. Since only a single antenna system was available, this has been obtained using Doppler measurements in single point mode. Therefore, no measurements will be available when the robot is stationary, and only low accuracy heading measurements are available when the robot is moving slowly.

The instrument setup for the follower vehicle is shown in Figure 4 and details of the equipment are shown in Table 1. The lead robot was similarly equipped, though without the camera and laser. A GPS reference station was set up nearby using a NovAtel DL-4 receiver and 702 antenna. This was done to facilitate traditional processing of the GPS data for quality checking. Dual frequency data was collected by all GPS receivers, though only single frequency data was used in regular processing. Both frequencies were used in creation of truth data.

GPS measurements included code, carrier phase, and Doppler measurements. Camera measurements included pan and tilt of the camera, as well as height, width, and x and y offsets of the colored cylinder, as shown in Figure 1. Laser measurements included the distance measured at each angular increment of 0.5 degrees between -90 and +90 degrees. All measurements were logged to the robots' onboard computers.

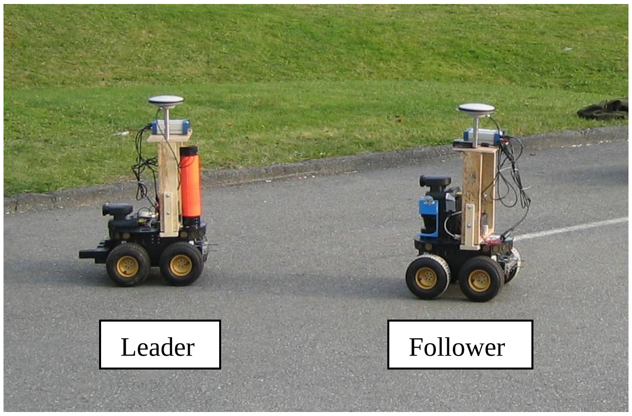

Figure 3: Image of Robots

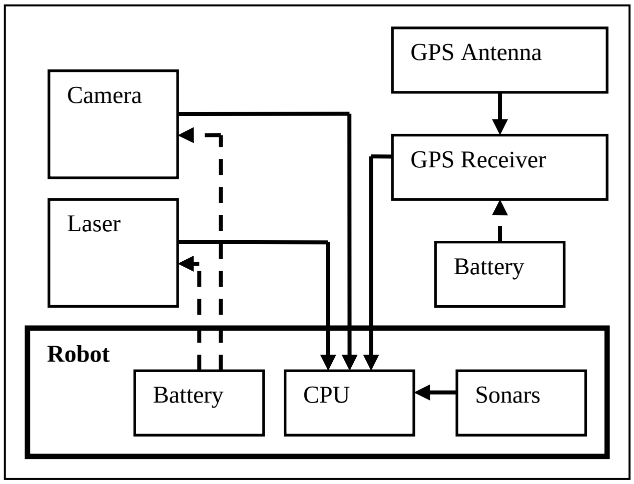

Figure 4: Instrument Setup for Follower Robot

Table 1: Details of Equipment of Follower Robot

Name of Equipment	Specification	Data Rate	Measurement Description
Mobile Robot	Pioneer 2	n/a	n/a
GPS	NovAtel DL-4 receiver, NovAtel 702 antenna	20 Hz	Pseudoranges, carrier phase, and Doppler measurements
Camera	Sony EVI-D30	>20 Hz	Size and position of colored blob in image
Laser	SICK LMS200	~5 Hz	Distance measurements at angular increments

Time tagging was performed using the CPU time at the time the sensors were polled. This rate was approximately 20 Hz. GPS data was also set to log at 20 Hz. Since it is difficult to align GPS time with the CPU time, data will be processed in accordance with the CPU clock-based measurements, simply using the most recent data available. Since the robots have relatively low dynamics, less than 1 m/s, the maximum timing error of 0.05 s would result in a maximum position error of 5 cm. It would be very rare for this maximum error to occur.

The sensors on the robots are clearly not collocated. The camera and laser are located in front of the GPS antenna on the follower robot, while the target seen by the camera and laser is behind the GPS antenna on the lead robot. As a result, adjustments to observations had to be made. It is difficult to locate the focus point for the laser and camera, therefore a constant offset empirically derived from the data was used. A constant offset is not the best choice, as the actual difference in distance measured by GPS versus the other sensors depends on the orientation of both robots. However, accurate headings of both robots would be required to make this more accurate correction. In general, the robots stay oriented in-line with each other.

FIELD TEST DESCRIPTION

Field testing took place on October 31, 2003, in a parking lot on the University of Sherbrooke campus. Benign conditions were present, primarily open sky conditions, and a flat surface to drive upon. The lead robot was remote controlled, while the follower robot smoothly followed it around the test track. Figure 5 shows the test area, and the path of the robots. Figure 6 shows a plot of the North and East position of the robot's trajectory.

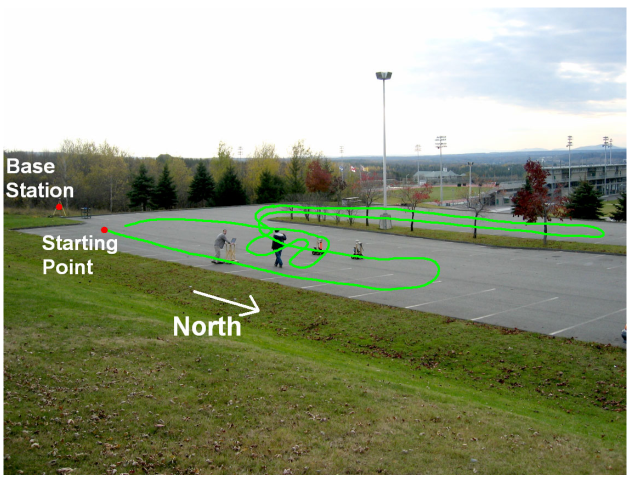

Figure 5: Path of Robots in Parking Lot

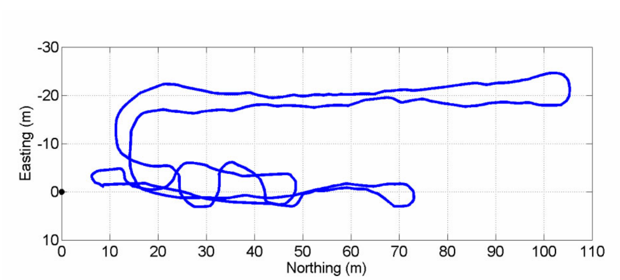

Figure 6: Path of Robots in Parking Lot

An average of eight satellites was tracked during the entire test, which lasted a total of 25 minutes. Distances between robots stayed in the 1 to 3 meter range.

A static period of about five minutes took place at the beginning and end of the test for testing purposes. In real vehicle navigation, static periods may not be available. Data may be altered post-mission to simulate less or no static time, data outages, and other phenomenon that vehicles might encounter in real conditions.

PROCESSING METHODOLOGY

A single program was created to process all data, using classes from the Navigation Development Library (NDL), Geomatics Engineering, University of Calgary (UTI Inc., 2002). At each epoch of processing, the first step is to read a record of camera data, a record of laser data, and a stream of GPS data into the program. The camera data and laser data are processed to obtain distance and angle measurements. The GPS data stream is decoded to obtain the latest epoch of GPS data available. Only single frequency GPS data is used. Preprocessing, such as tropospheric corrections and elevation mask application, are applied to the GPS data. Two Kalman filters are used, one to process single point data for the follower robot, and one to process differential data (including camera and laser) for the vector between the two robots.

The data from the follower robot is processed in single point mode, to compute position and velocity of that robot. Of primary interest is the velocity, which is then converted into a heading measurement, if the velocity is deemed sufficiently high. A threshold of 0.1 m/s was chosen based on examination of the velocity output. This heading measurement will be used later by the differential processor.

The differential processor first uses the camera and laser measurements, and then uses the differential GPS measurements, as shown in Figure 7. Code is first used, and then phase measurements, after which ambiguity resolution is attempted using the LAMBDA method (de Jonge and Tiberius, 1996). The states of the differential processor include distance, azimuth, pitch, and angle. Camera and laser measurements observe the distance and angle, while differential GPS measurements observe the distance, azimuth, and pitch. Pitch may be constrained to zero, since vehicles generally drive on a fairly level surface, but this was not performed in this test. Azimuth and angle seem somewhat redundant, being related simply by heading. This set up was used because if no heading is available, the filter for azimuth should not reset. Therefore, after the differential GPS has been processed, if a heading observation from the single point processor is available, it is combined with the azimuth output as a new observation to estimate the angle.

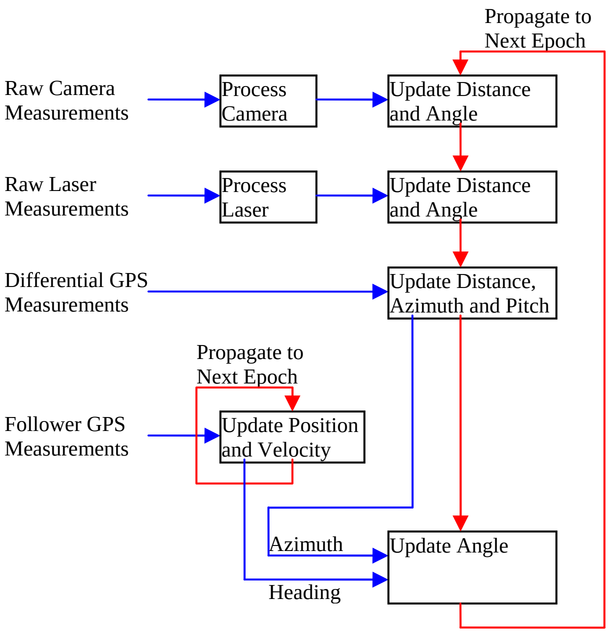

Figure 7: Flow Chart of Processing

For the processing of multiple sensors, careful choosing of noise values is important. The noise values must reflect the relative accuracy of the various sensors. For this experiment, noise values were chosen based on examination of sensor measurements, as well as past experience with sensors such as GPS. Standard deviation s are as shown in Table 2. Process noise was 10 cm/s for distance, and 0.1 degree/s for angle, azimuth, and pitch.

Table 2: Parameters Estimated and Noise Values for Sensors

Sensor	Parameters Estimated	Std. Dev.
Camera	Distance, Angle	25 cm distance 1 degree angle
Laser	Distance, Angle	5 cm distance 1 degree angle
Differential GPS	Distance, Azimuth, Pitch	50 cm code 0.02 cycle phase
Single Point GPS	Position, Velocity	50 cm code 0.1 Hz Doppler

EVALUATION METHODS

The primary metric for evaluating the performance of the sensors alone and in combination is to examine accuracy. Also, since GPS is likely to give the highest accuracy for distance, time to resolution of GPS ambiguities is also evaluated.

Accuracy is difficult to assess without a truth data set. An approximate truth data set for distance was created by using differential processing of dual frequency GPS data using the static reference station to give the positions of each robot, and then differencing these positions to compute distance between the robots. While this output will not necessarily be truth, it should be of very high accuracy. Truth creation as opposed to the regular processing is shown in Figure 8. In order to compare the test cases to the truth data set, careful alignment of times must be performed. The truth data is tagged using GPS time, while the test cases are tagged using CPU time. This will create a slight additional loss of accuracy.

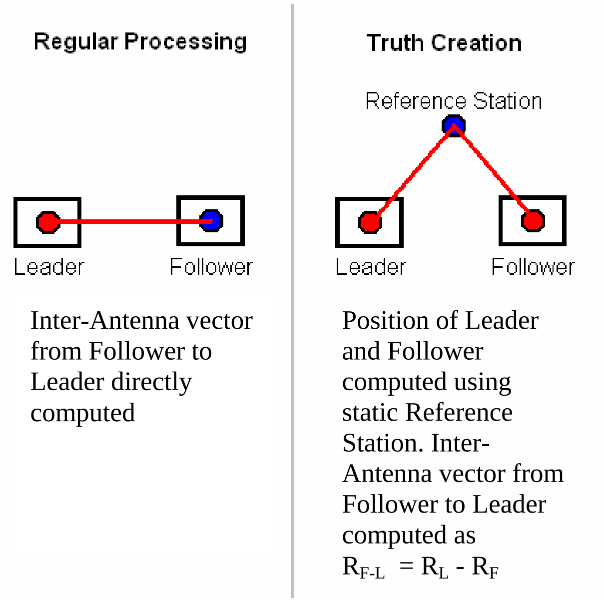

Figure 8: Creation of Truth Data

No truth data set may be created for the angle from the follower to the lead robot, as none of the sensors can give this with known high accuracy. Instead, angle is compared qualitatively.

RESULTS

Static Time Period

The first demonstration of results is to visually show the accuracy of the sensors' distance measurements. This is done by plotting the distance measurements over a few minute period of time during which the robots were not moving and therefore the distance should be constant. The following figures show the distance measured by GPS, the camera, and the laser. The camera and laser have had the collocation offset discussed earlier applied already to align with the GPS measurements.

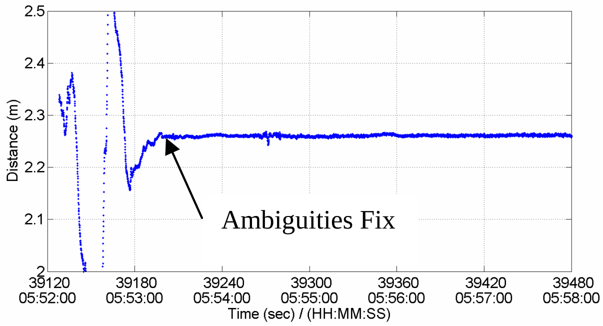

Figure 9: GPS-measured Distance During Static Period

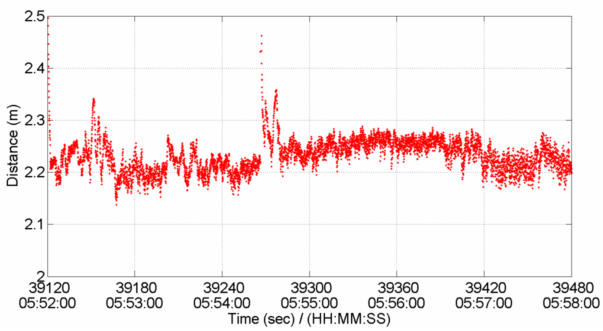

Figure 10: Camera-measured Distance During Static Period

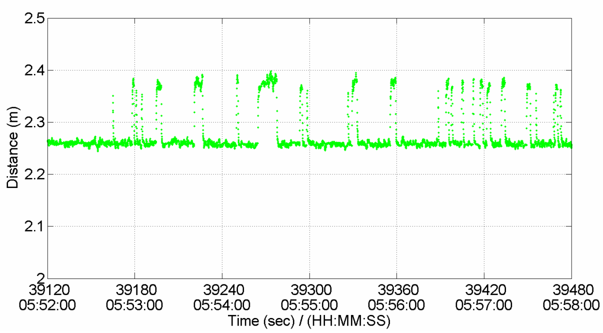

Figure 11: Laser-measured Distance During Static Period

The beginning of the GPS plot shows very poor results, as the measurement varies wildly. This is because the ambiguities have not yet had time to fix. Once the ambiguities have been fixed, the measurement stays very stable, within a centimeter.

The camera measurements show a much higher variance simply because this sensor is not as accurate. There is a scatter of values of around 10 cm.

The laser measurements generally remain within a centimeter of a mean value, but there are frequent jumps of around 12 cm. This occurs when the incorrect point is identified in the laser profile.

The following figures show the same static time period when the sensors are combined.

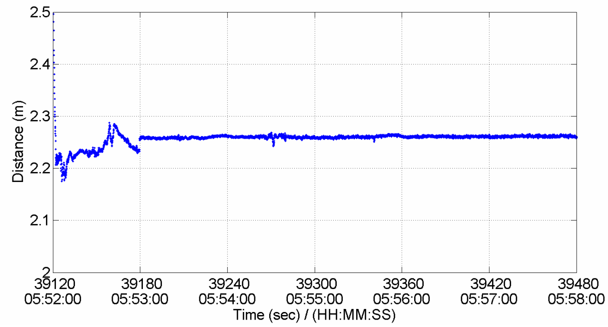

Figure 12: GPS+Camera-measured Distance During Static Period

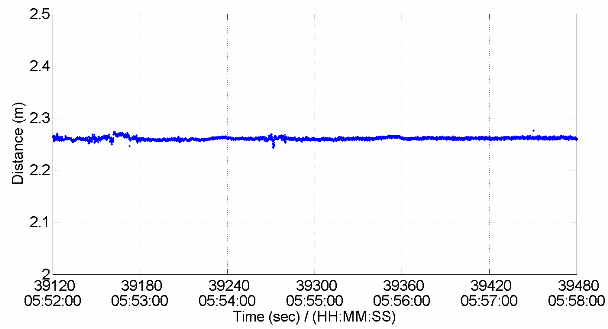

Figure 13: GPS+Laser-measured Distance During Static Period

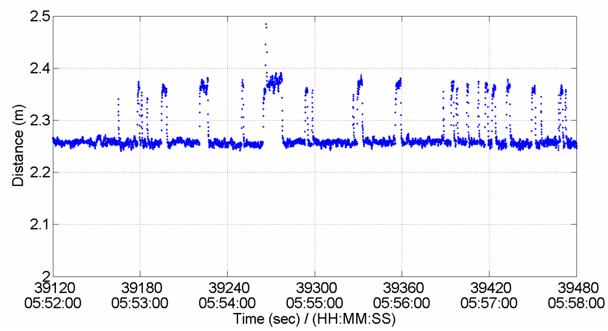

Figure 14: Camera+Laser-measured Distance During Static Period

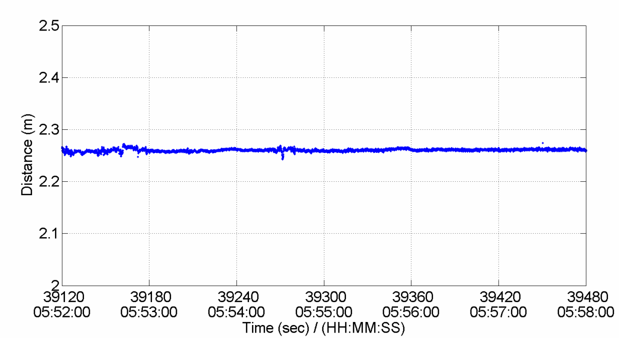

Figure 15: GPS+Camera+Laser-measured Distance Measured During Static Period

When GPS is combined with the camera, results are improved. Firstly, during the GPS float ambiguity time, the camera, with its lower standard deviation, keeps the output distance constrained close to its true value. Further, the ambiguities are then able to resolve to their integer values sooner, as will be discussed later in the results. Once the ambiguities are fixed, the highly accurate GPS dominates.

When GPS is combined with the laser, results are further improved. The data at the beginning of the plot is closer to the true value since the laser is better than the camera. After the ambiguities are fixed, the GPS solution is better than the laser, and so the outliers in the laser measurements have no effect, or are detected as blunders and removed.

When camera and laser measurements are combined, the higher accuracy laser dominates, and the output is virtually the same as the laser-only case. This is accurate except for the outliers created when the laser processing detects the wrong target. A new algorithm for blunder detection in laser measurements based on camera measurements could be developed, but has not been implemented here.

The final figure shows what happens when all three sensors are combined. The result is virtually identical to the case in which GPS and laser are combined. This is because the laser is available at almost all the same times as the camera measurement, and is much more accurate, and therefore the camera measurement is given so little weight it is not of value.

During the static period, no truth data is necessary to obtain the standard deviation of the output, since it should be constant. Table 3 shows these statistics for the distance measurements. Table 4 shows the statistics when compared to the truth data. These are taken over a three minute time period, after ambiguities are fixed.

Table 3: Statistics for Sensors' Actual Distance Values during Static Period

Sensors	Mean (m)	Std Dev (cm)	No. of Samples
GPS	2.260	0.2	3000
Camera	2.247	4.5	3000
Laser	2.278	4.3	3000
Camera + GPS	2.260	0.2	3000
Laser + GPS	2.261	0.2	3000
Camera + Laser	2.276	4.3	3000
Camera + Laser + GPS	2.261	0.2	3000
Truth	2.260	0.2	2990

Table 4: Statistics for Sensors' Distance Errors during Static Period

Sensors	Mean (cm)	Std Dev (cm)	RMS (cm)	No. of Samples
GPS	0.0	0.0	0.0	2990
Camera	-1.3	4.7	4.9	2334
Laser	1.7	4.3	4.6	2649
Camera + GPS	0.0	0.0	0.0	2990
Laser + GPS	0.0	0.0	0.0	2990
Camera + Laser	1.7	4.3	4.6	2334
Camera + Laser + GPS	0.0	0.0	0.0	2990

It is interesting to note that the truth data had a 2 mm standard deviation in actual values, even though it should have been exactly zero if it truly were truth. Also, in the "error" statistics where the output is compared to the truth, all combinations involving GPS has zero standard deviation. This indicated the errors in the GPS output directly correspond with the errors in the truth data.

The angle should also be constant during the static period. The following figures show the angle measured by the camera and laser. The GPS gives no measurement for angle during the static period, because no heading information is available.

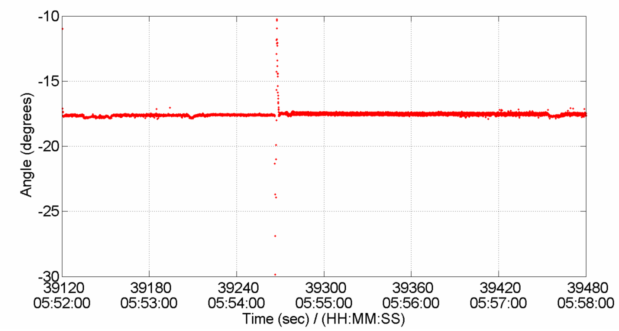

Figure 16: Camera-measured Angle During Static Period

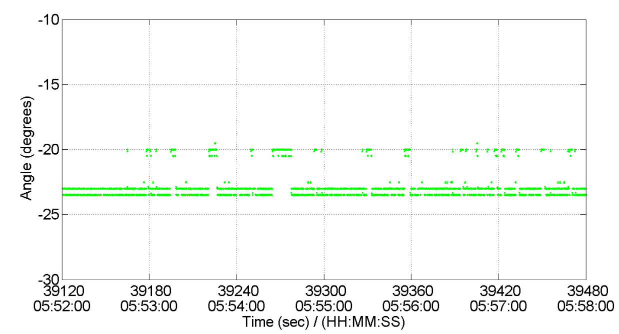

Figure 17: Laser-measured Angle During Static Period

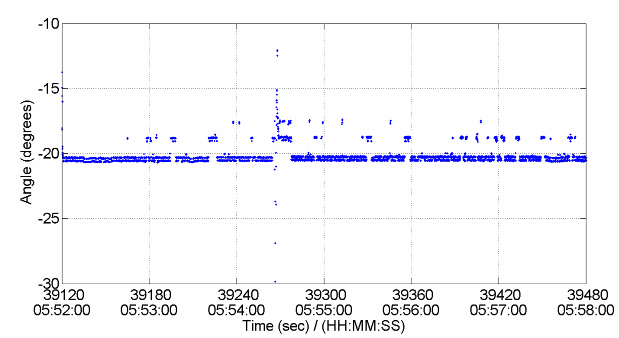

Figure 18: Camera+Laser-measured Angle During Static Period

During the static period of time, both the camera and the laser show near-constant values of angle. At one point, some error occurs in the camera measurement. There is also a bit of an anomaly in the distance measured by the camera at this time. Most likely, an error occurred in the image analysis stage of the processing, and the colored tube was not well identified. The laser shows a constant value, with occasional jumps. As mentioned before, these jumps are due to incorrect target identification. At the constant value, there appears to be two lines, due to the quantization (on 0.5 degree intervals) of the laser angle data.

When the camera and laser are combined, the result is a clear mix of the two. Errors existent in each sensor alone are still present, though with less magnitude. Table 5 shows the standard deviations of the angle values obtained from each sensor.

Table 5: Statistics for Sensors' Actual Angle Values during Static Period

Sensors	Mean (degrees)	Std Dev (degrees)	No. of Samples
Camera	-17.589	1.619	3000
Laser	-22.671	1.202	3000
Camera + Laser	-20.134	1.615	3000

Kinematic Time Period

This section describes the distance and angle measurements obtained during a three minute long subset of the data, during which the robots were moving. The following figures show the distance computed using each sensor during this period. The distance between the robots continuously varies during this period, from about 2.2 meters to 3.0 meters.

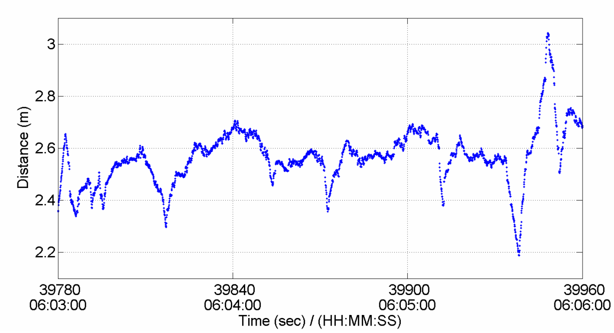

Figure 19: GPS-measured Distance During Kinematic Period

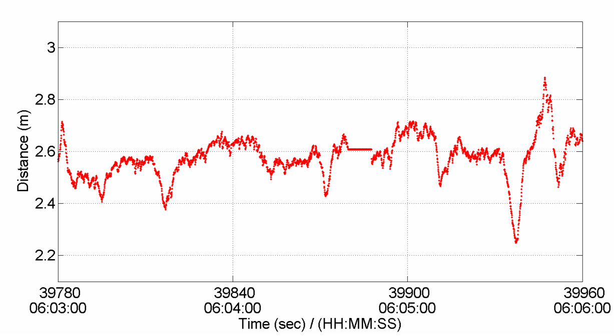

Figure 20: Camera-measured Distance During Kinematic Period

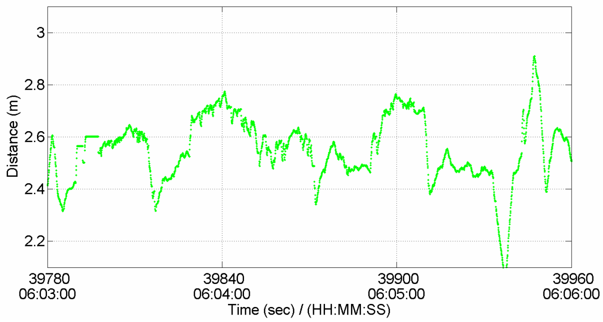

Figure 21: Laser-measured Distance During Kinematic Period

From the plots, GPS appears to be the most precise. Camera is surprisingly not much worse, due to the filtering taking place in the Kalman filter. The laser appears precise, but has some occasional sharp jumps. In both the camera and laser plots, there is evidence of data outages, indicated by the short horizontal line as the distance value does not change (though its variance increases).

When combining the data sets, since data from all sensors was present during this time, the same phenomenon occurs as during the static period. The hierarchy of GPS, laser, and camera still applies. Therefore, plots of combinations of sensors are omitted.

Table 6 shows the statistics of the distance measurements during the kinematic period described above. Truth data is created by the processing of dual frequency data from the follower and leader in differential mode with respect to the static reference station, using the Flykin™ software developed by the Positioning, Location, And Navigation (PLAN) group, University of Calgary. Output positions are differenced in order to compute the distance between the robots.

Table 6: Statistics of Sensor Combinations During Kinematic Time

Sensors	Mean (cm)	Std Dev (cm)	RMS (cm)	No. of Samples
GPS	0.1	0.5	0.5	2610
Camera	1.3	6.9	7.0	2029
Laser	-1.0	8.8	8.9	2325
Camera + GPS	0.1	0.5	0.5	2610
Laser + GPS	0.1	0.5	0.5	2610
Camera + Laser	-1.2	8.0	8.1	2029
Camera + Laser + GPS	0.1	0.5	0.5	2610

The GPS output is clearly the most accurate. Though there may be some bias since GPS was used to create truth data, although in a different way. The camera actually shows up as being more accurate than the laser, which is surprising. This may be due to errors in the laser identifying the correct target. When sensors are combined, since all sensor data is available, all combinations involving GPS give the same accuracy as GPS alone.

The following figures show the angle measurements created during the same few minutes of kinematic data.

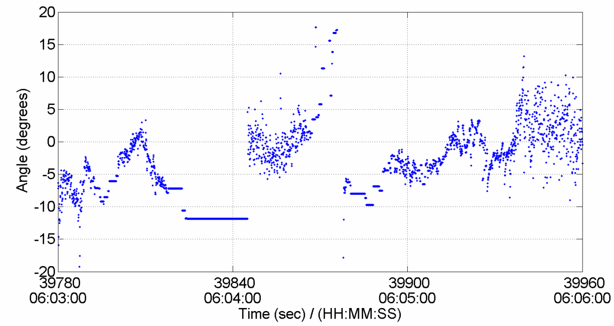

Figure 22: GPS-measured Angle During Kinematic Period

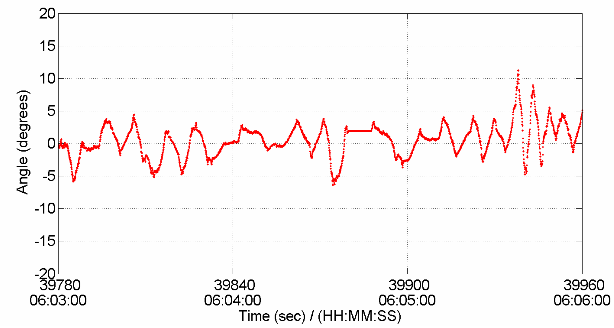

Figure 23: Camera-measured Angle During Kinematic Period

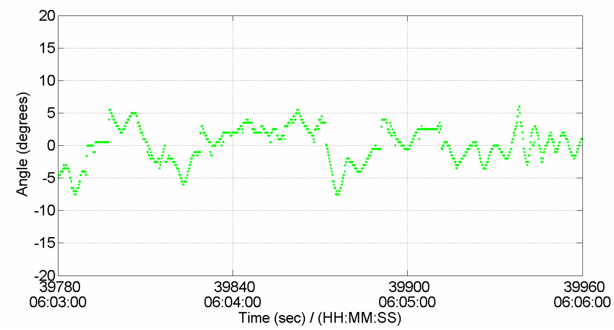

Figure 24: Laser-measured Angle During Kinematic Period

All three plots follow approximately the same pattern. The laser and camera are clearly much closer together, and much more accurate, than the GPS. For some periods of time, the GPS does not even update values, since the follower robot's speed was too low to provide a reasonable heading measurement. This shows beyond a doubt that a single-antenna per vehicle system is not sufficient alone to provide useful angle measurements.

For angles, there is no truth data for comparison.

GPS Data Outage

If the robots were to pass under a bridge, or near some tall buildings which block the line-of-sight to the GPS satellites, a GPS data outage would occur. If GPS was not assisted, there would be no measurements available during this time. Furthermore, once GPS is reestablished, it takes some time for ambiguities to resolve to their integer states. Therefore, combining GPS with other sensors should yield a significant improvement. GPS data was eliminated for a one minute period in the same time frame as the previous dynamic plots to test the ability to bridge an outage and aid in ambiguity resolution.

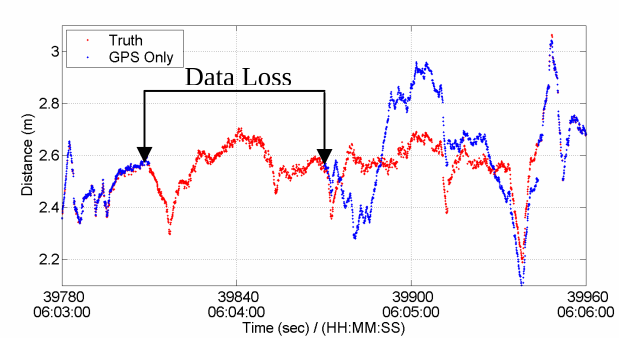

Figure 25: GPS-measured Distance During Dynamic Data Loss Period

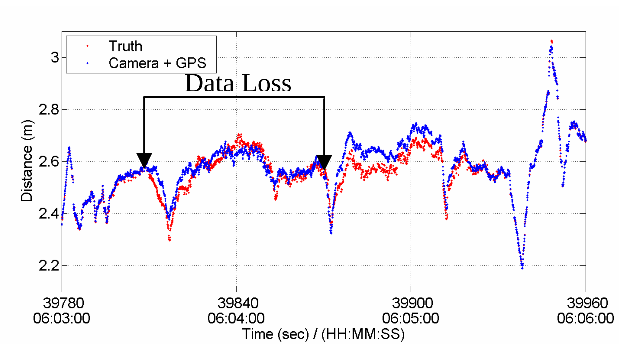

Figure 26: Camera+GPS-measured Distance During Dynamic Data Loss Period

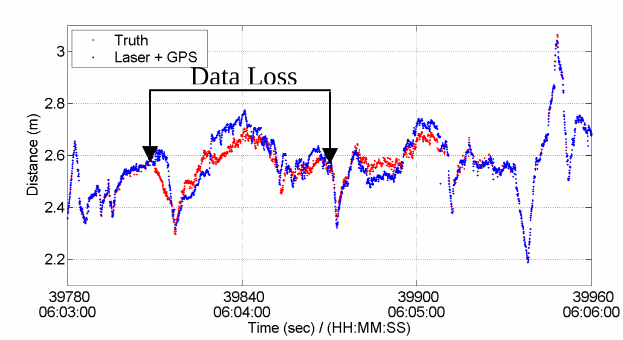

Figure 27: Laser+GPS-measured Distance During Dynamic Data Loss Period

In Figure 24, when GPS alone is used, there is no update to the distance measurement for a one minute period. Once GPS data returns, it is in float-ambiguity mode, and the accuracy is not very good. It takes more than another minute before ambiguities are resolved.

When camera data is present, the computed distance remains close to the truth distance throughout the data loss period, and after GPS data returns. The ambiguities are more quickly resolved than with the GPS-only case, after which point the accuracy is once again very high.

Adding laser data has much the same effect as adding camera data.

Table 6 shows the accuracy during the data outage, and Table 7 shows the accuracy during the minute immediately following the data outage when GPS is once again present with float ambiguities. In both cases, augmenting GPS with other sensors greatly improves the accuracy.

Table 7: Accuracies During Data Outage

Sensors	Mean (cm)	Std Dev (cm)	RMS (cm)	No. of Samples
GPS	0.2	8.0	8.0	880
Camera + GPS	1.2	3.7	3.9	880
Laser + GPS	3.0	5.6	6.4	880

Table 8: Accuracies During Minute After Data Outage

Sensors	Mean (cm)	Std Dev (cm)	RMS (cm)	No. of Samples
GPS	7.0	15.2	16.7	816
Camera + GPS	4.2	3.1	5.2	816
Laser + GPS	0.8	3.7	3.8	816

Ambiguity Resolution Speed

As mentioned previously, ambiguities should be resolved more quickly when other sensor data is present. This is because the other sensors constrain the value closer to its true value. Table 8 shows the time required to resolve ambiguities for GPS alone and in sensor combinations, at the beginning of the test (static time). Table 9 shows the same information for the resolution of ambiguities after the data loss described above.

Table 9: Time Needed to Resolve Ambiguities During Static Period

Sensors	Time to Ambiguity Resolution	% Improvement
GPS	70.4 seconds	
GPS + Camera	51.6 seconds	26.7 %
GPS + Laser	44.6 seconds	36.6 %

Table 10: Time Needed to Resolve Ambiguities During Kinematic Period After Data Loss

Sensors	Time to Ambiguity Resolution	% Improvement
GPS	73.6 seconds	
GPS + Camera	61.7 seconds	16.2 %
GPS + Laser	38.1 seconds	48.2 %

It is clear that in both cases, ambiguity resolution speed is reduced by combining GPS with other sensors. The laser has a greater improvement than the camera, most likely because it should be more accurate. Additional trials at different times throughout the test show similar results, with the camera augmentation showing some improvement and the laser showing greater improvement. When dealing with ambiguity resolution, noise values assigned to the sensors are particularly important. For example, if an overly low variance is given to the assisting sensor's data, then even if the measurement value is closer to the truth, the ambiguity search space is reduced so far as to exclude the true ambiguity set.

CONCLUSIONS

It has been shown that various sensors may be used individually in a Collaborative Driving System. Each sensor has some advantages and disadvantages.

GPS provides high accuracy distance measurements, but requires initialization time to reach fixed-ambiguity mode. Also, fixed ambiguity mode may be lost when GPS signal outage occurs. A final large disadvantage of GPS is that the local angle to the lead robot can not be directly computed, it must use a heading of the follower robot combined with an azimuth between robots. The heading of the follower robot is not always available, and has low accuracy, in this paper.

The digital camera provides distance and angle measurements immediately. However, the distance measurements have a much lower accuracy compared to GPS. It is difficult to evaluate the accuracy of the angular measurements. One of the primary disadvantages of the camera system is the requirement of a well defined colored object on the leader robot, that must be in view at all times. This is not very practical for real applications.

The laser also directly provides distance and angle measurements, of relatively high precision. However, observations are not always present, and blunders occur more frequently than with the other sensors, due to the difficulty present in identifying the lead robot in the laser profile. This would also be a problem in real applications, as vehicles have widely varying shapes.

By combining the GPS with the camera or laser, continuous distance and angle measurements are available. The GPS ambiguity resolution time is decreased, allowing the use of these high accuracy distance measurements. When the GPS signal is blocked, the vehicle may continue to navigate, though with slightly lower accuracy, using the other sensors alone. When camera or laser observations are blocked, GPS continues to provide accurate distance measurements, but accuracy of angular measurements is quite poor.

Future recommendations include using a two-antenna system on each vehicle. This will result in much higher quality, with more continuous availability, of heading observations from GPS (Cannon et al., 2003). This would allow the GPS system to operate more independently of the camera and laser sensors. Additionally, constraints can be used (Harvey, 1998) with multiple receivers to improve ambiguity resolution.

Another recommendation is to change the shape of the rear of the leader robot. This could improve the laser recognition of the lead robot, and therefore improve accuracy. For example, using an overall V-shaped rear end would result in a more easily recognized point.

Finally, experiments involving changing the noise associated with each sensor could be performed. Also, process noise could be adjusted, or additional states such as a distance rate and angle rate could be used.

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