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Autonomous vehicle based in cooperative GPS and inertial systems

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SUMMARY

A system including Global Positioning Systems (GPS) and digital cartography is a good solution to carry out vehicle's guidance. However, it has inconveniences like high sensibility to multipath and interference when the GPS signal is blocked by external agents. Another system is mandatory to avoid this error. This paper presents a cooperative system based on GPS and Inertial Navigation Systems (INS) for automated vehicle position. The control system includes a decision unit to choose which value is the correct. In case GPS is working at top precision, it takes the control. On the other part, GPS signal can be lost and inertial control system guides the car in this occasion. A third possibility is contemplated: we receive the signal from GPS but the accuracy is over one meter. Now, position value is obtained by means of both systems. Experimental results analyze two situations: guidance in an urban area where GPS signal can be occluded by buildings or trees during short time intervals and the possibility of loss of the signal in long time to simulate the circulation in tunnels. Good results have been observed in tests and it demonstrates how a cooperative system improves the automated vehicle guidance.

KEYWORDS: Automated guided vehicles; Global positioning systems; Inertial measurement unit; Intelligent transportation systems.

1. Introduction

Intelligent Transportation Systems (ITS) focus on synergistic technology and system engineering concepts for developing and improving transportation systems of all kinds.[10] ITS creates an interface between the vehicle and roadway which enables the driver to have better management and use of the transportation resources available. Furthermore, it is possible without any physical changes to the existing infrastructures. One of the concerns of ITS research is autonomous vehicle development whose final goal is to obtain an artificial driver that is able to manage the car actuator in the same way as humans do in free traffic, but with a higher degree of safety and road optimization. The main navigation information source for autonomous vehicles is GPS information [DARPA GRAND CHALLENGE][9] due to its capability of georeferencing a circulating vehicle in real time with enough accuracy and without temporal precision degradation.[12]

GPS is a system that is based on a 24-satellite cluster to obtain an exact position on the Earth anywhere, at any time, and in any weather. It represents an exact and precise method for determining vehicle position. A GPS receiver needs four satellites to determine its actual (x, y, z) position with a less than 20-meter precision error. Furthermore, it is possible to reduce this error to less than two centimeters with five satellites minimum, using a Differential Global Positioning System (DGPS). Nevertheless, car navigation with a DGPS has one drawback: the presence of obstacles (trees, tunnels, buildings) can cause signal block during several seconds resulting in information loss and vehicle guidance failure. To improve this, the integration of GPS data with an inertial system is an optimal solution.[3]

Inertial Navigation Systems (INS)[1] provide a vehicle's position by measuring the linear acceleration and angular velocity exerted on the system in an inertial reference frame with the Inertial Measurement Unit (IMU). An IMU is a measurement system consisting of angular rate sensors and accelerometers. With IMU information and the odometry, it is possible to calculate the actual position of a vehicle from an initial location, where the accuracy of the navigation is not dependent on external signals. Conversely, the dependence on correct initialization may cause unbounded error growth when estimating the vehicle's position. Additionally, inertial systems are dead-reckoning systems; this means that their accuracy degradates with time.

In open areas, like highways, the GPS has the advantage over dead-reckoning positioning techniques. However, the GPS signal can be lost and two situations then need to be considered. First of all, short-time faults where GPS signals are lost for less than one second, for example, in a city, where buildings may occlude satellite signals. This can produce undesirable maneuvering and abrupt steering wheel movement that must be smoothed. The second case is produced by a long- time fault, e.g., in a tunnel or circulating through a tree canopy, where another system must take control to prevent an accident.

In addition, using GPS and INS complementary properties to improve vehicle navigation is mandatory. Both systems provide long-term stability and independence of external signals. J. A. Farrel proposes a filter to integrate GPS/INS

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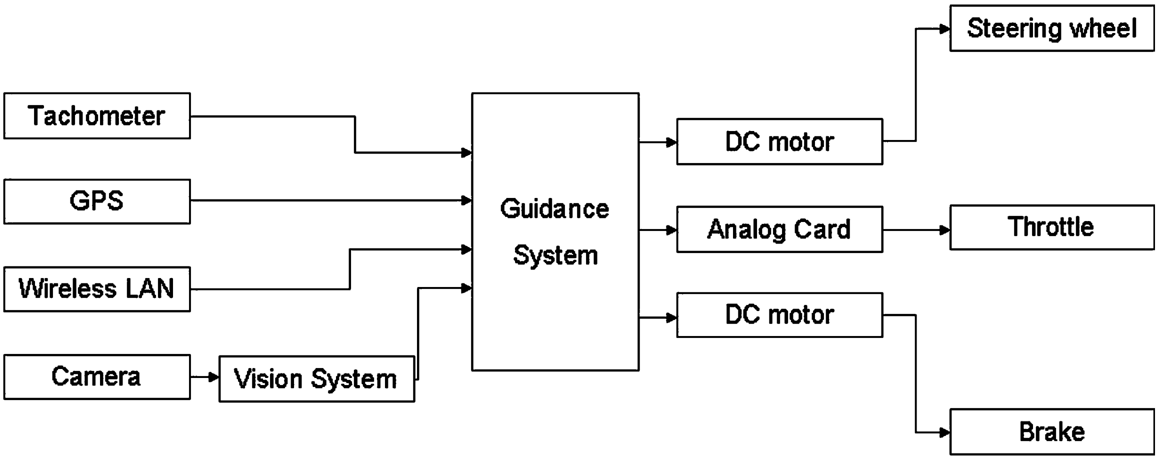


Fig. 1. The AUTOPIA system control structure.

systems to correct the GPS position.[2,4,7] D. Obradovic uses a Kalman filter that combines the GPS and INS to increase the number of guidance positions.[8] J. Wang performs the guidance with GPS/INS aided Vision-based lane- recognition (VBLR) systems.[11] S. Hong demonstrates the effect of lever arm errors on GPS/INS systems.[5–6]

In this paper, we present a solution to avoid guidance vehicle failures with a control system that combines the GPS and INS to know the vehicle's position in a global coordinate system at each moment. This control system consists of a decision unit that chooses the control mode. It receives all the sensory information and decides which is the best option.

This paper is organized as follows. Section 2 shows the Autopia Automatic Driving System whose goal is to develop a set of automated vehicles that can be automatically driven in a closed circuit. Section 3 explains the control system with GPS and IMU integration. Section 4 shows the experimental results and, finally, the conclusions are given in Section 5.

2. AUTOPIA Automatic Driving System

Until recently, in-vehicle computing was largely relegated to auxiliary tasks such as regulating cabin temperature, opening doors, and monitoring fuel, oil, and battery-charge levels. Now, however, computers are increasingly assuming driving-related tasks in some commercial models. Some of these tasks are:

- maintaining a reference velocity or keeping a safe distance from other vehicles,
- improving night vision with infrared cameras, and
- building maps and providing alternative routes.

AUTOPIA has two primary objectives. First, we want to implement automatic driving using real, mass-produced vehicles tested on real roads. Although this objective might be considered utopian at the moment, it is a great starting point for exploring the future. Our second aim is to develop our automated system using modular components that can be immediately applied in the automotive industry.

The system's main sensor inputs are a CCD (charge-coupled device) color camera and a high- precision global positioning system. With these, the system controls the vehicle-driving actuators, i.e., the steering, throttle, and brake pedals. The vehicle includes an onboard PC-based computer; a centimeter, real-time kinematic differential GPS (RTK DGPS); Wireless LAN support; two servomotors; and an analog/digital I/O card. We added a vision system to another computer connected to the control computer. Figure 1 shows the control system that we developed to manage all these devices.

The guidance system with the GPS is modeled using fuzzy variables and rules to correct the trajectory errors computed with the onboard GPS receiver and the high-precision digital cartography that defines the target route. In addition to the steering wheel and vehicle velocity functionalities, we also consider variables that the system can use in adaptive cruise control (ACC) and overtaking capabilities. Among these variables are the distance to the next bend and the distance to the lead vehicle (i.e., any vehicle driving directly in front of the automated vehicle).

Car driving is a special control problem because mathematical models are highly complex and cannot be accurately linearized. We use fuzzy logic because it is a well-tested method for dealing with this kind of system, provides good results, and can incorporate human procedural knowledge into control algorithms. Also, fuzzy logic lets us mimic human driving behavior to some extent. A common communication interface was defined and low-level driving computation, where human knowledge and experience reside, was modeled using fuzzy logic.

3. GPS and IMU Integration

After the control system to manage the car actuators had been defined, it was necessary to supply it with enough accurate information to perform human-like driving. RTK–DGPS information is optimal to reference the car from the digital cartography that defines the target route. However, it is necessary to add a secondary positioning system that complements the GPS when its accuracy is not enough to allow safe driving. In our case we added an inertial unit to the odometry signal in the very test-bed car. With this information, we obtain the car's true position (North, East) in any GPS circumstance.

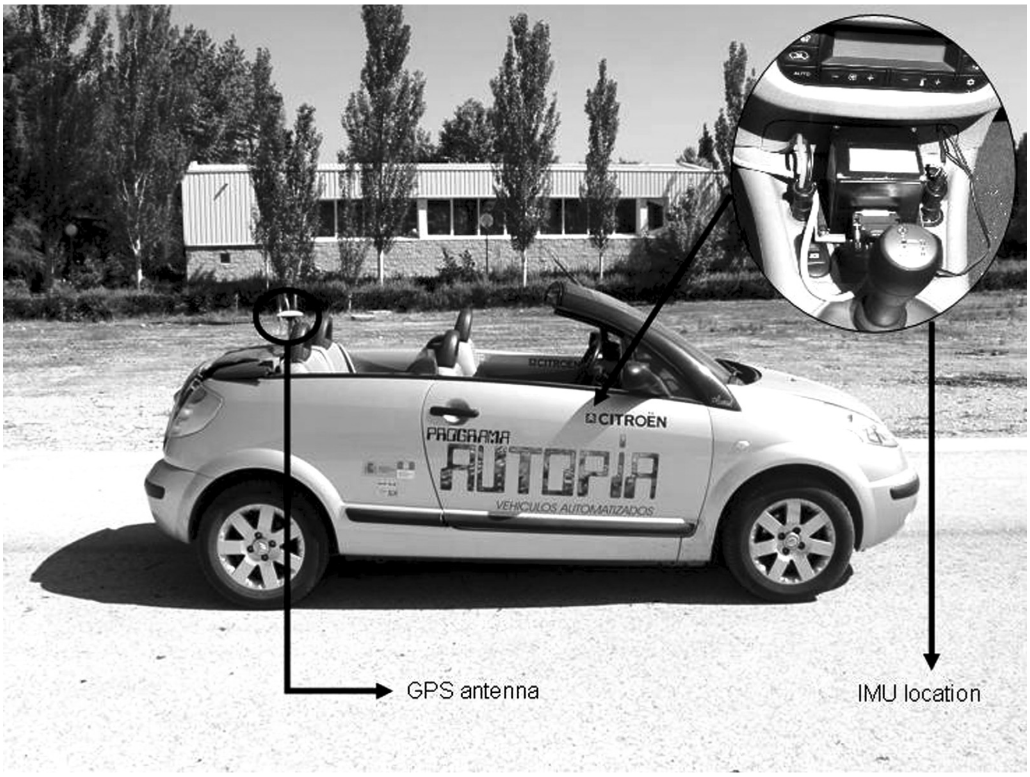


Fig. 2. Citroën C3 Pluriel; IMU location detail.

The IMU model used is a Crossbow IMU300CC placed close to the center of the vehicle. After fixing it to the vehicle it is mandatory to calibrate the IMU null offset and sensitivity.

The odometry is supplied by a set of built-in sensors in the wheels, whose measurements can be obtained with the Controller Area Network (CAN) bus of our vehicle, Citroën C3 Pluriel (Fig. 2). Specifically, we utilize the wheel-speed data to find the distance traveled (d_a), using Eq. 1.

$$d_a = \frac{v_{sensor} \cdot \Delta t}{3,6} \tag{1}$$

where v_{sensor} is the value obtained directly from the CAN bus in km/h and Δt is the time between two consecutive measurements. d_a is in meters.

Pitch and yaw angles are obtained from the IMU to determine the road's slopes and bends respectively. The IMU measures any increment in angular velocity but we need the absolute angle. Initialization values are thus required. With vehicle position (x, y) and altitude (z), it is possible to determine the initial angle (Table I).

We cannot rely on the car given distance to obtain the precision we desire. Thus we have done a correction to this data with the help of the centimetric GPS, in order to take into account the effects of slopes, pneumatic pressure, the number of passengers, and bends. Equation (2) projects d_a on the horizontal plane, so they are coherent with GPS measures. This is the reason to include ϕ_y in the formula. Furthermore an offset error e_d – Eq. (3)—is included to model the error in each sampling period.

$$d_r = d_a \cdot \cos(\phi_Y) - e_d \tag{2}$$

$$e_d = \frac{d_a \cdot \cos(\phi_Y) - d_{GPS}}{n} \tag{3}$$

where d_r is the corrected value of the distance, ϕ_Y is the pitch angle, and d_{GPS} is the distance given by the GPS during all the time that the DGPS is working correctly and n is the number of samples during this interval. e_d is being computed in real time while the GPS works at top precision until the IMU is to be used for the control.

Once the real distance has been obtained, if the GPS looses the fixed precision we can calculate the next vehicle

Table I. Initial angle.

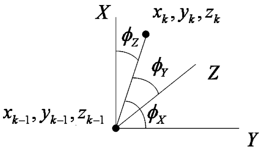
Coordinates	Angle	Expression
	ϕ_Z	$\phi_Z = \text{arctg}\frac{y_k - y_{k-1}}{x_k - x_{k-1}}$
	ϕ_Y	$\phi_Y = \text{arctg}\frac{z_k - z_{k-1}}{\sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2}}$

Table II. Fourier filter parameters.

Parameter	Value
Cutting frequency	0,01 Hz
Sample period	0,00714 s
Number of samples	28

position as

$$X_{GPS,k+1} = X_{GPS,k} + d_{real} \cdot \cos(\phi_Z) \quad (4)$$

$$Y_{GPS,k+1} = Y_{GPS,k} + d_{real} \cdot \sin(\phi_Z) \quad (5)$$

Moreover, the number of samples per second received by the sensors is different. GPS frequency is 5 Hz, wheel sensors receive a sample every 25 ms and IMU frequency is greater than 100 Hz. GPS frequency is used as the control system clock due to its accuracy. The GPS frequency will be used to perform position computations and a Fourier filter is used to determine the angular velocity. With the Fourier filter we obtain a smooth value in the angular velocity measurement and a decrease in the drift error. The values for the filter are shown in Table II.

We calculate the pitch and yaw angles from the value of angular velocities given by the IMU every time as

$$\phi_{k+1} = \phi_k + w_k \cdot \Delta t \quad (6)$$

where w_k is the angular velocity at k instant in rad/s and ϕ is the angle in rad.

The procedure to obtain the IMU position is always performed but we only integrate it with the GPS one, depending on its quality. GPS presents five different operation modes according to the positioning accuracy:

- Mode 0: in this mode, the GPS does not receive a signal.
- Mode 1: GPS accuracy is between 15 and 20 meters.
- Mode 2: measurement error is about two meters and it is impossible to obtain guidance with this mode.
- Mode 4: two-centimeter error is obtained with this mode. It is the convenient mode for determining the vehicle's position in a global coordinate system.
- Mode 5: steering wheel behavior is abrupt in this mode where accuracy is less than one meter.

The decision unit was implemented to determine the accuracy output at every moment. When GPS quality drops to mode 0, 1, or 2, the IMU takes control because the measurement errors are big enough to reject GPS values in these modes. The GPS takes control in mode 4, where the inclusion of other sensors causes signal deterioration. In mode 5, we combine the IMU and GPS because although initially the IMU is more accurate, the degradation due to drift recommends including a small percentage of the GPS value to correct this error. The essential function is like a director vector. The decision unit block diagram is presented in Fig. 3.

Transitions from the GPS to the IMU (mode 4 to mode 0, 1, or 2) are smooth but we have to consider transitions from the IMU to GPS (mode 2 or 5 to mode 4) due to undesirable steering wheel movements. Accordingly, a smooth adjustment is needed to solve this. Figure 4 shows the implemented transition state.

Once the control has returned to mode 4, the initial angle is calculated with the GPS to avoid degradation in the vehicleŠs position during all this time from drift.

4. Experiments

The control system was implemented in a Citroën C3 Pluriel car. The resulting experiments show the behavior in different situations, and very good results were achieved.

One of these tests tries to simulate a real situation in which centimeter accuracy (mode 4) is lost during several seconds between the initial and final point of a trajectory on various occasions. Figure 5 shows the route speed which, due to the bends, is less than 25 km/h. The figure also shows the value of GPS quality at each moment.

Figure 6 illustrates the map, plotted in GPS coordinates, of the private driving circuit at the IAI facilities, which

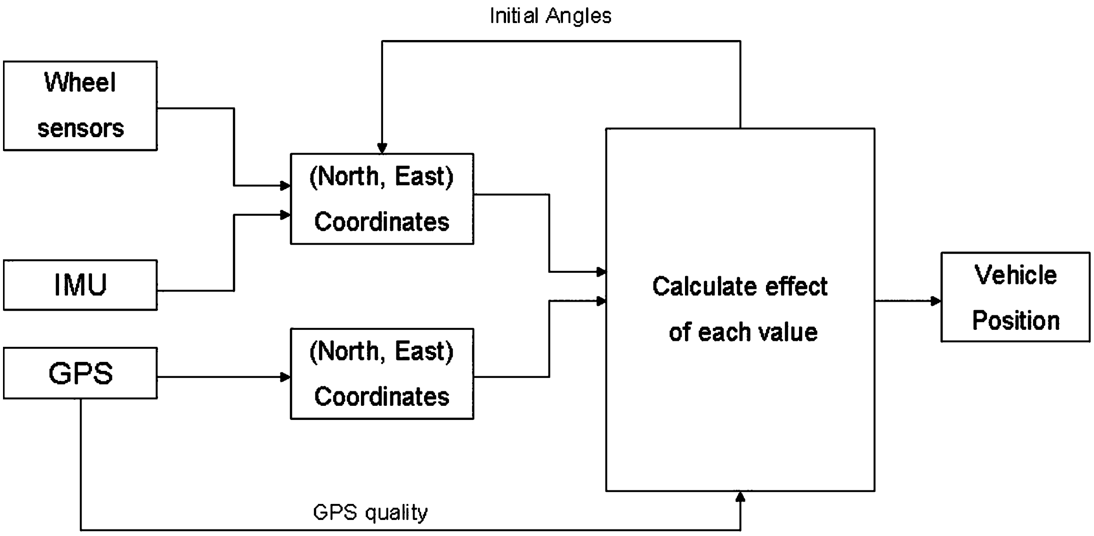


Fig. 3. Decision unit scheme.

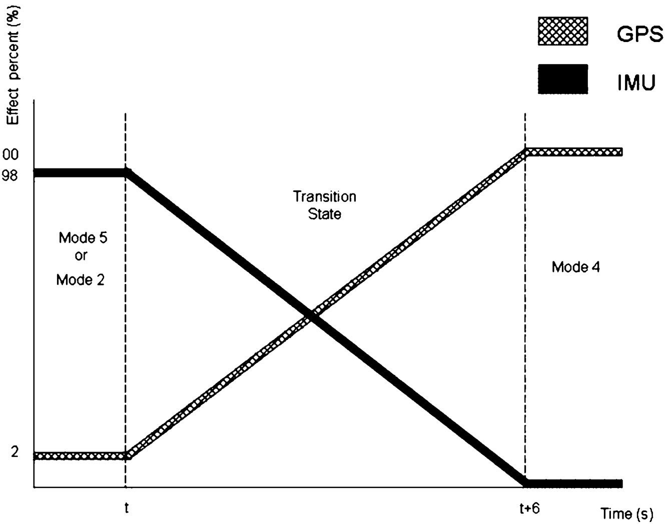


Fig. 4. Transition state diagram.

represents an inner city area, with a combination of straight-road segments, bends, and 90° crossroads. The test begins in mode 4 and before the first bend changes to mode 5 during a one-second interval where the IMU takes control. During the next six seconds, a combined GPS and IMU system is used to guide the vehicle. If the vehicle's position is compared with GPS coordinates, a smooth trajectory is observed. The third straight stretch presents quality loss too and, on this occasion, the GPS mode is 2 at some points. This figure shows two points where the GPS makes serious mistakes that would cause abrupt steering wheel movement, but at these points the IMU system takes control and avoids it. Finally, the GPS signal is changing during 31.6 seconds where cooperative control corrects the trajectory until the fifth bend where the GPS mode becomes 4 again.

This test shows how an automated vehicle position control system with a GPS sensor is improved with an IMU and sensory fusion between GPS-aided IMU. Thus, the

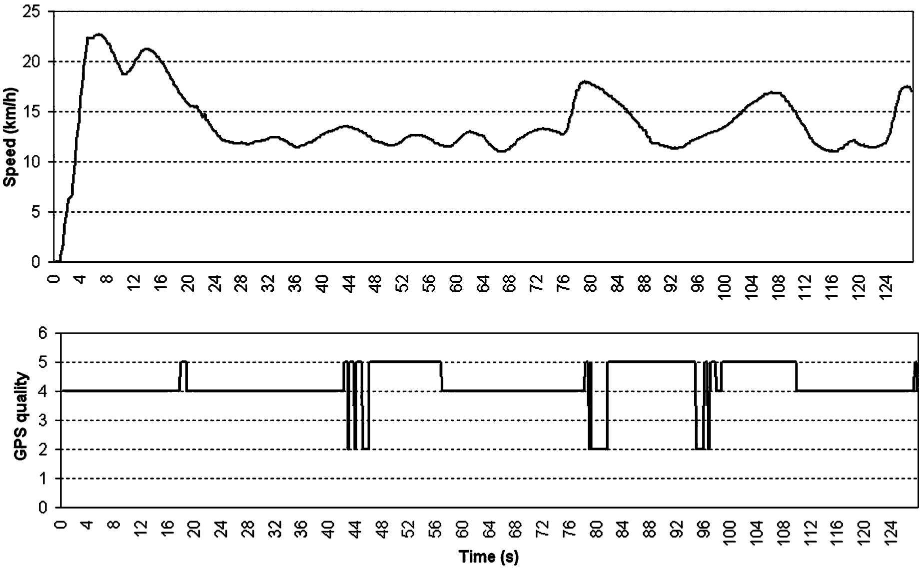


Fig. 5. Speed and GPS quality for the first lap.

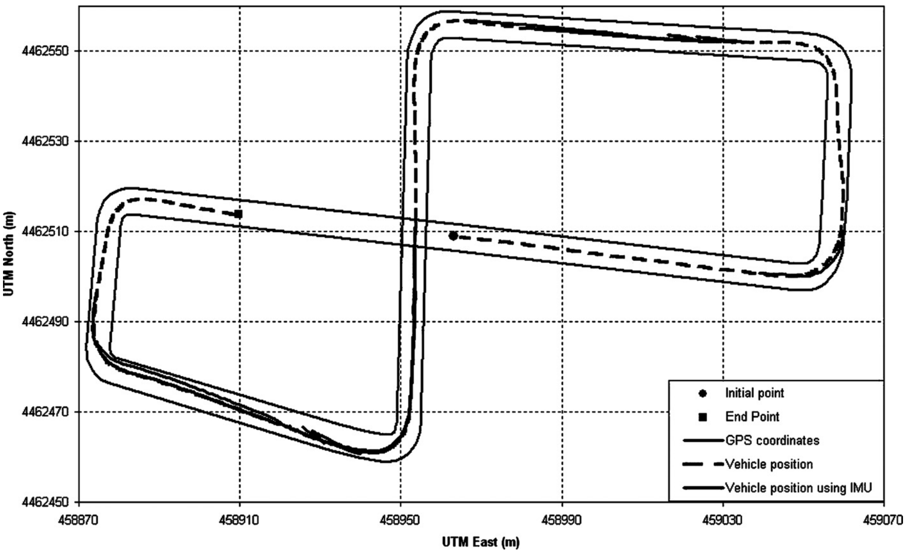


Fig. 6. Test trajectory for quality loss in short time intervals.

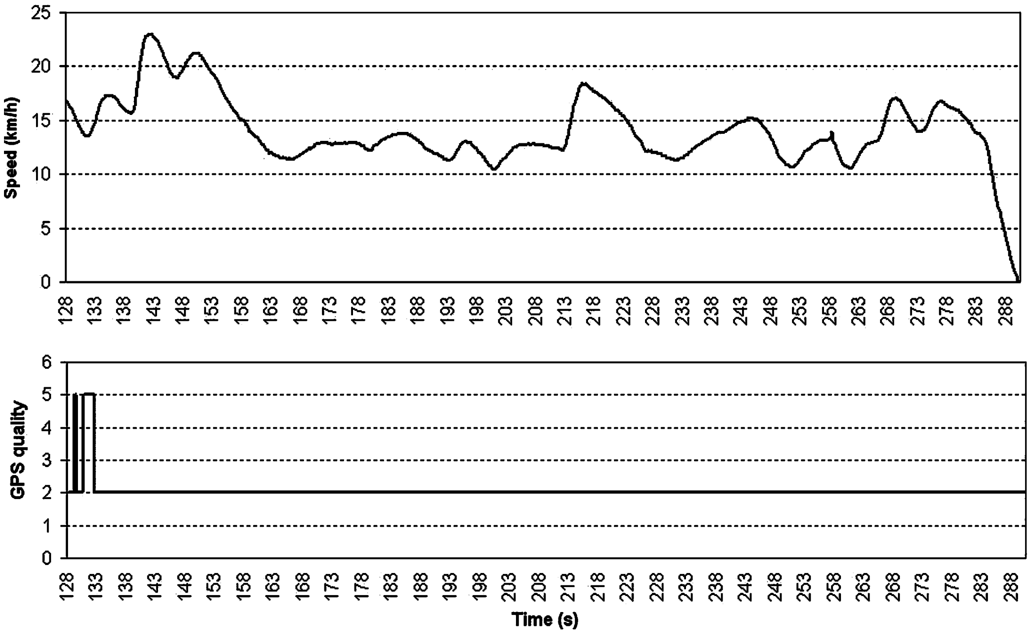


Fig. 7. Speed and GPS quality for the second lap.

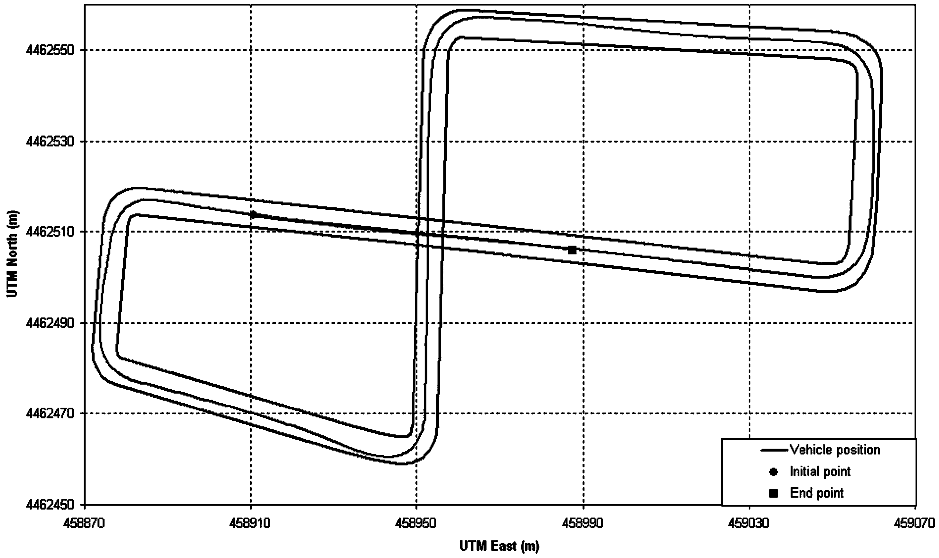


Fig. 8. Test trajectory quality loss for long time intervals.

possibility of smooth control with the addition of an inertial system is proved.

The second part of this test presents the continuation of this route where another lap is covered from the final to the initial point of the route. We present another common situation: quality loss during long time intervals.

Figure 7 shows the speed, whose values are similar to the ones obtained in the first lap. During the first 4.6 seconds, GPS quality is changing between modes 2 and 5. After that, it remains always in mode 2 and control with the GPS is impossible. In this situation, vehicle guidance is taken over by the IMU. This test also proves whether it is possible to use the IMU control system by itself for long time intervals.

We can analyze the trajectory in Fig. 8. Along the first straight stretch, the IMU control system drives as well as the GPS control system. Smooth steering wheel movements can be observed in bend stretches. This test shows good behavior during 162 seconds and it demonstrates that automated vehicle guidance in areas without the GPS signal for long time intervals is possible.

5. Conclusions

The use of global-navigation satellite systems applied to automatic vehicles is a powerful technique that enables absolute positioning with a high level of accuracy. However, one drawback of this technique is that GPS signal blocking requires another control system to perform vehicle guidance.

A system based on combining three sensors: two IMU and one wheel is a good solution to take control in the event of GPS signal failure. The resulting test proves how it is possible to drive during long time intervals without another assistant.

Using this system, automated vehicle guidance is possible in city areas without any problem. We have tested our system for up to 5 minutes before the drift is too high.

Furthermore, loss of accuracy during short time intervals due to trajectory interference (e.g., canopy) can be solved by combining the GPS and IMU control system to avoid undesirable steering wheel movements.

It is also demonstrated that IMU error due to drift is bounded. Parameters are reset every time GPS quality changes to mode 4, thereby enabling the vehicle control system to achieve robustness, smoothness, and durability.

Acknowledgements

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