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Application of robust, high-accuracy positioning for autonomous ground vehicles

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Abstract. In this paper we review the need for robust, high-accuracy positioning for path guidance in the presence of large structures (such as buildings and trees) and for the integration of sensor data. Such capability is necessary in many applications that require precision over vast areas of operation. We find that unless integrated tightly, combined INS/GPS systems diverge significantly when line of sight to GPS satellites is lost. This results in a long recovery period especially when cm level positioning is required. High-accuracy inertial sensing is also useful when registering sensor data taken from a moving vehicle. This is particularly the case when data from a scanning sensor must be integrated over time to form a composite picture that aids in detecting obstacles that would hinder an autonomous vehicle. We show how a tight integration between inertial sensing and GPS positioning resolves some issues in the loss and reacquisition of satellites and how the inertial positioning is used to register sensor data. We present results from two applications of autonomous ground vehicles that use integrated GPS/INS systems to follow prescribed paths [8] and to sense the environment around them [11, 12]. One operates in smooth terrains, and the other is intended for cross-country operation.

1. Introduction

GPS provides a practical, easy-to-use means of estimating location. When combined with a source of differential correction, the accuracy of the GPS position estimate can be as much as 2cm. This kind of accuracy combined with almost world-wide availability of the GPS satellite network would seem to cast it as the ideal outdoor localization sensor. However, signals from the GPS satellites can be blocked by solid objects such as buildings and trees, and the time to reacquire satellites can be large especially when cm level accuracy is desired. Additionally, in some cases, position estimates are confounded by undistinguished multipath-- GPS signals that bounce off solid objects.

Hence, in operation on an autonomous vehicle, GPS alone does not provide the level of reliability necessary for robust outdoor autonomous operation. To achieve this level of robustness, GPS is often coupled with inertial sensors that measure velocities and accelerations. While GPS positioning can be noisy and somewhat slow, inertial measurements can be made at high rates (typically 100-500hz) and high quality instruments can produce a smooth output that drifts only slowly overtime. By combining both sets of measurements, a coupled INS/GPS positioning system is able to provide a position estimate more accurate and robust than either system alone.

A coupled localization system resolves many issues surrounding outdoor autonomous operations requiring high accuracy and reliability. A highly reliable localization system makes such tasks as autonomous route following much more reliable. High fidelity of a coupled localization system is also useful when registering sensor data taken from a moving vehicle, for example when a system is required to integrate over time data from a scanning sensor to form a 3-D map of an area. Such a map can then be used in detecting obstacles that would otherwise hinder an autonomous vehicle. While integrated INS/GPS systems have been developed since the 1960s [1], and various forms of robustness have been demonstrated using redundant components [2], additional satellite-like transponders [3] and systems that incorporate GPS as well as GLONASS satellites [4], only recently has high integrity and fidelity been demonstrated in commercial packages. These systems use a "tight" coupling between INS and GPS to produce accurate estimates of position and attitude in the presence of occluding structures. In this paper, we review some of the benefits of using a coupled localization system for use in mobile robot applications, two of which are shown in Figure 1.

Figure 1 Mobile Robot applications that require high integrity and high fidelity localization. (left) mower used for turf maintenance (right) vehicle intended for use in scouting in cross-country terrain. In the first case, it is important to achieve 5 cm accuracy over a vast area even in the presence of objects that would occlude GPS signals. In the second case, obstacle avoidance during high speed operation (4-10 m/s) requires accurate registration of data from an onboard laser scanner.

In Section 2, we give an overview of how a tightly coupled localization system works and describe the differences between it and a loosely-coupled system. In Section 3, we describe the benefits of the high integrity of the position estimate provided by a tightly coupled system. Finally in section Section 4 we discuss how the high fidelity position estimate can be useful in creating 3-dimensional maps used in obstacle detection.

2. Theory of Operation

The adjectives “tightly” and “loosely” coupled describe how tightly integrated the GPS and IMU measurements are within the position estimator. The difference in the structures for these two solutions is shown in Figure 2.

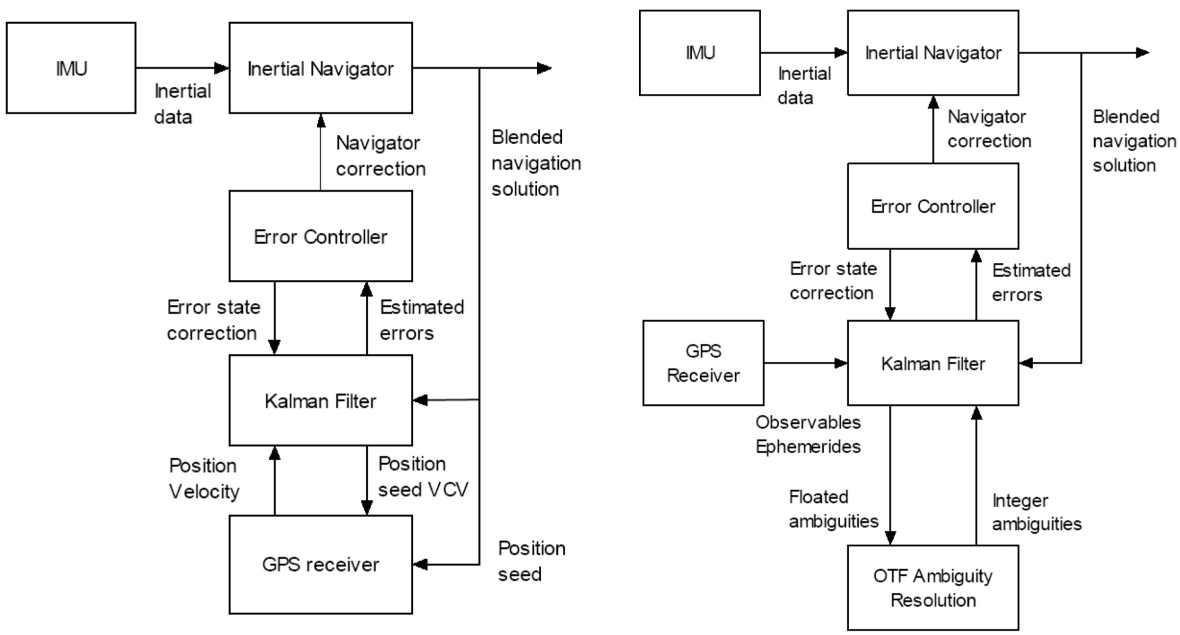

Figure 2 Loosely (left) vs. tightly (right) integrated INS/GPS [6].

The advantage a tightly coupled system holds over a loosely coupled system is in its ability to use even a single GPS range measurement to aid it in its position calculation [5, 6, 7]. A loosely coupled inertial plus GPS integration combines GPS position and velocity information with measurements from the IMU to produce a position estimate. The loosely coupled system also uses the inertially computed position to shorten the amount of time required to obtain a fixed integer RTK solution. Because the loosely coupled system uses only the GPS calculated position to aid its inertial position, at least 5 satellites must be observed before the RTK GPS position can influence the position calculation.

The tightly coupled INS/GPS system we have tested[1] uses the pseudorange, phase and Doppler observations in its position calculations. Because it uses the raw observables from each GPS satellite, it is able to use observations of even a single satellite to curtail IMU drift.

3. High-Integrity Localization

High-accuracy and high-integrity position estimates are necessary in several autonomous outdoor applications, some of which require a highly reliable position estimate at all times. In particular, golf course mowing applications require centimeter accuracy to maintain appearance of fairways and greens. This ensures that the area is covered fully and efficiently (without need for considerable overlap). High accuracy positioning also enables regular patterns that are created for aesthetic reasons-- typically these patters require a deviation from a straight line of no more than 5 cm over 100 m. Finally, accurate positioning ensures that the vehicle stays away from obstacles such as trees and drop-offs along the boundary of the course.

We have experimented with several integrated INS/GPS systems for positioning that can be used to autonomously follow prescribed paths. In our experience, loss of RTK level accuracy when a vehicle is close to tall structures results in significant drift (1-2 m) even over short distances (20-30m). Since dead-reckoning alone can produce lower drift as evidenced by lower drift rates when GPS signals are abruptly interrupted completely (for example upon entry into a tunnel), it is likely that this drift occurs due to the uncertainty associated with measurements from the small number of satellites that continue to be visible. Typically, it is possible to recover from such errors once the vehicle is able to acquire RTK once again but only after a significant drift from the designated

1. Applanix POS LV uses 2 GPS antennas and a Honeywell HG1700 IMU.

path. Our experiments show that in the conditions where a loosely coupled system would drift, tightly coupled systems are able to produce the accurate and reliable estimates.

An experiment with a loosely-coupled INS/GPS highlights this phenomena. Figure 3 shows the response of a vehicle commanded to drive under tree cover. While under cover for approximately 20 m, the path drifts by as much as a 1.5 m. When the vehicle has time to recover RTK positioning, the offset is automatically corrected. Analysis of the uncertainties reported by the positioning system show that once under tree cover, the uncertainties continue to grow until RTK lock is achieved again.

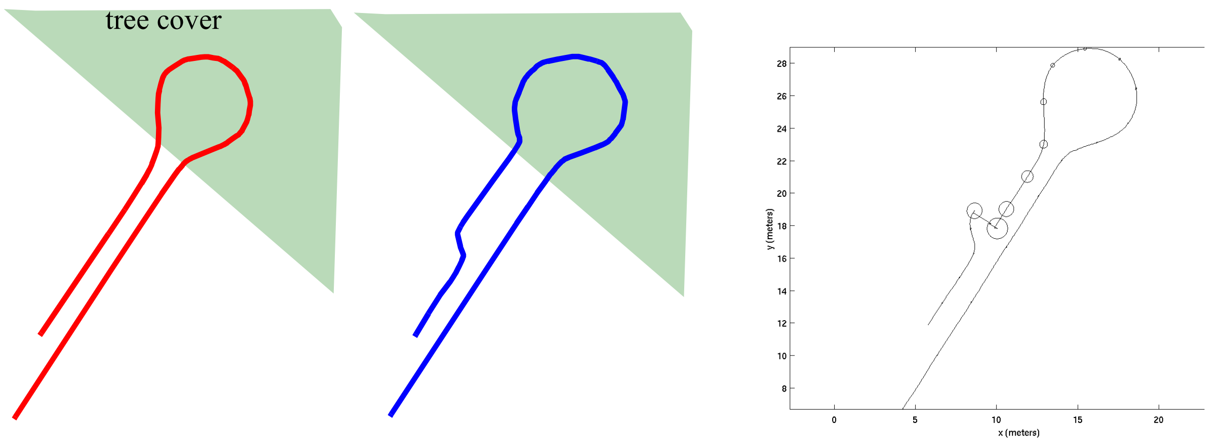

Figure 3 (left) commanded path partly under tree cover. (center) Path followed by the autonomous vehicle. (right) Position estimates during execution. Circles on the path show uncertainty (1 STD) in positioning along the path.

To illustrate the difference between a loosely and tightly coupled system, we drove the vehicle on a similar path with partial tree cover. The Applanix POS-LV and a loosely coupled system were both mounted on the vehicle and simultaneously supplied the system with position estimates. Both systems received 2cm RTK differential corrections.

Figure 4 shows the position data from one complete loop. The plot of the loosely coupled system's position estimate clearly shows a discontinuity at the end of the loop. The system required

18s and travelled a distance of 70m before it was able to regain an accurate GPS position once it left the tree cover. During that time, the error in position had grown to approximately 2.5m as evidenced by the corresponding discontinuity in position.

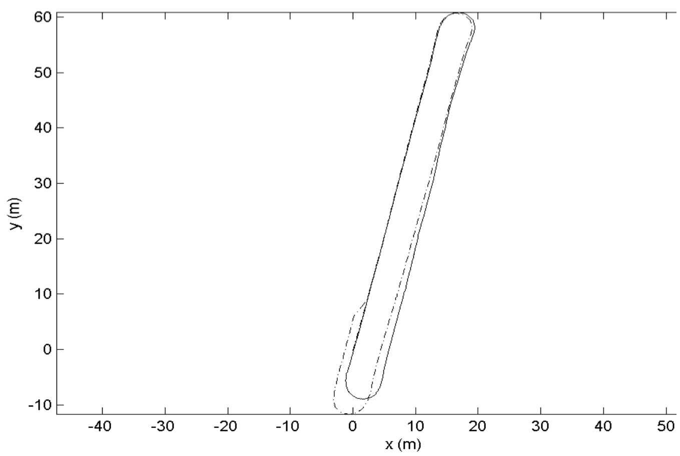

Figure 4 Position output by the Applanix POS-LV and a loosely coupled localization system as a vehicle travelled in and out of tree cover. The Applanix data is shown as a solid line and the loosely coupled data is shown by the dotted line. The vehicle began the loop at (0,0) and travelled clockwise. The vehicle travelled through tree cover at the top of the loop. The vehicle remained under tree cover for approximately 15 seconds and during this time, the number of satellites in view was reduced to 5, but lost the fixed RTK GPS position. The vehicle was travelling at 4m/s over the straight sections of path and 1m/s over the curved sections. The loosely coupled system shows a 1.5m offset in position when finishing the loop while the tightly coupled data remains smooth throughout the path.

The data from the POS-LV system does not show any such large discontinuities, and the position estimate at the beginning and end of the loop are the same showing the absolute accuracy of the position. However, the POS-LV data is not completely free of position discontinuities. At the point where the vehicle leaves the area of tree cover, there is a small 10cm jump in position, but this discontinuity is still much less than that shown by the loosely coupled system.

4. High-Fidelity Localization

High-fidelity localization in position and attitude is essential for robotic vehicles travelling at high speeds, especially when operating in outdoor environments. In some cases, traversability of a path can be evaluated by sensors such as stereo vision that make range measurements instantaneously within a significant field of view [9, 10, 11]. However, accurate sensing of the environment typically requires sensors (such as laser rangefinders) that must be scanned to reliably detect obstacles. At low speeds it is possible to use methods that can cope with the fact that the sensor data is taken from a continuously changing point of view [12], but at higher speeds, multiple scanners might be required to produce sufficient density of measurements. In this case, it is necessary to register data in a common coordinate frame despite six DOF motion of the sensor. The high accuracy and reliability of a tightly-coupled localization system makes the task of integrating sensor data over time much easier and less error-prone.

For our scouting vehicle we use a sweeping laser system combined with a POS-LV system to generate a 3-D point cloud used in obstacle detection at high (4m/s) speeds. (Figure 5).

Figure 5 Sweeping laser scanner consists of a commercial single axis scanner that is panned in a fan like motion to generate an elevation map of the terrain ahead of the vehicle.

The sweeping laser system consists of a Sick laser mounted so it is scans vertically and a motor that sweeps the laser back and forth to scan the area in front of the vehicle. The obstacle detection module combines the range and angular information from the sweeping laser with the pose data from the POS-LV to generate a 3-dimensional point cloud. This point cloud is analyzed by fitting small local planar patches over the entire cloud. Obstacles are indicated by range data sufficiently far from the planar patch (object that could cause collision, or pot hole), or slopes that would indicate a pitch or roll hazard. This is illustrated in Figure 6.

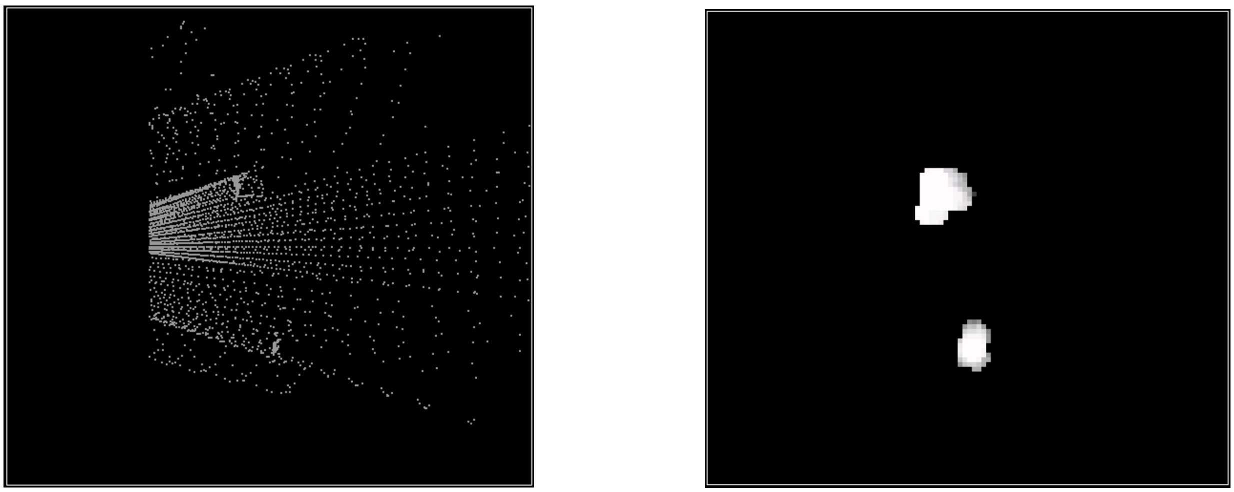

Figure 6 A traversability map created from a sweeping laser scanner. The figure on the left shows the point cloud generated when observing two obstacles in front of the vehicle. The vehicle is on the left hand side of the image and the image is a top down view. The figure on the right shows the traversability map costs. White shows a high cost and black shows low cost. The two obstacles show up as white blobs. Since the sensor moves in 6 DOF while the data is taken it is important to register the data in a common reference frame.

Another illustration is from a laser range data taken while the vehicle drives adjacent to a row of trees with significant displacement in all six degrees of freedom. The pitch and roll motion of the vehicle during data collection is shown in Figure 7. The generated point cloud is shown in Figure 8. Because the pose of the vehicle can be measured with high accuracy, a cohesive three dimensional view of the world can be reconstruted even though the vehicle is moving, The accurate correspondence between laser and pose data can create point clouds of very high accuracy and enable detection of smaller obstacles within the data even at high vehicle speeds.

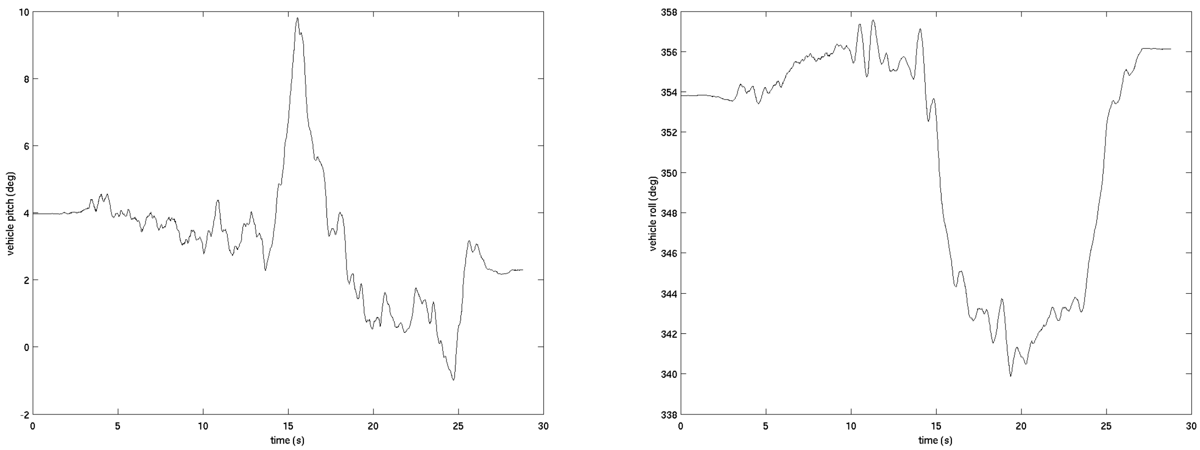

Figure 7   Pitch and roll of vehicle during data collection

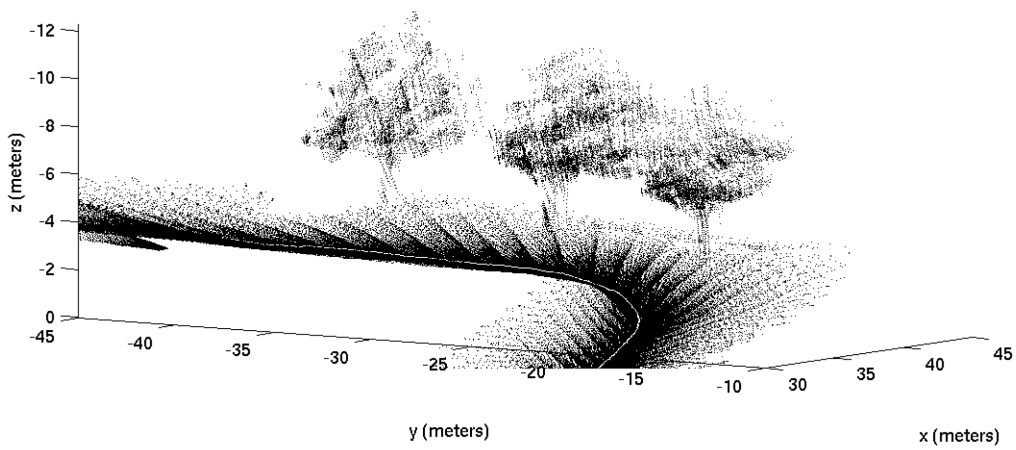

Figure 8   The sweeping laser used to create the 3-dimensional maps of the area in front of the vehicle. Using the range data from the laser, the motor's yaw angle and the pose information from the POS-LV system, the laser range data can be transformed into a point cloud in world coordinates.

5. Conclusions

The high integrity and fidelity of the position data from a tightly coupled localization system makes outdoor autonomous vehicular applications more robust. Without a tight integration of the INS and GPS systems, position estimates can quickly diverge when line of sight to GPS satellites is lost. The amount of time required to recover acceptable position accuracy can be lengthy especially when cm level accuracies are required. The lack of integrity of the position estimate directly affects the robustness of the autonomous vehicle when using the pose estimate for path guidance.

The high accuracy is also useful when integrating sensor measurements over time to perform tasks such as obstacle detection and mapping.

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