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GPS Augmented Vehicle Dynamics Control

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ABSTRACT

Measurements from a Global Navigation System in conjunction with an Inertial Measurement Unit were recently introduced in different aerial and ground vehicles as an input to control vehicle dynamics. In automobiles this approach could help to further improve braking and / or stability control systems as information like velocity over ground and side slip angle becomes available. This paper presents the technical background, validation through test results and the evaluation of potential benefits of such an “INS/GPS” setup. As a result of the extended measuring capabilities a reduction in braking distance and a more effective stability control becomes possible. The results show an excellent performance that should be exploited in future automotive applications.

INTRODUCTION

The safety standard of today’s automobiles would not be possible without vehicle dynamics control systems that help the driver to maneuver the vehicle even under critical conditions. In addition these systems permit engineers a certain degree of freedom to tune vehicle characteristics to abide by a certain philosophy regarding handling, ride and safety. For the past 25 years these systems grew by number and in performance so that the automotive industry has been moving towards a scenario where vehicle dynamics can be vastly controlled by electronic systems. Even if the task of navigating a vehicle through traffic is still the driver’s responsibility, sub tasks such as stability or longitudinal control are being performed by at least partly autonomous systems. As vehicle dynamic control systems penetrate the automotive world, the inputs to the related controllers have not always kept up with the requirements for a comprehensive controller approach. One very prominent example is the stability control or yaw control system often referred to as DSC, ESP or VSC. No commercially available solution is known that uses the side slip angle as a controller input, which would directly measure the motion that determines driving stability. Instead, all existing systems rely mainly on yaw rate and lateral acceleration. In contrary, GPS based systems provide a more holistic set of information to determine the vehicle’s dynamic state. This technology has been introduced in the aerospace and farming industries, but not yet in the automotive industry. The question arises if and how this technology can be adapted to automobiles to improve existing control systems.

INPUTS FOR VEHICLE DYNAMICS CONTROL SYSTEMS

The history of vehicle dynamics control systems began with the introduction of the first ABS controller in passenger vehicles in 1978 [1]. Wheel speed sensors served and still serve as the main input to this brake control system as they measure the angular velocity of the wheels and help to prevent wheel lock-up that would sacrifice lateral maneuverability. The next major step in the history of vehicle dynamics control systems was to use a yaw rate sensor in conjunction with a sensor for lateral acceleration, enabling the stability control system that is commonly called DSC, ESP, or VSC. In this case, the controller influences the yaw rate of the car mainly by braking individual wheels so that a compensating yaw moment is generated. These systems were introduced to passenger vehicles in the mid 1990’s [2] and can today be found in almost any vehicle category. The mentioned sensor inputs (wheel speeds, yaw rate and lateral acceleration) are still the only signals to measure the horizontal vehicle motion (see figure 1).

This still holds true even for the latest achievements in vehicle dynamics control, which are active steering systems [3, 4] that show a significant step forward towards the often discussed drive by wire applications. However, the performance of the mentioned control systems could be further improved if additional inputs to measure vehicle dynamics were available [5]. The following examples are the most important ones:

- absolute velocity over ground
- side slip angle
- wheel forces
- adhesion coefficient tire / road surface

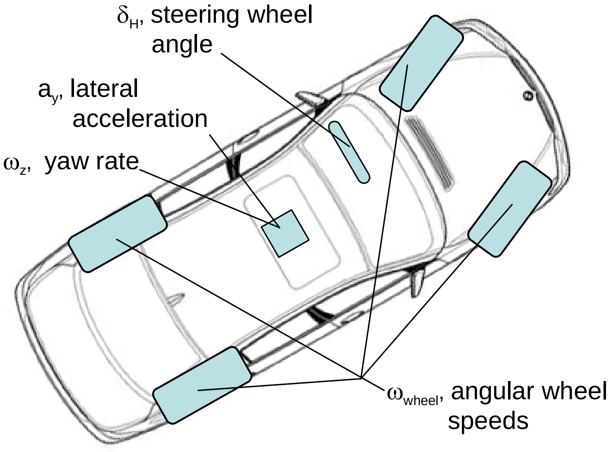

Figure 1: Inputs to vehicle dynamics control systems

This information would help to derive more comprehensive information on the vehicle motion and the interaction between the tire and road surface. This potentially enables controlling the vehicle as an overall system and also the individual wheels as the most important sub-system more accurately and effectively. Today, it does not seem feasible to monitor the interaction between the tire and road surface reliably enough for series application due to too many unknown parameters such as different tire characteristics and road surfaces [6]. However, absolute velocity over ground and sideslip angle are more likely to be measured reliably enough even in a production vehicle and at reasonable cost. On the one hand, ideas have been discussed that promise absolute velocity information based on radar, optical or acoustic technology [7, 8] that could be implemented into production vehicles with an adequate effort. On the other hand, recent achievements [9, 10, 11] show that GPS based technology can be used to measure the motion of any object in space comprehensively and accurately enough for dynamics control. As this technology grows in the field of farming vehicles and also in unmanned aerial vehicles (UAVs), it seems to be reasonable to investigate if and how the automotive industry can benefit from this approach.

GROUND AND AERIAL VEHICLE DYNAMICS & CONTROL

From a macroscopic view the control tasks for ground and aerial vehicles seem to be very similar: In both cases the objective is to transport passengers and / or cargo with a vehicle that is not guided by rails or other. Also, in both cases the transport task shall be performed in a safe, efficient and sometimes at least partly autonomous way.

An obvious difference is that all six degrees of freedom can theoretically be controlled independently in an aircraft whereas the driver of a ground vehicle typically controls just the horizontal motion with the vertical dynamics being coupled by the vehicle's transfer function and the road characteristic (see figure 2).

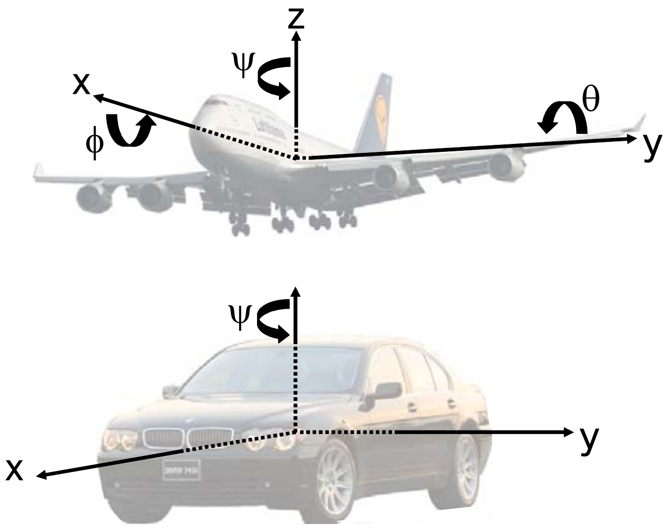

Figure 2: Degrees of freedom for an aircraft and automobile that can be controlled independently

Nevertheless, researchers and engineers have been trying to convey synergies in either direction among the two groups of transportation systems with the field of human machine interaction (HMI) being one very good example [12]. In this field the drive-by-wire concepts are often referred to as a profound source for synergies between these industries. However, the basic by-wire idea in the sense of replacing mechanical links between the controls and the actuators does not automatically convey from aerospace to ground vehicles due to different cost, package and safety reasons. Especially automotive applications tend to stay with more traditional, purely mechanical or hydraulic systems that use electric/electronic add-ons for control purposes. Nevertheless, there seem to be several opportunities where similarities can be shared in the fields of sensor and controller aspects to improve control system in either field.

CHAIN OF DYNAMICS, POSSIBLE INTERACTIONS

Precise determination of dynamics is equally essential to control aerial as well as ground vehicles, even if the individual motions are different. This general task can be analyzed on three different levels along the chain of dynamics "acceleration – velocity – displacement" (see figure 3). Technically it is just possible to influence acceleration directly while velocity and position (displacement) can only be influenced indirectly. This is even more important to realize as the latter are essential for navigating any kind of vehicle through any kind of situation. Figure 3 shows how forces work along the chain of dynamics through acceleration, velocity and eventually displacement. Consequently, acceleration needs to be measured to determine the input into the dynamic chain. For this purpose, solid state accelerometers have been developed for quite some time and are part of many control systems today, whereas positioning is still an evolving technology within the field of transportation, with laser / radar ranging devices and RF navigation services as typical solutions. Velocity however is still very difficult to measure precisely, especially when undisturbed information on absolute velocity over ground is required. Nevertheless, this physical value is very significant for vehicle dynamics as it relates to vehicle handling and safety. Consequently the key to the next stage in dynamics control systems is velocity measurement with magnitude and heading. It becomes clear that this task should be addressed to accomplish further improvement in automotive control systems. Synergies among different fields of transportation should be evaluated to realize these potentials.

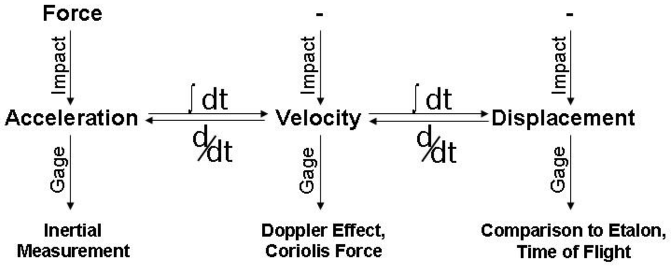

Figure 3: Overview on the chain of dynamics

SATELLITE BASED VELOCITY MEASUREMENT

Among the different transportation systems there is a variety of solutions in use to measure velocity. In aircraft for instance the following examples have been applied for decades but most of them could not be used in automobiles (main impediment for deployment in parenthesis):

- pitot pressure (wind)
- laser based systems (cost, false echoes, dirt)
- radar based systems (cost, false echoes)

With the introduction of Global Navigation Satellite Systems (GNSS) such as GPS or GLONASS there has been an ubiquitous reference system available that is not only used for positioning but also to determine the velocity of a vehicle. To do so, the Doppler Shift in the received satellite signal can be calculated which gives the opportunity to measure velocity with respect to a basically space-fixed reference system at an accuracy that is sufficient for most vehicle dynamics control tasks. In addition, information from GNSS can also be used in conjunction with inertial measurements to give very accurate information on the overall dynamics of a vehicle which could be very beneficial to feed navigation and control systems. Recently, very cost effective solutions have been presented that get used in “Unmanned Aerial Vehicles” (UAV) such as miniature exploratory + monitoring aircraft [9] and meanwhile with a similar approach also in “Unmanned Ground Vehicles” (UGV) as well as farming vehicles [10]. It can be expected that these products will find their way to manned aircrafts which can already be observed with some products for small planes [11]. It needs to be investigated if and how the solutions that are used in UAVs, UGVs and farming vehicles would fit automotive requirements.

INERTIAL NAVIGATION COMBINED WITH GPS

INS/GPS applications seem to be the solution for a variety of systems in aerial and ground vehicles so that this technology deserves a closer look regarding it’s applicability to automotive control tasks. An Inertial Navigation System / Global Positioning System (INS/GPS) consists of two branches that complement each other very effectively. Such a system can be used in two different ways (figure 4). This is either an enhancement for the positioning task or the enhancement for the dynamics measurement with focus on attitude. The farther application will not be further-evaluated in this paper but the latter seems to be very beneficial to measure speed over ground and side slip as already mentioned before.

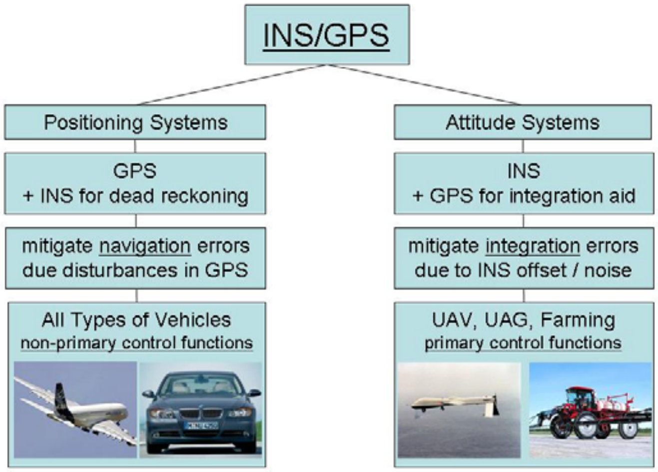

Figure 4: INS/GPS for different vehicle applications
UAV – Unmanned Aerial Vehicle
UGV – Unmanned Ground Vehicle

The inertial navigation system typically comprises accelerometers and gyros to measure the vehicle’s motion on the level of accelerations and angular velocities. As discussed earlier, these measurements are not sufficient to monitor the vehicle’s motion comprehensively. Integration over time would be a solution to gain velocity and heading information, but in practice this approach is highly susceptible to noise and sensor offsets.

Since GPS, the GNSS service operated by the US Department of Defense, is the most common solution for satellite based global positioning, it is the one to be used in applications discussed here. GPS consists of 24 satellites at an approximate altitude of roughly twenty thousand kilometers in space transmitting pseudo random code signals that are decoded in a terrestrial receiver unit. As the positions of the satellites are known and the time of flight for the signal can be determined, it is possible to determine the distance from the transmitting satellite to the receiver. According to the basic principles of triangulation, three different satellites are needed to calculate the receiver's position. Since time synchronization of the satellites and the receiver cannot be guaranteed, at least four satellites are needed in practice [13]. In addition to positioning, the frequency of the received signal can be used to get information on the velocity of the receiver relative to a certain satellite. As the pseudo random code for commercial applications is broadcasted at a specific carrier frequency (e.g. 1.57 GHz) and the receiver / vehicle moves relatively to the satellite, the received signal has a slightly higher or lower frequency due to the Doppler Effect depending on whether the two are moving towards or away from each other. If at least four signals from different satellites are processed, the velocity information becomes a characteristic vector in space. Finally it is even possible to calculate the real velocity over ground with an accuracy of about 0.01 km/h [14].

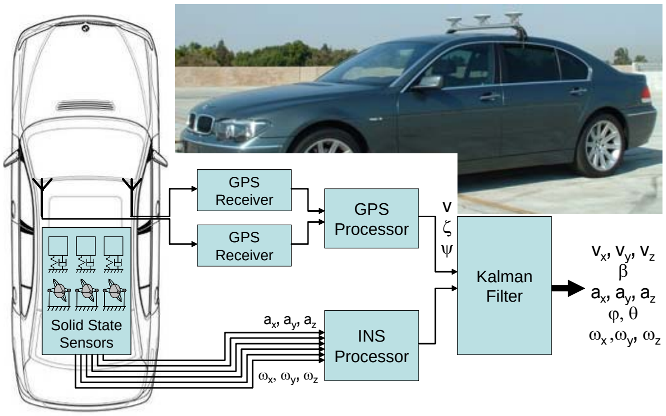

Figure 5: INS/GPS basic setup for automotive evaluation

Figure 5 shows the basic concept of an INS/GPS setup. A typical setup measures three-dimensional acceleration as well as three-dimensional angular velocity through the INS part while absolute velocity, heading angle and attitude angle are measured through the GPS branch [14]. It was mentioned before that velocity v and heading ζ can be derived through the Doppler Effect from the GPS signals; for the attitude information however, an additional effort is necessary. Therefore, the positions in space of three points on the vehicle need to be determined so that the attitude angle can be calculated. Consequently, attitude is measured by placing three GPS antennas in different locations on the vehicle. In order to maximize the accuracy, the antennas need to be as far apart from each other as possible and carrier phase differential techniques should be used to compute the individual GPS signals [14]. Consequently three individual antennas / receivers would give the complete three dimensional orientation of the vehicle plane in space. For automotive applications it is generally sufficient to use two antennas that are mounted at a reasonable distance ($\geq$ 1.0 m) with respect to the horizontal plane and a dual receiver system to calculate the yaw angle ψ. Finally, in order to get side slip angle β, the difference of ζ and ψ needs to be calculated (see also figure 6):

$$\beta = \zeta - \psi$$

These measurements can be very beneficial for automotive control systems such as ABS, traction / stability control or active steering systems. The challenge however remains the update rate offered by GPS receivers (1 to 50 Hz) typically not being sufficient for vehicle dynamic control tasks (about 1 kHz required). That is why the INS and GPS branches complement each other so well. The INS part permits high update rates (solid state sensors work well above 1 kHz), but suffers from noise and drift problems when integrating signals over time. On the other hand, the GPS part gives very accurate velocity and heading information but only at a relatively low update rate. Consequently, an approach that combines the two branches through a Kalman filter should benefit from the merits of both subsystems, while compromising neither long term stability nor bandwidth [14].

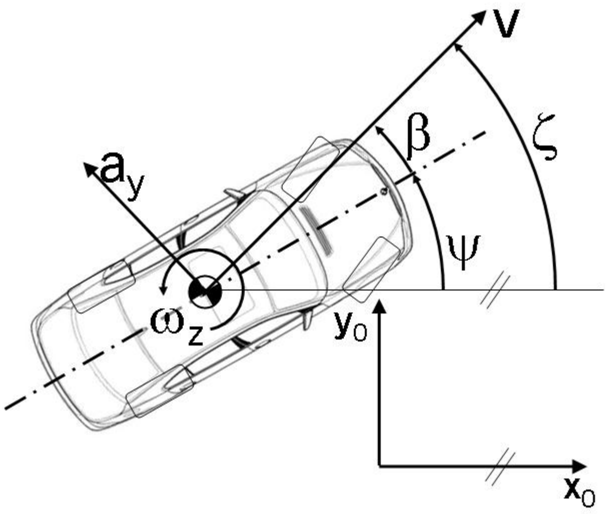

Figure 6: Basic vehicle dynamics measurements

INS/GPS TEST SETUP, SERIES APPLICATION

BASIC CONFIGURATION

To perform the test maneuvers discussed hereafter, an INS/GPS setup was used comprising solid state accelerometers / gyros from *Analog Devices* commonly used in automotive dynamics control systems and a *NovAtel Beeline* multi receiver GPS system. For the latter, the antennas were mounted on a roof rack at a distance of about 1.0 m apart from each other. The data processing including the Kalman Filter approach was performed with a *MATLAB/Simulink* model running on an *XPC* [14, 15]. In addition the setup was connected to the vehicle's controller network (CAN) to log data such as steering wheel angle, ABS reference velocity or brake pressure. In the maneuvers discussed here, the INS/GPS approach was only used as a measuring setup without any feedback for closed loop control.

SYSTEM INTEGRITY

For future steps it needs to be evaluated which systems should be connected to an INS/GPS setup bearing in mind that performance could be disturbed in case of potential GPS dropouts or outages. Certainly this is a significant limitation, especially when safety critical systems are to use the GPS based inputs. But there are solutions to overcome this GPS inherent challenge; one will be pointed out at the end of this paper in the outlook. In general it is to say that GPS-assistance must only be used to enhance but not to ensure functionality of safety critical systems. The following examples of test maneuvers will show that this is possible as today's control systems operate in a safe way by themselves but can benefit from GPS if available.

PROOF OF FEASIBILITY FOR AN AUTOMOTIVE INS/GPS

Proof of feasibility for an automotive INS/GPS setup needs to cover two steps to check performance as well as practicability. First, the performance of the basic concept needs to be compared to a reference system to prove accuracy and reliability. In this case an optical system, the *Datron V Sensor* from *Corrsys*, was used as a reference for speed over ground and side slip angle. It can be considered as state of the art in vehicle dynamic testing. Second, the proposed INS/GPS setup needs to be tested in various maneuvers and under various conditions to prove the practicability of such a system as well as its benefits for automotive applications.

COMPARISON TO REFERENCE SYSTEM

Figure 7 shows the signals from the optical reference system and the INS/GPS setup at the beginning of an emergency braking at an initial speed of about 120 km/h. In addition to these two signals the reference velocity from the vehicle's ABS controller is shown. It can be found that the displayed velocity signals match reasonably well at normal driving situations prior to the actual braking phase (negative time stamps). The optical system however is to a larger extent disturbed by noise that relates back to irregularities in the pavement and reflections from other objects on the ground. The other interesting insight is the transient behavior at the beginning of the braking phase (0.0 – 0.5 s). Obviously the INS/GPS setup seems to show less of a time lag than the optical system. Even if considering that both systems actually measure a different vehicle motion due to the vehicle's pitch motion (GPS measures the velocity with the antennas mounted on the roof about 1.5 m above the ground and the optical system is mounted on the front bumper about 0.4 m above the ground), the GPS approach detects the edge of the beginning deceleration earlier. In addition, the internal signal processing in both cases is supposed to compensate for pitch and roll. In either case this maneuver shows that INS/GPS gives a velocity signal that has a better signal to noise ratio and is faster than the optical system.

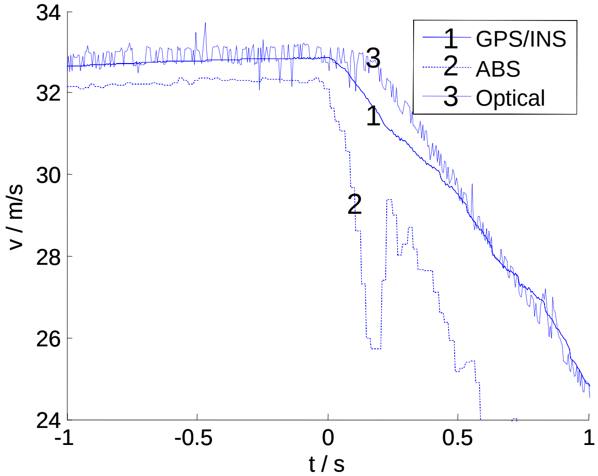

Figure 7: Velocity during an emergency braking situation

In another maneuver, figure 8 depicts a lane change situation at the limit of adhesion on dry concrete and an initial speed of about 100 km/h. The two depicted signals show side slip angle measured by the optical system as well as the INS/GPS setup. It is obvious that the magnitude of the two signals match relatively well (steady state and transient phase) but that there is a time delay of about 0.1 s.

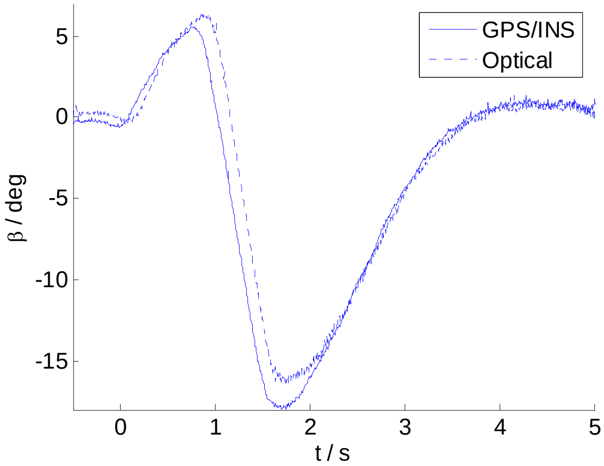

Figure 8: Side slip angle during a lane change maneuver

These two maneuvers show that the information from INS/GPS is less delayed than the optical reference but that the steady state measurements match relatively well. Also, INS/GPS shows a better signal to noise ratio than the optical system.

ASESSMENT OF TEST DATA

In order to evaluate the INS/GPS approach for automotive use a variety of tests were performed. They included steady state and transient maneuvers like: standing still, accelerating, straight driving, step steering, steady state cornering, lane changing, sinusoidal steering, braking in a turn and hard braking. In order to cover a variety of test conditions the tests were carried out under different road conditions (dry, wet, snow, ice), with different tires (summer, winter) and different loads. In general, the INS/GPS setup generates consistently reliable and clear information on the vehicle motion. In fact, from the nature of the approach, no susceptibility to environmental conditions were expected since INS/GPS does not depend on vehicle characteristics or road conditions at all but it needs to be evaluated whether there are any sensitivities due to certain parameter changes. In order to give an insight into the performed tests, the following examples prove the fidelity of the setup and show the benefit of such a system for automotive use.

STRAIGHT DRIVING, EMERGENCY BRAKING

Figure 7 shows good results for the velocity information during the straight driving phase prior to the braking section ($t < 0$). The importance of an accurate velocity reading becomes even more obvious during the braking phase ($t > 0$) as the information from the ABS controller, which is derived from the wheel speed sensors, is very much affected by large longitudinal wheel slip. In this case the INS/GPS setup serves as a very viable input to control systems as it is a non-contact measurement and does not rely on certain assumptions concerning vehicle or tire characteristics.

LANE CHANGING

Figure 8 proves the capabilities of the proposed setup during the transient phase of a lateral maneuver. It can be found that the data recorded by INS/GPS tracks the horizontal vehicle motion accurately and gives valuable insight into the vehicle's dynamics. It reveals the initial counter swing at the beginning of the sideward motion (0.0 – 0.2 s), the yield towards the (positive) side slip maximum (0.2 – 1.0 s), the very consistent counter swing that generates very significant side slip (1.0 – 1.8 s) and finally the stabilization phase while returning to low side slip angles (1.8 – 4.0 s). It is important to note that the side slip signal returns to zero at the end of the lateral motion (> 4.0 s) which emphasizes the fidelity of the approach as no signal drift is apparent.

QUASI STATIONARY CORNERING

In this maneuver the vehicle speed was increased very slowly while the steering wheel angle was fixed at 270°. The test was performed on dry concrete beginning from standing still ($a_y = 0$) to the limit of adhesion which limits the lateral acceleration to about 9 m/s^2. Figure 9 shows the side slip measurements over lateral acceleration proving that INS/GPS works well at all levels of lateral acceleration. The vehicle's motion can again be tracked very accurately, revealing the side slip angle decreasing with increasing vehicle speeds. This again shows the ability of the proposed system to provide very accurate measurements that would be useful for control systems. Here it also gives a very valuable insight into the specific vehicle performance that would even be helpful to fine tune a vehicle's characteristic dynamics.

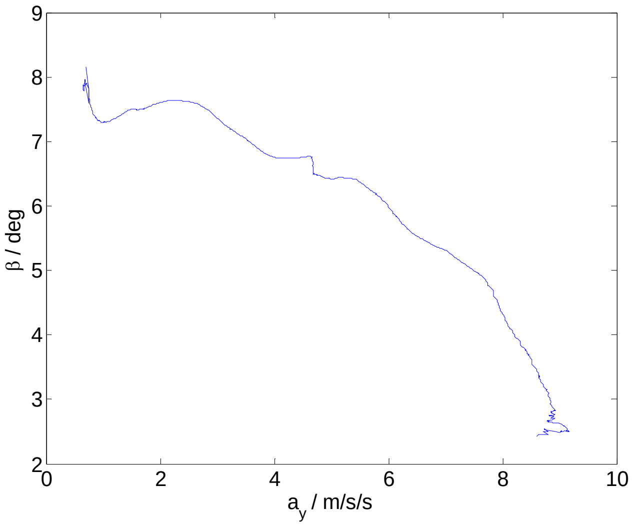

Figure 9: Side slip angle, quasi stationary cornering (signal filtered w/ moving average 100 ms)

SINUSOIDAL STEERING

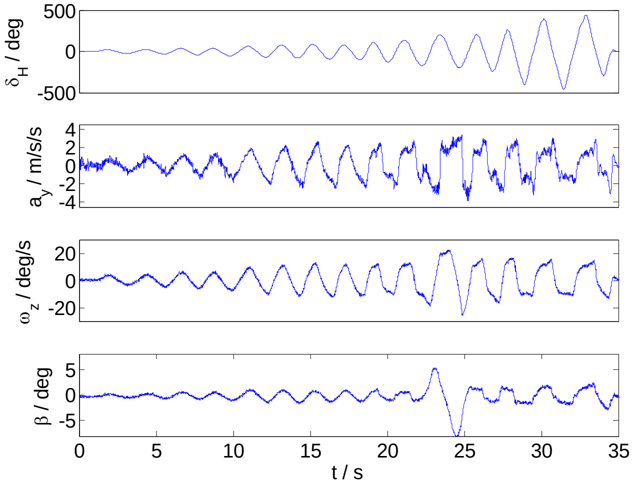

Figure 10: Signals during sinusoidal steering

The maneuver depicted in Figure 10 shows a 0.5 Hz sinusoidal steering input with increasing amplitude at an initial speed of about 30 km/h on an icy road surface. The INS/GPS setup tracks the vehicle motion very accurately again. Starting with the linear region followed by the non-linear region of the vehicle dynamics it shows that the vehicle's transfer function eventually becomes inconsistent as the tires reach the limit of adhesion ($t > 20$ s). The other measurements, lateral acceleration and yaw rate, do not show this inconsistency that explicitly. This is another important example for the INS/GPS setup being a very valuable input for control systems or even vehicle dynamics testing.

APPLICATION / OUTLOOK

BENEFIT FOR AUTOMOTVE APPLICATIONS

The benefit of INS/GPS for automotive applications can generally be summarized as measuring velocity over ground and side slip angle with an accuracy and reliability that permit use in vehicle dynamics control. The following two examples will explain the benefits for control systems in more detail.

EXAMPLE 1: ABS CONTROL

In addition to the before mentioned aspects, figure 7 also shows the challenge that needs to be addressed in production vehicles to calculate the reference velocity in an ABS controller. As ABS increases, retains or decreases the individual brake pressure depending on the current wheel slip and angular acceleration [16], true speed over ground v_{Gnd} is helpful if not essential to monitor wheel dynamics. As discussed earlier INS/GPS offers the opportunity to measure true speed over ground so that it becomes possible to accurately calculate longitudinal slip S depending on the angular wheel velocity ω_{wheel}:

$$S = (v_{Gnd} - R \times \omega_{wheel})/v_{Gnd}$$

It needs to be clarified that the wheel radius R is not exactly known, but it can be estimated during phases of negligible traction forces. The other parameter that can be estimated through observation is the specific slip at which the traction force reaches its maximum. In both cases measuring true speed over ground would be especially helpful to identify those tire characteristics.

The following evaluation shows the advantage of an ABS approach using true speed over ground as an input compared to a conventional ABS that computes the reference velocity from the wheel speed sensors. For this comparison it is assumed that wheel slip at which braking force reaches its maximum is known so that the wheel can be controlled accordingly which should result in an optimized stopping distance.

Figure 11 shows simulation results of the two discussed ABS approaches revealing the difference in stopping difference as well as the overshoot velocity. The conventionally controlled vehicle still moves forward at a speed of about 7 m/s when the one with a GPS augmented braking system has come already to a stop. Various simulations show a potential of 5-10% shorter stopping distance through the proposed setup with INS/GPS compared to conventional ABS layouts.

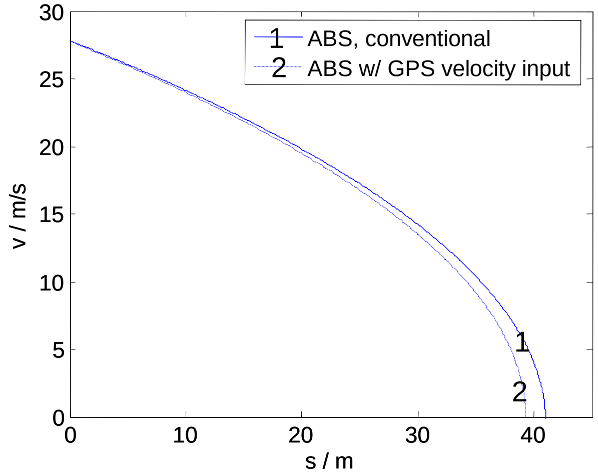

Figure 11: Velocity over distance during an emergency braking for two different ABS layouts

EXAMPLE 2: YAW CONTROL

Figure 12 depicts a situation where the vehicle enters an unstable situation after a step steer input where the side slip angle does not settle on a certain level. In this case the tires reach the limit of adhesion while the vehicle is maneuvered on an icy surface and the lateral acceleration reaches 1.7 m/s^2.

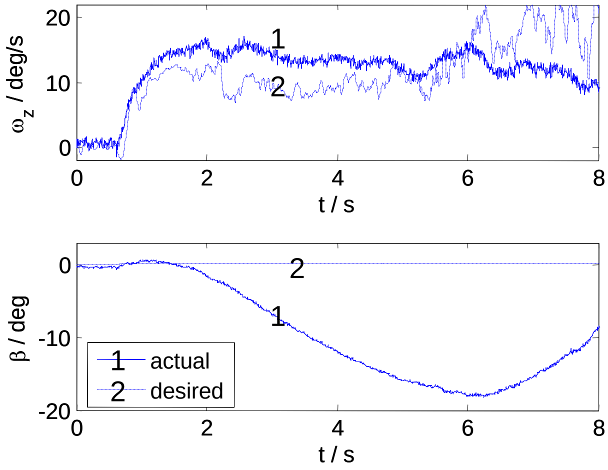

Figure 12: Step steer on icy surface at 40 km/h

The yaw rate (upper diagram in figure 12) does not show the instability very clearly as the actual signal just slightly exceeds the desired rate ω_{des} which can be derived from lateral acceleration a_y and velocity v assuming that the vehicle moves in steady state conditions:

$$\omega_{z\ des} = a_y / v$$

The side slip angle (lower diagram) however shows very obviously that the vehicle moves in an undesired mode as the measurement deviates increasingly form the desired value β_{des} that can be calculated through a simplified vehicle model (e.g. bicycle model) from steering wheel angle δ_H and velocity v:

$$\beta_{des} = f(v, \delta_H)$$

In this maneuver the actual side slip angle should settle on a constant level after the transient phase as v and δ_H do not change any further. Figure 12 shows very clearly that this requirement is not fulfilled as the vehicle moves in an undesired mode and it would need to be stabilized by intervention of a control system. Conclusively, this maneuver proves that side slip angle is essential to detect an unstable situation. It becomes obvious that side slip angle shows instability much more transparently than yaw rate, which is typically being used in today's stability control systems like ESP or others. This understanding is fundamental for the design of vehicle dynamics control systems [17].

OUTLOOK: INTEGRATION INTO CONTROL SYSTEMS

INS/GPS needs to be further evaluated for automotive applications since it has potential being used as the central unit to measure vehicle dynamics. It would be very beneficial to integrate the proposed setup into the network of automotive controllers such as vehicle dynamics control and driver assistance systems. Consequently it would also serve as an essential input for drive by wire systems to come. Of course, any GPS-assisted system needs to be designed such that a possible GPS outage (e.g. satellite downtime) or even more likely GPS dropouts (tunnels, urban canyons…) do not compromise safety. Therefore, the functions that rely on GPS information must have a backup, which could be realized using the inertial sensors only. This basically means degradation to today's sensor inputs so that the control systems are still able to operate with a limited set of measurements [15]. Future work needs to address these issues and should focus on failsafe system layout as well as solutions to mitigate the impact of temporary GPS dropouts. In addition, information from INS/GPS could be used to gain virtual signals that cannot be measured directly but estimated from the vehicle motion if the inputs such as steering, engine / brake torque are known. Some early research gives already an outlook at the estimation of tire characteristics to help preconditioning e.g. stability control systems [15]. First results on this approach look promising as the distinction of cornering stiffness for summer and winter tires seems to be possible. It needs to be evaluated if such an idea could be turned into a series application.

CONCLUSION

It has been discussed that INS/GPS can be used as a relatively inexpensive but effective setup to measure dynamics of aerial or ground vehicles. It is currently introduced in UAVs and is moving towards commercial aircrafts. As such a setup gives very accurate velocity and heading information, it could be used in automobiles to measure velocity over ground and side slip angle. In this regard the prototype INS/GPS unit presented in this paper reaches and even exceeds the performance of test equipment for vehicle evaluation commonly used today. As the technical setup can be realized at reasonable cost it seems possible to apply the presented approach to production vehicles to further improve dynamic control systems. The result would be a centralized measurement unit that provides not only today's dynamics data but also additional information for stability and braking control. In order to move the proposed setup towards series applications, basic problems related to the GPS integrity need to be addressed.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ABS	Anti-Lock Braking System
CAN	Controller Area Network
DSC	Dynamic Stability Control
ESP	Electronic Stability Program
INS	Inertial Navigation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
UAV	Unmanned Arial vehicle
UGV	Unmanned Ground Vehicle
VSC	Vehicle Stability Control

a	acceleration
H	hand (e.g. steering wheel angle)
S	slip
v	velocity
x	longitudinal coordinate
y	lateral coordinate
z	vertical coordinate
β	side slip angle
δ	steering angle
φ	roll angle
θ	pitch angle
ω	angular velocity
ψ	yaw angle
ζ	heading angle