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Addressing the availability and reliability of satellite-based vehicle positioning methods in a future connected-vehicle environment for the purposes of riding assistance systems

Abstract

Research question / Starting point for investigation:
The application of Autonomous Emergency Braking on Motorcycles (MAEB) relies on the solution of a number of open research questions. The collision represents a dangerous and safety critical event to be avoided with high priority. However, focusing on the triggering methods, the recommendation from literature is to deploy automated braking only when the collision becomes inevitable, the priority in this initial phase of development being the avoidance of false positive activation. The identification of Inevitable Collision States (ICS) adopting existing car technologies is particularly challenging though, due to the tilting and nimble nature of powered two wheelers.

Due to injury and even fatality risks in case of wrong activation when no collision takes place and in case of missing activation when collision takes place, according to transportation and standardization community MAEB has to be considered a "safety of life" application. Safety requirements therefore imply the use of accurate but above all reliable positioning system - a characteristics called “integrity”. Satellite navigation systems are an interesting mean to provide accurate, reliable and safe positioning service to transportation systems. Satellite navigation faults need to be accurately monitored and mitigated since they can cause both wrong activation in case of no collision and missed activation in case of collision. A safety analysis identify the risk to be associated to each safety critical events in terms of maximum probability of occurrence. Given these conditions, the MAEB, the satellite navigation receiver and each part of the system need to be designed to satisfy the associated risk.

In this paper we analysed the possible application of satellite technologies as resource for the identification of accurate and safe relative position of vehicles in emergency situations to support the MAEB system.

Methods:
We combined the knowledge on MAEB with recent updates on global positioning and performed a review of state of the art and future methodologies for reliable and safe geo-localization in transportation. The problem of safety was addressed considering that the positioning is obtained with a certain accuracy and a given uncertainty: the user is located within a given region and with a given probability. There is then a risk for the user to be

outside the high-likelihood region. This risk needs to be properly quantified, controlled and mitigated in a safety application such that of MAEB.

Results:

The outcome of the review was a set of technologies and methods suitable for MAEB application, including localisation based on satellite navigation systems augmented with high accuracy and integrity services. Last frontier of GNSS pushing the boundaries of this technology is the use and integration with 5G communications to exploit the mutual positioning, in which each entity assesses its position relative to the others.

Impacts / Effects / Consequences:

Our results showed that a proper combination of current technologies may be used to build a cooperative transportation system suitable for MAEB applications.

Keywords: Active safety, Autonomous emergency braking, GNSS, system integrity, cooperative transportation.

Introduction

Road crash statistics in Europe clearly show that in the last decade a substantial plateau has been reached in terms of motorcycle and moped fatalities [1]. Further improvements are strongly warranted. These may be obtained introducing safety systems, including novel technologies for powered two wheelers that have not been feasible so far and that may benefit from the availability of high accuracy data such those derived from newly available global satellite systems.

Among the possible list of safety systems, autonomous emergency braking was predicted to be effectively applicable for motorcycle safety [2]. The analysis of real world motorcycle crashes suggests that MAEB may be relevant to a percentage of cases that ranges from approximately a fourth, up to more than a third of the cases [3], [4], with an estimated speed reduction at impact of up to 10 km/h. Such values are obtained assuming an activation time of approximately 600 ms and using a target automatic deceleration of 3 m/s2 (in case of no braking action from the rider).

The application of Autonomous Emergency Braking on Motorcycles (MAEB) relies on the solution of a number of open research questions that include the feasibility of an accurate detection of the triggering conditions [5], the feasibility of the automatic decelerations in realistic riding conditions [6], the threshold deceleration and jerk that can be safely applied [7], the quantitative assessment of the potential injury reduction that slowing down the PTW may have prior to crash [8], just to name a few.

Focusing on the triggering methods, the recommendation from the literature in the field of motorcycle safety systems is to deploy automated braking when the collision becomes physically inevitable, i.e. the point in time at which no combination of manoeuvres from the ego motorcycle and the opponent vehicle may prevent the crash anymore, assuming vehicle accelerations of up to 1 g. It was shown that this criterion is typically fulfilled less than 600 ms ahead from actual collision, thus posing a tight limit in the time available for the automatic system to take an action and produce an effect. One motivation of such approach was to maximise the user acceptability for MAEB: it was shown that motorcycle riders hardly accept a system that takes over the control of the vehicle [9], but in this case the system intervenes only when the complete crash avoidance is beyond the possibilities of the rider/driver’s avoidance actions. A slight relaxation of this criterion was proposed in [8], by considering a lower threshold for the extreme accelerations used to compute the set of possible avoidance manoeuvres. Another reason for adopting this triggering approach is related to the liability of manufacturers, as with different approaches system developers may hardly prove that MAEB was not a contributing factor of any crash event involving MAEB activation.

The triggering criterion is clearly a critical aspect of MAEB. A correct MAEB intervention may reduce the likelihood for the rider to sustain fatal injuries [8], whereas with a missed activation (misdetection) the system fails to deliver its safety contribution, and any wrong activation (false alarm) in non-critical riding situations may introduce an undesirable crash risk with a probability of causing harm to the user.

Notwithstanding the possible different thresholds set for the avoidance manoeuvres, the identification of Inevitable Collision States (ICS) on a motorcycle via existing passenger car sensors is particularly challenging, as it was well documented from previous research [10].

In this paper we analysed the possible application of satellite technologies as resource for the identification of accurate relative pose of vehicles in emergency situations for the purposes of MAEB. We combined the latest knowledge on MAEB with recent updates on global positioning and performed a review of state-of-the-art and future methodologies for reliable and safe geo-localization in transportation.

First, a state of art overview of satellite navigation systems will be provided focusing on the wide range of new services and systems offered by Europe, China, Japan, Russia and other countries in addition to the well-known Global Positioning System (GPS) of the United States. Then, the technical characteristics and driving performance factors for supporting MAEB applications will be presented, including deterministic versus probabilistic positioning, the discretization and resolution of the collision region, the refresh rate of the positioning and finally the integrity of the service.

Global Navigation Satellite Systems

The scenario of satellite navigation has rapidly evolved in the last years. After 25 years of monopoly of Global Positioning System (GPS), a military American system, several countries decided to become independent from US government for their civil transportation service (in particular aviation) and started developing autonomous and independent systems. In particular, the European Commission developed Galileo, Russia modernized its existing system GLONASS, and China developed BeiDou. Nowadays ground users have signals from more than hundreds of satellites to be used to locate themselves on the earth. This new worldwide service is called Global Navigation Satellite System (GNSS).

Advantages with respect to other positioning systems are the availability of the signals free of charge since the services are provided for civil use and protected by public institutions. Besides thanks to the miniaturization of the hardware, the cost of one chip and one antenna reduced so drastically that GNSS chips are integrated in all smartphones nowadays.
The development of new constellations of satellites implied the use of additional signals, a frequency diversity and a widening of the bandwidth. This characteristic is of essential

importance, since navigation signals are affected by several error sources which need to be modelled and corrected before assessing the user position. One of these sources is related to the propagation through the ionosphere which introduces a signal delay. In reality the dispersion through the ionosphere has a deterministic dependency on the frequency and if the user can measure signals from at least two different frequencies, is able to correct completely the ionospheric errors. This characteristic led a significant improvement in the accuracy obtained with novel GNSS receivers with respect to GPS ones. Thanks to this approach the accuracy evolved from tens of meters to below one meter. However, this achievement may not be sufficient for applications such as MAEB, as it will be explained later in this paper.

To push further the performance and reach higher accuracy, recent systems provide additional augmentation or high accuracy services, that is additional service providing corrections of signals, the so-called differential systems (DGNSS). These services are provided by reference stations on ground in the proximity of the receiver (Real Time Kinematic, RTK, or Precise Point Positioning, PPP) or geostationary satellites (Satellite Based Augmentation, SBAS). Galileo for example will transmit a High Accuracy service, completely free of charge, through the satellite signals [11]. This service, currently under operational testing phase, will provide users with ranging corrections, similar to PPP service, allowing to reach decimetre- and centimetre-level accuracies. In addition, multisensory solutions are exploited and needed when GNSS signals are masked, as for example in urban canyons. The receiver uses additional local sensors to “coast”, that is to compute temporary solutions until the next satellite signals are tracked again. The position obtained in this case degrades during the coasting interval, usually linearly over time and proportionally to the drift characteristic of the inertial sensor. Over few minutes the degradation is often considered acceptable and the solution still accurate and reliable for applications such as navigation systems. For MAEB applications, the time span in which coasting may offer acceptable results should be further studied, however it could be estimated in the order of a few dozens of seconds assuming the adoption of high quality and expensive sensors or high-accuracy sensor fusion techniques.

Last frontier of GNSS pushing the boundaries of this technology is the use and integration with 5G communications to exploit the mutual positioning, in which each entity assesses its position relative to the others. This allows to have a cooperative transportation system. In an automatic braking system, a minimum exchange of information is needed, such as position of the opponent vehicle and its velocity. In such collaborative system where vehicles exchange raw or processed GNSS data, the dataflow architecture and the allocation of the processing burden should be established in advance.

If the receivers are mounted on the same vehicle, the novel approach can provide an attitude estimation of the motorcycle and enhance the braking system. It is in fact important to consider the dimension of the motorcycle, its orientation and its attitude.

Deterministic vs. Probabilistic approach for positioning

In [12] a method was proposed to assess the fulfilment of the “inevitable collision state” condition, adopting a deterministic approach to solve the complex problem of the identification of the triggering event. As said, the proposed condition for the activation of MAEB (or any other intrusive “last-resort” safety function) stated that no combination of feasible manoeuvres perfomed by the host motorcycle and the opponent vehicle could lead to avoid the imminent collision. The deterministic approach consisted in pre-computing a set of combined manoeuvres at the physical limit of adherence for a set of initial states and check whether or not the collision can be avoided. The initial state assumed that the motorcycle traveled along a straight path with a given speed, and the opponent vehicle was located at a given relative position travelling with a given relative vectorial speed. Such initial state was described via five scalar values: host vehicle forward speed v_{ptw}, opponent vehicle position x_{ov}, y_{ov}, and relative speed components v_{x_ov}, v_{y_ov}. The pre-computing process leads to the identification of a dataset of initial states associated with the binary variable “inevitable collision” assuming the values of either true or false. By simply checking whether the current state is associated with a pre-computed inevitable collision state, the problem of the identification of the triggering event was solved in a deterministic way. Such approach was inspired by the one proposed for passenger cars in [13]. However, this approach is a simplification of a probabilistic problem. In particular, the current state can only be identified with approximation. In other words, the given position and speed of both host and opponent vehicles cornensponding to the initial state is affected by uncertainty that can be well handled in probabilistic terms. Second, it is reasonable to think that some avoidance manoeuvres are less likely to be performed than others. Furthermore, it was shown that a non-professional rider is less likely to perform an optimal braking manoeuvre at the limit of adherence than just braking at lower decelerations in emergency situations [14]. However, this latter aspect goes beyond the scope of the present paper and will be discussed in a future work.

A simple way to move from the deterministic to a probabilistic solution, is to consider more than one state at each time step. In other words, instead of assuming that the computed state describes the actual state with probability 1, the state of each time step is described as a set of possibile states, each one having a probability below 1, the sum of which is not greater than 1. The probability of being in an inevitable collision state is the sum of the probabilities of those states that were associated with ICS using the same method of the deterministic approach as described above.

Discretisation issues

In [12], the initial state was discretized in terms of space, speed, and heading. A spatial grid of 20x20 cm was proposed to locate the geometrical centre of the opponent vehicle. The vehicle speed was discretised with steps of 3 m/s and the relative heading was divided in steps of 5 deg.

Given these assumptions and the fact that these represent the solution of the problem imposes to have this minimum resolution, the GNSS service need to reach centimetre level accuracy, that is include Precise Point Positioning. Such approach may provide adequate accuracy for the identification of both the relative positioning and also the relative attitude. In fact, the heading of the motorcycle may be obtained with one sensor located in the front and one sensor located in the rear of the vehicle. The 5 deg accuracy can be obtained via accurate positioning of each sensor. Considering that a 5 deg rotation of a 2 m long motorcycle corresponds to a lateral displacement of 1 m * sin (5 deg) for each sensor (equivalent to approximately 8.7 cm from the geometrical centre of the vehicle), the localisation accuracy should be again within a few centimetres.

In addition, the situation of the motorcycle imposes strict requirement in terms of continuity of the service. It is in fact not acceptable to have interruption due to satellite masking in urban canyon or tunnels. In this case, multisensory solutions or other solutions (see for example the so called clock coasting [15]) enhance the continuity and availability performance and bridge gaps of the positioning services.

Refresh rate

The minimum operating refresh rate of an inevitable collision state estimation for MAEB can be defined considering a number of parameters, including the pre-crash speeds of the host motorcycle in the pre-crash phase, the typical working frequencies of state-of-the-art braking systems, and the constraints of the vehicle data acquisition system. Previous studies show that the typical pre-crash speed of the motorcycle where MAEB may contribute is in the range between 10 and 30 m/s [3], [8]. State-of-the-art braking systems operate with working cycles in the range between 4 and 10 Hz. When considering for example a host motorcycle speed of 20 m/s and stationary obstacle, together with the recommended spacial grid with 0.20 m of extension, a single step in the grid is covered in 10 ms, which translates in an ideal refresh rate of the state estimation device of 100 Hz. When considering that a typical triggering timing is 600 ms ahead of crash, a refresh rate of 20 Hz in the inevitable state detection would result in a loss of 7% of impact speed reduction at a deceleration of 5 m/s2: from a theoretical value of 11.5 km/h to 10.7 km/h. A refresh rate of 10 Hz or 5 Hz would result in a loss of respectively 17% and 34%.

When the position is not deterministic and the accuracy is taken into account, the user is located in a certain region with a certain probability. The velocity in a GNSS receiver can be estimated through time difference of consecutive positions or throught the doppler shift of the received signals. In both cases also the velocity has a certain probability associated to it. Given these uncertainties, the position and velocities cannot be updated too frequently to avoid that the measurements are degraded and impacted by the inaccuracies of the sensors. The regions in which the users are located must be much smaller than the distance between consecutive positions. Let us image for example to measure the GNSS of a static user. Due to the mentioned uncertainty, the positions will be each epoch different, but within a certain region. If the user starts moving the receiver will be able to provide information on the shift only if it is significantly larger than the uncertainty region. The distance, position and velocity refresh rates must therefore take into account the receiver accuracy uncertainty. Again, if we assume a speed of 20 m/s for the host motorcycle, high accuracy of 3 cm (in terms of radius) is feasible at 100 Hz when High Accuracy PPP is available, as the actual displacement of the GNSS receiever mounted on the motorcycle exceeds twice the radius of accuracy (6 cm) in less than a third of the desider refresh time step of 0.01 s. For a slow opponent vehicle instead, for example with an assumed speed of 3 m/s, this condition is not fulfulled, as the GNSS received mounted in the vehicle takes twice the refresh time step to cover twice the 3 cm accuracy radius. However, in this condition the 100 Hz refresh frequency for the GNSS is not required, as Kalman filter techniques guarantee the required accuracy of the positioning at the desired refresh rate.

Integrity

Due to the risks associated to missing and wrong activations, according to transportation and standardization community MAEB has to be considered a "safety of life" application. Safety requirements therefore imply the use of accurate but above all reliable positioning system - a characteristics called “integrity”. Satellite navigation systems are an interesting mean to provide accurate, reliable and safe positioning service to transportation systems, since the constellation of satellites provides information on the probability of faults within the system and allows the user to assess the risk of having a wrong positioning service and to monitor the constellation itself.
In simple terms, the probability that an initial state in a given riding scenario may lead to a given level of injuries for the rider, say for example, severe injuries represented by MAIS (maximum abbreviated injury score) equal to 3 and above including fatal injuries, is the product of the probability that such state may lead to a crash, multiplied by the probability that in case of such crash the rider may sustain the given level of injuries.

$$P_{MAIS3+F}=P_{crash}*P_{inj\_crash} \qquad (1)$$

In case of MAEB correct intervention (ideal triggering), assuming a $P_{crash}=1$, the likelihood for the rider to sustain severe injuries is reduced, according to the effectiveness of the system η_{MAEB}:

$$P(\text{crash with ideal trigg})_{MAIS3+F}=1*P_{inj\_crash}*(1-\eta_{MAEB}) \qquad (2)$$

When expressing the probability of a correct intervention of MAEB as P_{MAEB} (probability that MAEB actually triggers in an ICS, missed detection probability being $1-_{PMAEB}$) and the probability of a wrong activation (false alarm) P_{FA}, the probability of sustaining severe injuries for the rider in a generic state is expressed by the following:

$$P(MAEB)_{MAIS3+F}=P_{crash}*P_{inj\_crash}*P_{MAEB}*(1-\eta_{MAEB})+(1-P_{crash})*P_{inj\_MAEB}*P_{FA} \qquad (3)$$

where P_{inj_MAEB} is the probability to sustain injuries as a consequence of a wrong activation of MAEB. We may expect that $P_{inj\_crash}>>P_{inj\_MAEB}$, as the former is always associated with a collision with an opponent vehicle, whereas the latter is not necessarily linked with a fall or collision, as MAEB wrong activation by design should be correctly handled by the user in almost every condition [6].
On one side, MAEB introduces the risk of causing a crash in a situation in which the crash probability is low or even approximately zero. However, MAEB is beneficial for the rider in case of a crash as it reduces the likelihood of sustaining severe injuries. When the probability of false alarms is low, together with a high probability of deploying when needed and high effectiveness in reducing injuries, the system is beneficial and worth the development efforts. In this perspective, the characteristic of integrity of GNSS approach for the detection of triggering events is an added value that contributes to achieve the strict requirements of “safety of life” applications.
In the automotive field, the implementation of MAEB would be subjected to ISO 26262. The standard includes a declination specifically designed for motorcycles indicating the main steps (e.g. HAZOP – Hazard and Operability – Analysis) to be performed to identify potentially critical failures and to quantify their consequences in the MSIL (Motorcycle Safety Integrity

Level, derived from Automotive ASIL) risk scale. In particular, the risk level depends on Severity, Exposure and Controllability of the event. Depending on the MSIL, an estimation of the maximum acceptable probability of failure (for example identified as a loss of integrity of the positioning signal) can be obtained and compared with the probability achievable via GNSS.

Conclusions

In this paper we discussed the possibilities offered by satellite-based vehicle positioning methods for supporting the implementation of riding assistance systems and in particular MAEB. Our results showed that a proper combination of current technologies may be used to build a cooperative transportation system suitable for MAEB applications. One interesting advantage of GNSS use for the detection of the relative positions of conflicting vehicles is the characteristic of integrity, which is fundamental for “safety of life” applications such as MAEB.

Open issues relate to the definition of a system architecture with corresponding allocation of the computation burdens and dataflow among vehicles. Another challenging follow up will be field testing the theoretical availability and reliability of the satellite-based geo-localisation in real world settings. For that purposes, special testing protocols will be required, such as the one proposed in the ABRAM project [16] allowing for data collection during the pre-collision phase of emulated real-world motorcycle crashes .

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