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A GNSS Integrity Augmentation System for Airport Ground Vehicle Operations

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Abstract

Global Navigation Satellite Systems (GNSS) are the primary source of navigation data in various ground vehicle applications and have the potential of enhancing accuracy, reliability and affordability of highly automated guidance and control systems in several applications. In airport applications, autonomous ground vehicle operations supported by GNSS can also potentially improve safety ratings by eliminating human error arising from stress, fatigue and boredom. However, the widespread use of GNSS for autonomous ground vehicle operations presents several challenges. One of them is adherence to stringent integrity requirements in all phases of operations, which can be addressed by detecting GNSS signal errors and faults, and alerting the control system/remote operator in a timely manner. An innovative integrity monitoring and augmentation system is presented in this paper that can detect GNSS signal degradations or losses, and provide steering commands to the guidance component in a timely manner. The system is developed by modelling GNSS error sources including antenna masking, signal attenuation and multipath, and assigning appropriate threshold values for generating both caution and warning integrity alerts. The performance of the integrity augmentation system in terms of generating predictive and reactive alerts in a timely manner is validated through a realistic simulation case study performed in a virtual 3-D airport environment. A four-wheeled ground vehicle dynamics model is used to generate the vehicle trajectories and the capability of the integrity augmentation system to successfully detect GNSS errors and respond by issuing timely and usable predictive (caution) and reactive (warning) integrity flags is verified.

Keywords: GNSS integrity augmentation, Autonomous ground vehicle operations,Trajectory planning and optimization.

1. Introduction

In the last several decades, innovation within the automotive sector has been aimed at creating safer, efficient, cleaner and cost-effective vehicles. Recent research is targeted at introducing higher levels of automation, supported by the introduction of autonomous features and increased electrification, targeting the development of All-Electric Vehicles (AEV). In conjunction with the use of electric power trains, automation directly lower the overall carbon emissions associated with ground vehicle operations. In addition to the generation of cost-effective trajectories that fulfill environmental and economic constraints, Mission-Management Systems (MMS) for robotic vehicles are required to fulfill operational objectives including satisfying the Required Navigation Performance (RNP), Required Surveillance Performance (RSP) and Required Communication Performance (RCP). The use of the Global Navigation Satellite Systems (GNSS) for positioning and navigation applications is integral to the successful implementation of several autonomous ground vehicle system concepts and technologies and to fulfil the RNP. However, the accuracy and integrity of GNSS-based navigation is often compromised by various factors including atmospheric errors, signal multipath, Doppler effects and adverse satellite geometries. Differential Global Navigation Satellite System

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(GNSS) receivers measuring carrier-phase to compute position are capable of a high degree of accuracy. However GNSS is subject to various error modes such as antenna masking, signal loss and multipath, which potentially corrupt the data and result in an erroneous position. The probability of error introduced in the GNSS solution requires large error boundaries to be specified for autonomous vehicles to ensure safe-separation. This places large constraints on trajectory planning, which is required to optimize for energy consumption over the trajectory, while obeying the constraints imposed by limited navigation accuracy and integrity. The predictive detection of GNSS error sources can allow minimization of the cost function in trajectory optimization without requiring large separation distances to compensate for limitations in navigation accuracy. GNSS integrity augmentation refers to a suite of methods used to detect GNSS error sources and alert the manned/unmanned system in the event of navigation error exceeding predefined safety limits. Methods used to monitor the integrity of GNSS data include Satellite Based Augmentation Systems (SBAS and Ground Based Augmentation Systems (GBAS). These methods utilize reference receivers to check the integrity of the computed GNSS position, and issue alerts to the user if an error is detected. An alternative means of integrity augmentation for aerial navigation was proposed in [1-4] , known as Aircraft Based Integrity Augmentation (ABIA) which addresses the limitations of SBAS and GBAS. GNSS error sources in ground environments are dominated by multipath and masking, as opposed to error sources in aerial navigation. This paper adapts the ABIA system to ground vehicles in complex environments. GNSS signal propagation in ground environments are analyzed to design an Integrity Augmentation system for ground vehicle MMS. The system assesses GNSS data integrity and raises alerts to the onboard trajectory planning and optimization module and the control station operator as shown in Fig. 1. The timely triggering of integrity alerts enables the system or the operator to initiate preventive measures and/or corrective action such as the generation of alternate trajectories to avoid the detected GNSS fault. The system is developed by modeling GNSS error sources like antenna masking, signal attenuation and multipath, and is designed to operate alongside a trajectory optimization module. The combined functionalities of GNSS integrity augmentation and trajectory optimization supports the optimal usage of space and energy, while maintaining navigation system integrity. A case study is performed on the GNSS-based navigation of an electric ground vehicle engaged in ground operations at an airport. The trajectory of the vehicle through the airport environment is simulated to corroborate the performance of the designed system.

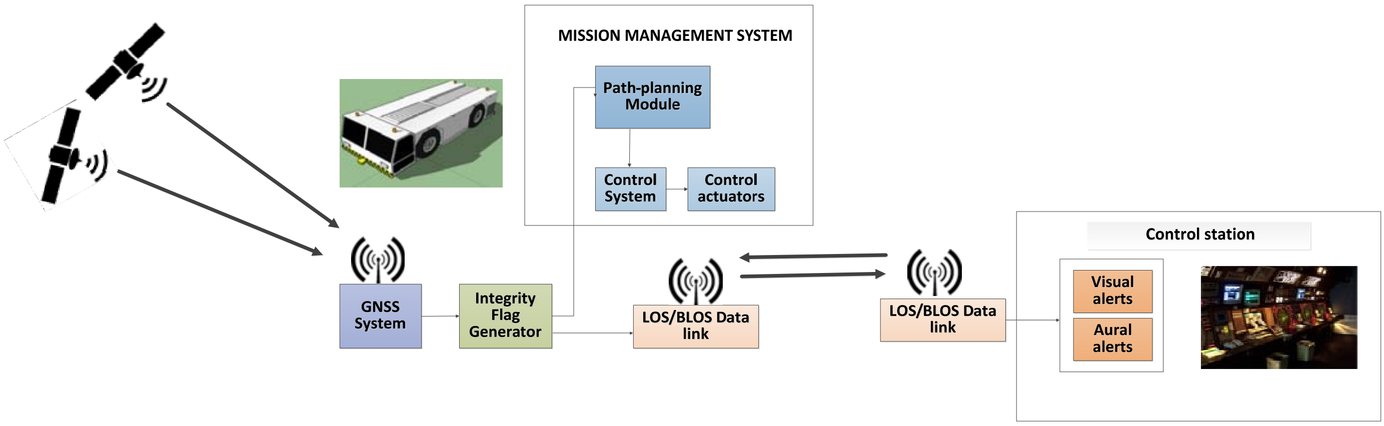


Fig. 1. Integrity augmentation system for autonomous ground vehicles

2. GNSS Integrity Augmentation

System integrity is defined as the ability of the system to detect a degradation of GNSS signals that introduce error into the computed position and/or impact the ability of the receiver to acquire and track the signal. Integrity includes the ability to issue alerts to the vehicles on-board mission management system and to a remote operator (for autonomous vehicles).

The anomalies affecting GNSS integrity are primarily:

1. Signal losses: The strength of the signal can drop below the minimum required power level of the receiver. Although receivers are designed using a link budget that accounts for propagation losses and receiver noise, unmodelled effects can cause deep fades in the signal that impede the receivers' ability to track the signal.
2. Antenna masking: Obscuration of the receiver antenna by objects in the environment potentially decreases the accuracy of the computed solution or prevents the computation of a solution altogether (If a minimum of four satellites are not visible). In ground vehicle navigation, satellite visibility is dictated primarily by the presence of obstacles (buildings, trees, and other reflective surfaces).
3. Multipath: Reflection of GNSS signals from surfaces in the vicinity of the receiver antenna introduces error in the satellite-receiver range measurement, thereby biasing the computed position. Additionally, the reflection(s) attenuate the amplitude of the incident signal.

Conventional Integrity Augmentation (GBAS and SBAS) techniques cannot provide integrity in the presence of local GNSS errors like signal multipath, which dominates pseudorange error in complex ground environments [5]. The proposed system monitors GNSS integrity through algorithms implemented onboard the vehicle itself, rather than relying on external base stations.

3. ABIA System for ground vehicles

The designed integrity augmentation system is illustrated in Fig. 2. The system raises the following alerts in response to a predicted GNSS fault or a fault that has already occurred [1, 2] due to the error sources mentioned in Section 2 :

Caution Integrity Flag (CIF): A predictive alert that a GNSS fault that violates the Required Navigation Performance (RNP) for the current flight is imminent.

Warning Integrity Flag (WIF): A reactive alert that a fault has caused GNSS data to fail to meet the RNP.

The alerts are raised to the Mission Management System (MMS) which then initiates avoidance measures or corrective action. The upper limit on the maximum allowable time between a GNSS fault developing and the Mission Management System being made aware of it is defined as the Time-To-Alert (TTA) [6]. In the context of the proposed system in this paper, the following definitions of TTA are applicable [1, 2, 7]:

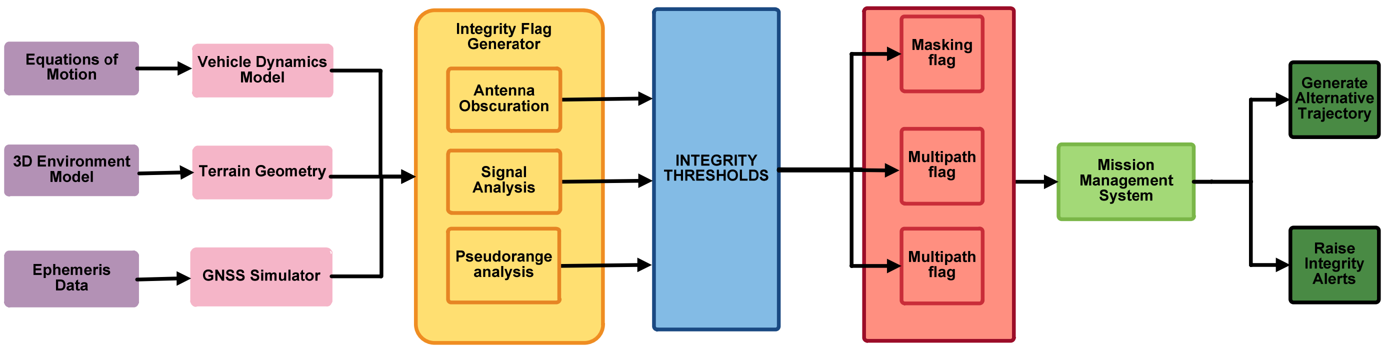


Fig. 2. Modules of the integrity augmentation system

Time-To-Caution (TTC): The minimum time allowed for a caution flag to be produced and provided to the MMS and to the operator before the onset of a GNSS fault resulting in a violation of the RNP.

Time-To-Warning (TTW): The maximum time allowed between the detection of a GNSS fault and the ABIA system providing a warning flag to the MMS and to the operator.

4. GNSS signal modelling

The following aspects of signal propagation are modelled:

4.1. Carrier-to-Noise Ratio

Lowered signal strength due to propagation losses and multipath-induced fading is modelled using the carrier to noise ratio C/N_0 as shown in Equation 1.

$$C/N_0 = EIRP + G_t + G_r - L_f - L_{atm} - N_t \tag{1}$$

where EIRP is the Equivalent Isotropic Radiated Power of the transmitted signal. L_f and L_{atm} are the signal losses in free space and the atmosphere respectively. N_t is the receiver antenna thermal noise. G_t and G_r are the satellite and receiver antenna gains respectively.

4.2. Multipath

Positioning error due to signal multipath from reflective surfaces in the environment: Multipath, or signal reflection prior to arriving at the receiver antenna introduces error in the carrier-phase measurement. Multipath for a single reflection from a reflective surface in the vicinity of the GNSS receiver antenna is modelled using the ray-tracing method described in [8] and illustrated in Fig. 3.

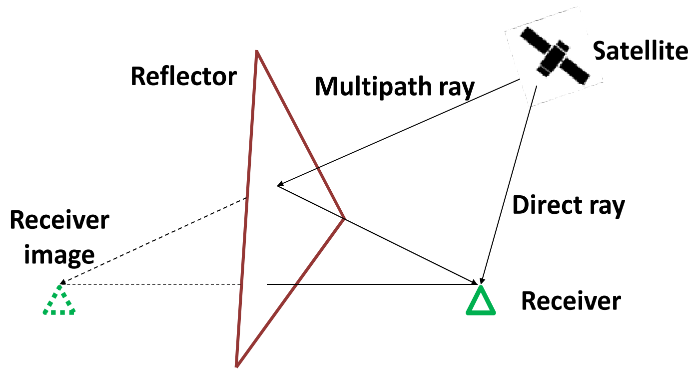


Fig. 3. Multipath determination by ray-tracing

The ray-tracing method assumes that the GNSS signal is a plane wave, an assumption that is valid owing to the large separation between the source (satellite) and the reflecting surface. A key advantage of the ray-tracing method over existing empirical models [9, 10] of signal propagation in urban environments is the ability to deterministically model local signal-terrain interactions in the vicinity of the receiver antenna.The phase shift ϕ of the multipath ray (relative to the direct path ray) is directly proportional to the difference in path lengths between the direct path and multipath rays and is given by:

$$\tilde{\phi}_1 = \frac{L_m - L_d}{\lambda} \quad (2)$$

where L_m and L_d are the path lengths of the multipath-signal and the direct signal respectively. The GNSS receiver measures in-phase (I) and quadrature-phase (Q) components of the signal to estimate the carrier-phase ψ_d. The presence of the multipath ray introduces error ψ in the carrier-phase measurement.Using the ray-tracing algorithm, the carrier-phase error ψ due to multipath can be predicted by using Equation 3[8] :

$$\psi = tan^{-1}\left[\frac{\alpha sin\phi}{1+\alpha\ cos\phi}\right] \quad (3)$$

where α is the Multipath-to-Direct ratio quantifying the effect of a single reflection on signal strength. This parameter is dependent on the material of the reflector, and the gain of the receiver antenna. ϕ is the phase shift of a multipath signal and is dependent on the relative geometry between the reflector and the receiver antenna. In conjunction with the geometry of the satellite constellation, which is quantified by the Dilution of Precision (DOP), the carrier-phase error ψ causes the computed position to deviate from the true position.

4.3. Antenna masking

As in the case of signal multipath, obscuration or masking of the receiver antenna is site-dependent and cannot be modelled independently of the surrounding terrain and the satellite-receiver relative position. Antenna masking does not directly introduce error in the signal measurement, but can degrade the constellation geometry, and in extreme cases, render the receiver unable to compute position. Antenna masking is modelled in this research through the use of detailed terrain models and almanacs.

5. Integrity Thresholds

Table 1 describes the thresholds for triggering caution and warning flags for all error sources that the flag generator is able to detect. The thresholds for signal attenuation are based on the signal strength that a given receiver can successfully track. The thresholds for antenna masking are based on the number of visible satellites required to compute a position. The key contribution of this research lies in the integrity thresholds assigned for multipath-induced error. The integrity thresholds assigned for the augmentation system to raise alerts is presented in Table 1.

Table 1. Integrity alert thresholds

Type of alert	Error Source	Thresholds

Caution Flag	Masking	When number of visible satellites drops to below 5
	Multipath	When 2×drms ≥ 0.90× min(HAL, VAL)
	Signal attenuation	When C/N_0 drops below 25 dB-Hz
Warning Flag	Masking	When number of visible satellites drops to below 4
	Multipath	When 2×drms ≥ 0.85× min(HAL, VAL)
	Signal attenuation	When C/N_0 drops below 24 dB-Hz

The thresholds for multipath-induced positioning error are based on the Horizontal Alert Limit (HAL) and the Vertical Alert Limit (VAL). The HAL and VAL specify the limits within which the position error must be contained to navigate safely.

6. Vehicle model

The Integrity alert system was tested on a trajectory planned through a simulated environment at an airport. The simulated trajectory was generated by modelling the motion and dynamics of a ground vehicle representative of an electric luggage transport or an electric tug used to tow aircraft. The following assumptions are made:

The airport surface vehicle tyres are always in contact with the ground. Forces at the contact patches of the tyres can be resolved into components in the vehicles xy-plane.The vehicle has a sufficiently low centre of gravity and hence any roll can be neglected. The vehicle is front-wheel steered and the steering angle for both front wheels is the same. The stated assumptions allow the front and rear wheel pairs to be collapsed into a single front wheel and rear wheel. The front wheel has a lateral stiffness (sideslip coefficient) equivalent to twice the lateral stiffness of each individual front wheel and the same condition holds good for the rear wheel. The equations of motion for a vehicle of this type are given in state-space form by [11], [12]:

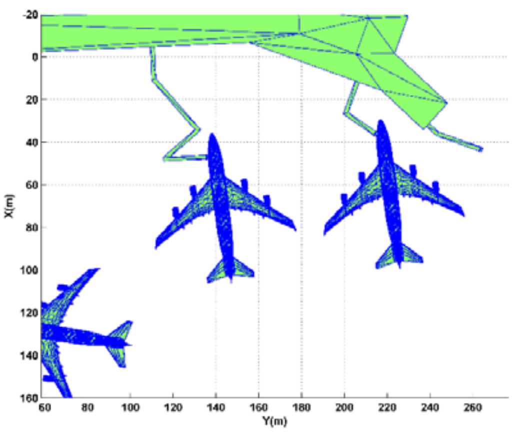
$$\begin{bmatrix} \dot{v}_y \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -\frac{C_{\alpha f}+C_{\alpha r}}{m v_x} & \frac{-a_1 C_{\alpha f}+a_2 C_{\alpha r}}{m v_x} \\ -\frac{a_1 C_{\alpha f}-a_2 C_{\alpha r}}{I_z v_x} & -\frac{-a_1{}^2 C_{\alpha f}-a_2{}^2 C_{\alpha r}}{I_z v_x} \end{bmatrix} \begin{bmatrix} v_y \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_{\alpha f}}{m} \\ \frac{a_1 C_{\alpha f}}{I_z} \end{bmatrix} \delta \tag{4}$$

The vehicle parameters are mass m, moment of inertia about the z-axis I_z, the distance between the centre of mass and the front and rear axles a_1 and a_2. The lateral stiffness of the front and rear pairs of tyres are $C_{\alpha f}$ and $C_{\alpha r}$. The states of the vehicle are the the lateral velocity v_y and the yaw rate r. F_x is the tractive force at the interface between the drive wheels and the road. The input to the vehicle model is the steering angle δ. As a simplifying assumption, a constant longitudinal velocity v_x is assumed.

7. Simulation case study

The dynamic model presented in section 6 is used to generate a trajectory representative of the operations of an airport ground vehicle. Three-dimensional models of airport buildings and parked aircraft were built and discretized as shown in Fig. 4 (a), prior to import into the MATLAB environment.

a)



b)

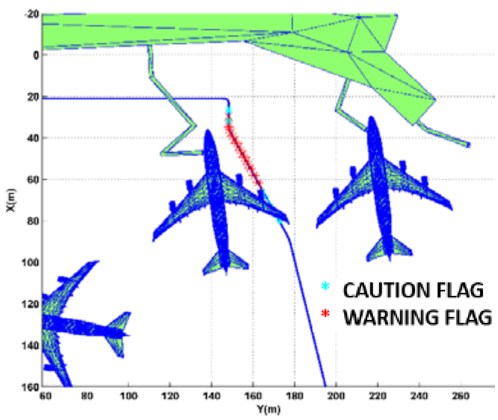


Fig. 4. (a) Airside scenario and (b) Generation of integrity alerts for planned trajectory

The generation of alert flags due to multipath induced positioning error using the algorithms described previously is visualized in Figure 4 (b), and the time steps at which the flags are raised are presented in Table 2. A similar pattern of integrity alerts was observed for signal attenuation due to propagation losses and multipath as the vehicle approached reflective surfaces such as building walls and parked aircraft. No warning flags were raised for antenna masking, implying that the number of visible satellites remained above 4 for the duration of the simulation.

Table 2. Multipath alert time-steps

Multipath Integrity Alert Times [sec]	
Caution Flag	11~48; 67~78
Warning Flag	16~35

8. Conclusions

A differential GNSS based Navigation and Guidance System (NGS) for autonomous ground vehicle operations was presented. The system is designed to provide trusted autonomy in ground operations including future robotic cargo-handling, aircraft-towing, passenger transport, etc. Based on the identified GNSS signal errors, an integrity monitoring and augmentation system was presented to produce timely and usable alert flags so as to exhibit a corrective behaviour in addition to be reactive for signal degradations and losses. The dynamics and motion of a vehicle representative of an electric tug or a luggage transport was modelled, and a trajectory was generated in a simulated airside environment. During the simulated autonomous run, integrity alerts were generated in real-time. Based on this simulation, the presented integrity augmentation system is capable of early detection of GNSS accuracy and signal degradations due to multipath, masking and attenuation. This makes the system well suited to meet the integrity requirements for autonomous vehicles cooperatively navigating in complex ground environments.

9. Future work

The modular nature of the implemented integrity augmentation system makes it suitable to integrate alongside trajectory optimization and path-planning algorithms. Future research will focus on the implementation of trajectory optimization algorithms that balance the tradeoff between efficiency of a planned trajectory (for example, in terms of fuel/battery consumption) and safety requirements imposed by positioning accuracy. This involves formulating the GNSS error sources as penalties to be minimized in the cost function of a trajectory optimization algorithm.

10. References

[1] R. Sabatini, T. Moore, and C. Hill, "A New Avionics-Based GNSS Integrity Augmentation System: Part 1–Fundamentals," *Journal of Navigation,* vol. 66, pp. 363-384, 2013.

[2] R. Sabatini, T. Moore, and C. Hill, "A New Avionics-Based GNSS Integrity Augmentation System: Part 2–Integrity Flags," *Journal of Navigation,* vol. 66, pp. 501-522, 2013.

[3] R. Sabatini, T. Moore, and C. Hill, "Avionics-based integrity augmentation system for mission-and safety-critical GNSS applications," in *proceedings of 25th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2012), Nashville, TN*, 2012, pp. 743-763.

[4] R. Sabatini, T. Moore, C. Hill, and S. Ramasamy, "Assessing avionics-based GNSS integrity augmentation performance in UAS mission-and safety-critical tasks," in *Unmanned Aircraft Systems (ICUAS), 2015 International Conference on*, 2015, pp. 650-659.

[5] S. Andrés and C. Daniel, "Integrity monitoring applied to the reception of GNSS signals in urban environments," 2012.

[6] W. Y. Ochieng, K. Sauer, D. Walsh, G. Brodin, S. Griffin, and M. Denney, "GPS integrity and potential impact on aviation safety," *The journal of navigation,* vol. 56, pp. 51-65, 2003.

[7] R. Sabatini, T. Moore, C. Hill, and S. Ramasamy, "Investigation of GNSS Integrity Augmentation Synergies with Unmanned Aircraft Sense-and-Avoid Systems," SAE Technical Paper 0148-7191, 2015.

[8] L. Lau and P. Cross, "Development and testing of a new ray-tracing approach to GNSS carrier-phase multipath modelling," *Journal of Geodesy,* vol. 81, pp. 713-732, 2007.

[9] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE transactions on Vehicular Technology,* vol. 29, pp. 317-325, 1980.

[10] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda, "Field strength and its variability in VHF and UHF land-mobile radio service," *Rev. Elec. Commun. Lab,* vol. 16, pp. 825-73, 1968.

[11] R. N. Jazar, *Vehicle dynamics: theory and application*: Springer Science & Business Media, 2013.

[12] A. G. Ulsoy, H. Peng, and M. Çakmakci, *Automotive control systems*: Cambridge University Press, 2012.