A Methodology to Elaborate Aircraft Localization Requirements for Airport Navigation

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BIOGRAPHIES

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Christophe MACABIAU graduated as an electronics engineer in 1992 from the ENAC in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D in 1997 and has been in charge of the signal processing lab of ENAC since 2000.

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ABSTRACT

The general increase in air traffic and the complexity of modern airport layouts have led to think about new system opportunities to assist pilots during maneuvers on airport surface.

Two applications will be considered in this paper: guidance and control. Guidance application provides indication to the pilot to navigate on the airport surface whereas control application provides steering indications. These two applications will allow the pilot to drive under low visibility conditions.

This assistance is based on the knowledge of the aircraft position on the airport surface. However, precise requirements on aircraft localization service on the airport surface, in terms of accuracy, integrity, continuity and availability, have not been completely expressed by existing standards.

This paper proposes a methodology to derive these requirements based on FHA (Functional Hazard Analysis) method. FHA is a predictive technique whose goal is to explore the functional effects of failures on parts of the system.

It results in the suggestion of 95% accuracy, integrity risk, HAL (Horizontal Alert Limit) and TTA (Time To Alert) requirements according to the visibility conditions for the different operations.

INTRODUCTION

In compliance with ICAO recommendations, the safety of aircraft surface movement is mostly ensured by the principle of "see and be seen" [1]. This basic

principle becomes difficult to apply particularly in low visibility condition.

In the 90's, ICAO develops the A-SMGCS (Advanced Surface Movement Guidance and Control System) concept to take into account new technologies and to cope with the air traffic increase and the airport complexity. A-SMGCS is a surface management system interfacing with the ATM (Air Traffic Management) system. It considers four connected main functions: Surveillance, Control, Routing and Guidance whose definitions can be found in [1].

Surveillance function displays to the ATC (Air Traffic Control) the position and the identification of all aircraft and vehicles on the airport surface. Classical equipments of Surveillance function are the primary radar, the ADS-B (Automatic Dependent Surveillance – Broadcast) or the mode S multilateration. The aim of Control function at ATC level is to detect conflicts (between moving aircraft and authorized vehicles on the movement area) and provides to each aircraft the constraints and alerts relative to its followed path. Routing function designates the most efficient route to follow for each aircraft or vehicle. Guidance function gives pilot indications to follow the assigned route.

The mid term new concepts concern guidance (use of guidance terminology is as per A-SMGCS concept definition) and steering applications onboard. These applications include airport navigation in low visibility condition.

It may be felt that the navigation performance will depend on the operational condition in which the system is used. Integrity requirements on position estimate will not be the same if the system is used as an help for situational awareness, or if it is used as a navigation or control means of the aircraft. Endsley [18] has defined the awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future".

This paper deals with a methodology to elaborate aircraft localization requirements when the embedded airport navigation system is used for aircraft piloting. The organization of the paper is the following. First section reminds the different operational phases on airport surface and the main characteristics of airports according to their classification. In the second part, the two considered applications, guidance and steering, are detailed. The third section introduces the FHA-method and a description of the risk classification according to the effects on aircraft and/or passengers. The last part presents propositions of aircraft localization requirements, based on FHA-method, for the two considered applications. This results in the suggestion of 95% accuracy, continuity risk, integrity risk, HAL (Horizontal Alert Limit) and TTA (Time To Alert) requirements according to the visibility conditions for the different operations and/or airports categories.

I   AIRPORT CHARACTERISTICS

Airports categories, divided into 6 categories, are defined according to the size of the aircraft allowed to circulate on the airport. Two classifications have been elaborated, one by the FAA [2] and another by the ICAO [3] as shown in table 1. The ICAO airport classification is used in this paper.

FAA coding	ICAO coding	Wing span	Main gear wheel span
I	A	Up to 15 m	Up to 4.5 m
II	B	15 – 24 m	4.5 – 6 m
III	C	24 – 36 m	6 – 9 m
IV	D	36 – 52 m	9 – 14m
V	E	52 – 65m	9 – 14 m
VI	F	65 – 80 m	14 – 16 m

Table 1: Airport classification

Typical aircrafts supported on airport category D (such as A320, B737) are allowed on airport category F. The reciprocal is not true, an A380 or a B777-300 is not accommodated to circulate on an airport category D.

Code letters A and B correspond to private airports, and code letters C to F are employed to commercial airports. This paper will focus on category D to F airports (a similar approach can be conducted for category A to C airports).

The airport surface is decomposed into 5 different zones [3] where navigation operations have different characteristics as depicted in figure 1:
- Runway (RWY): used for landing and take-off
- High-speed taxiway (HS TWY): taxiway connected to the runway, it is designated to allow turn off with a higher speed and hence minimize the occupancy time in the runway
- Taxiway (TWY): used for the taxiing of the aircraft, it is the link between aerodrome parts.
- Apron: used to load or unload passengers, fuelling, parking and maintenance away from airport terminals.

❑ Gate: used to load or unload passengers, fuelling, parking, connected to airport terminals.
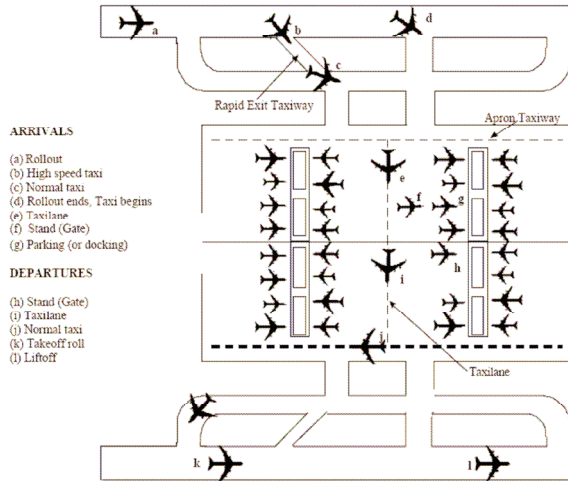

Figure 1: Airport operational phases [4]

Movements scenario are not the same after landing or before taking-off since the high speed taxiway is not used for take-off. Figure 2 depicts the scenario in this paper.
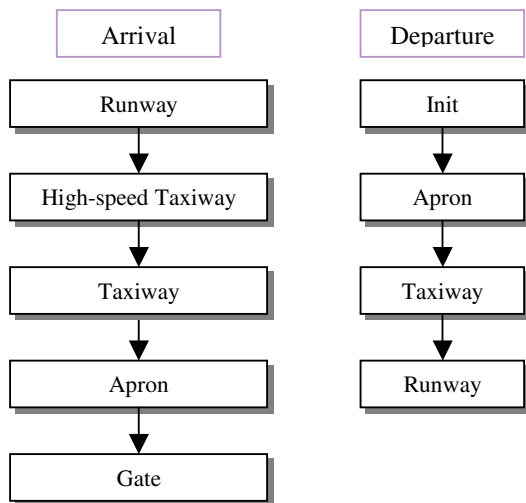

Figure 2: Arrival and departure scenario

The init phase, in the departure case, is an initialisation phase. When the aircraft is at the gate, the navigation system is not used because a tractor is used to place the aircraft on the apron, but the localization system must be initialized in order to make sure it is ready for the next operational phases.

The surface taxi speed is defined in [4] and depends on where the aircraft is situated. The table below summarizes the range of speed assumed for the different phases of surface movement and the associated exposure time. As we can see, the total exposure time is roughly 15 minutes.

Taxi Phase	Taxi Speed (knots)	Exposure Time (Minutes)
Rapid Exit (High Speed)	30 – 50	0.5
Normal/Apron taxiway - straight	10 – 30	6
Taxilane	0 – 10	3
Gate Operation	0 – 10	6

Table 2: Surface taxi speed and exposure time [4]

To derive some of the performance parameters used in this study, the knowledge of the taxiway width is necessary. The width of taxiway, introduced in table 3, is defined in paragraph 3.9.5 of [3].

	Airport cat D	Airport cat E	Airport cat F
Taxiway width	18 m 23 m	23 m	25 m

Table 3: Taxiway width

For category D airports, it must be considered 18m if the taxiway is intended to be used by aeroplanes with an outer main gear wheel span of less than 9m and 23m if the taxiway is intended to be used by aeroplanes with an outer main gear wheel span equal to or greater than 9 m.

II   GUIDANCE AND STEERING APPLICATIONS

II.1   GUIDANCE APPLICATION

A guidance application will provide the pilot with indications for navigation on the airport surface in accordance with the ATC routing instructions [1].

To reduce the crew workload and to help the pilot, systems dedicated to maneuvers on the ground have been developed. These systems plot the aircraft estimated position on electronic maps displayed to the pilots.

Among systems currently used in civil aviation providing guidance application for airport navigation, there are the EFB (Electronic Flight Bag) developed by Jeppesen and the OANS (Onboard Airport Navigation System) developed by THALES, which are implemented on Boeing and Airbus aircraft.

II.2   STEERING APPLICATION

Steering application will allow the pilot to drive in all weather conditions using steering indications relative to synthetic vision for example. A virtual 3D image of the aircraft in the airport environment from the pilot perspective is generated from aircraft position and orientation, and displayed to the pilot. Inside the image, indications can be added showing the flight path as well as steering control information so that the pilot can optimally pilot his aircraft during taxi operations

In the final stage of implementation of airport navigation systems, automatic control of the aircraft will combine the guidance and steering capability to enable an automatic control of the aircraft on the airport surface without human aid (contrary to guidance and steering applications where pilot is present). It is also called autotaxi.

III   FHA-METHOD

During conception of aeronautical systems, a safety analysis is conducted to obtain certification. Such analysis tries to identify all cases that may cause a degraded situation for the aircraft and hence generate damage to passengers, crew or other people close to the aircraft.

To conduct a safety analysis, there are three analysis levels: the aircraft, the embedded systems and the equipments which composed the system. Different types of analysis exist. To evaluate the risk associated to each function (determine the failure condition and classify the risk associated) a Functional Hazard Assessment (FHA) is produced. The method to evaluate the system security is called a System Safety Assessment (SSA). To analyze the common causes, complementary studies, Common Cause Analysis (CCA), are conducted. In this paper, we focus on FHA method to our applications.

The safety standards documents are ARP 4754 [5] (*Certification considerations for highly-integrated or complex aircraft systems*) and ARP 4761 [6] (*Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment*). ARP 4754 gives recommendations to demonstrate that complex systems (systems whose security level cannot be demonstrated with tests or whose understanding requires support tools) or highly integrated systems (which contribute to several functions) satisfy navigability requirements. ARP 4761 suggests methods to evaluate aircraft safety analysis for its certification.

The main steps of the method are:
- ❑ To identify the different functions
- ❑ To search for the Failure Conditions (FC)
- ❑ To define the criticality associated to each FC according to the produced effects (see table 4)
- ❑ To deduce requirements to prevent each FC (maximum risk) or maintain consequences to an acceptable level (see table 5)
- ❑ To demonstrate that study is complete and results are conformed to the regulation (all of the FC probabilities are lower than or equal to the targeted probabilities).

The next tables introduce the safety criticality classification (table 4) and the risk associated to each classification (table 5). The probability of occurrence given in table 5 is per exposure time defined according to the operation.

Criticality classification	Results in one or more of the following effects
Catastrophic	- The loss of the aircraft - Multiple fatalities
Hazardous	- A large reduction in safety margins - Physical distress or a workload such that the flight crew cannot be relied on to perform their tasks accurately or completely - Serious injury or death of a relatively small proportion of the occupants
Major	- A significant reduction in safety margins - A reduction in the ability of the flight crew to cope with adverse operating conditions as a result of increase in a workload or as a result of conditions impairing to emergency - Injury to occupants
Minor	- Nuisance - Operating limitations: emergency procedures

Table 4: Safety criticality classification [1]

Quantitative probability of occurrence	JAR 25 Qualitative probability of occurence	Classification of effect
$1 - 10^{-3}$	Frequent	Minor
$10^{-3} - 10^{-5}$	Reasonably probable	
$10^{-5} - 10^{-7}$	Remote	Major
$10^{-7} - 10^{-9}$	Extremely remote	Hazardous
$< 10^{-9}$	Extremely improbable	Catastrophic

Table 5: Risk tolerability matrix [1]

First, FHA is described for the whole aircraft and then for each subsystem. FHA is a predictive technique and its goal is to explore the effects of a functional failure of parts of a system. Its primary aim is to identify failure conditions leading functions to hazardous behaviors. The FHA method can be described as depicted in figure 3 [7].
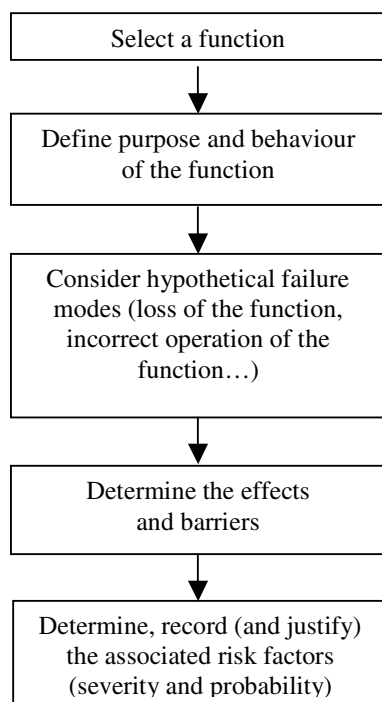

Figure 3: FHA method

FHA results are generally presented in a table organized as follows [7].

Function	Failure condition	Phase	Effect	Class verification

Table 6: Typical FHA record format

To conclude, the aim of FHA is to determine the safety objectives in terms of acceptable hazardous events frequency with a certain severity.

The FHA-method is thus applied to our applications to determine the failure modes which contribute to undesired top-level events.
In our case, the considered aircraft functions and sub functions are:
- ❑ To navigate on an airport surface
  - o To select trajectory with ATC
  - o To locate the aircraft at the airport surface on the mapping
  - o To compute the guidance information relative to the negotiated trajectory and the estimated position.
  - o To display the navigation information to follow the selected trajectory.
- ❑ To manually drive the aircraft
  - o To control the aircraft motors, brakes and steering wheel by the pilot.
  - o To locate the aircraft at the airport surface
  - o To compute the synthetic landscape corresponding to the estimated position and heading.
  - o To compute steering information
  - o To determine the aircraft position estimate on the airport
  - o To display the aids enabling the pilot to drive safely along the taxiways.
- ❑ To automatically control the aircraft on the airport surface
  - o To navigate on an airport surface without human aid.
  - o To drive the aircraft automatically.

Other functions associated to A-SMGCS system such as to transmit the aircraft position to the ATC or to receive and manage position of other aircrafts are not considered in this paper.

Among all the sub-functions, the considered sub-function is "To locate the aircraft at the airport surface". Following failures conditions are taken into account:
- ❑ To provide position with degraded accuracy (known)

□ To provide undetected failed position information outside a TTA delay

□ To loose the position after a detected failure.

The operational effects on the aircraft navigation and control capabilities associated to these failure conditions are:

□ To loss assisted navigation capability on the airport

□ To navigate on the wrong taxiway / to miss a traffic alert

□ To steer off the pavement or to collide an obstacle with low speed

□ To steer off the pavement or to collide an obstacle with high speed

It must be noted that the criticality classification of these effect will depend on the operational concept defining their usage in the overall A-SMGCS concept design. It may depend on a number of factor including the visibility conditions,the operational phases (taxiway, apron …), the potential mitigations at aircraft level (speed reduction) or overall ASMGCS level (surveillance …). The criticality classification for the failure effect "is proposed" as follows (these propositions have not been validated by certification authorities):

□ Major when the aircraft goes to close from obstacles leading to a reduction in the safety margins, or operational capabilities.

□ Hazardous when there is a collision or run off pavement, leading to the aircraft damages or passengers injuries (see figure 4 which is an example of Major/Hazardous runway excursion [20]).

□ Catastrophic when there is a risk of collision or run off pavement leading to the loss of the aircraft and/or passengers (see figure 5 which is an example of Catastrophic runway excursion [20]).

Figure 4: Example of Major/Hazardous runway excursion – Landing case [20]

Figure 5: Example of Catastrophic runway excursion – Landing case [20]

It is assumed in this paper that a procedure to reduce the aircraft speed in low visibility condition may be established in all operational phases except for the runway phase.

The FHA of our system is given in the next section.

IV   AIRCRAFT LOCALIZATION REQUIREMENTS

The common point of the two applications is the use of the aircraft current real time (with low latency) position estimated by the onboard positioning system. This position is mandatory to compute guidance and steering information. An aircraft position estimate is characterized by the navigation performance parameters, which are accuracy, integrity, continuity and availability. Definitions can be found for example in [8] and [17]. This paper focuses only on aircraft position, but it can be noted that aircraft velocity estimate performance is another parameter to determine, particularly for steering application.

The accuracy is defined as the 95% statistical difference over time between the estimated or measured position/velocity of a platform and its true position/velocity.

The integrity is a measure of the trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system must not be used for the intended operation [8].

The continuity of a system is defined to be the ability of the total system (including all elements necessary to maintain aircraft position within the defined airspace, ie to provide required accuracy and integrity) to perform its function without interruption

during intended operation supposing the function is available at its initiation [17].

The availability of a navigation system is the ability of a system to provide the required function and performance (accuracy, integrity and continuity). It is expressed in percentage of time that navigational signals transmitted from external sources are available by the system for use.

The integrity requirements defined by the ICAO for a specific application are described by three parameters: Integrity Risk, Time-to-Alert (TTA) and Alert Limits:

❑ The Integrity Risk, expressed per hour or per operation, is the probability of an undetectable positioning failure not detected within the TTA.

❑ The time to alert is the elapsed time from the onset of an out of tolerance condition until the equipment annunciates the alert

❑ Alert Limits represent the largest position error, which results in a safe operation. There are Horizontal Alert Limit (HAL) and Vertical Alert Limit (VAL). In our case, only HAL is interesting.

It may be felt that this navigation performance will depend on the operational condition in which the system is used. Integrity requirements on position will not be the same whether the system is used for situational awareness, or it is used for navigation or aircraft control.

To determine the aircraft incapacity to follow with exactitude an ideal predetermined trajectory, 3 types of errors are defined:

❑ The Path Definition Error (**PDE**): the error on the definition of the path to follow.

❑ The Flight Technical Error (**FTE**): the error associated to the pilot's effort to keep the aircraft near the centerline of the RWY or the TWY. This error includes display error.

❑ The Navigation System Error (**NSE**): the position error given by the navigation system. It includes the navigation sensor error and receiver error.

The Total System Error (**TSE**) is the sum of the 3 errors, and so is the variance of the TSE:

$$\sigma_{TSE}{}^2 = \sigma_{NSE}{}^2 + \sigma_{FTE}{}^2 + \sigma_{PDE}{}^2$$

This formula is only valid when the errors are independent. We suppose in this paper that the errors have a centered Gaussian distribution.

In this paper, we assume the PDE is considered as negligible. Based on input from operational experts, the FTE has been characterized by a uniform distribution centered on centerline with a range of 2m for runways and 1m for taxiways [20]. The standard deviation is derived from range using the following equation:

$$\sigma_{FTE} = \frac{range}{\sqrt{12}}$$

So for runways and taxiways, we get:

$$\sigma_{FTE\_RWY} = \frac{range}{\sqrt{12}} = \frac{2}{\sqrt{12}} = 0.57m$$

$$\sigma_{FTE\_TWY} = \frac{range}{\sqrt{12}} = \frac{1}{\sqrt{12}} = 0.28m$$

The same FTE for the apron and at the gate as on taxiway is assumed in this paper:

$$\sigma_{FTE\_TWY} = \sigma_{FTE\_APRON} = \sigma_{FTE\_GATE} = 0.28$$

Precise requirements on aircraft localization service on the airport surface, in terms of accuracy, integrity and continuity, have not been completely expressed by existing standards.

In this section we propose requirements elaborated from reasoning about the main risk associated to each application. One of the main risks is to reduce the safety margin around the aircraft and to be under the minimum safety margin. The minimum safety margin between an aircraft and any adjacent building, aircraft or other objects is 7.5m [3]. A collision may be assumed when the safety margin is lower than 7.5m.

The integrity risk proposition is derived from FHA analysis.

IV.1 GUIDANCE APPLICATION

Guidance application only uses signals and information provided by navigation system and does not depend on the airplane performance. Thus, the positioning error we get is directly the NSE.

Accuracy

The necessary accuracy is derived from HMI considerations (Human Machine Interface).

The display accuracy should permits to distinguish where the aircraft is situated from the centre line (to the right of the centre or to the left). If the aircraft is on the centre of the runway, it is preferable that it is

displayed on the central third of the taxiway width to not alter the pilot confidence. So, the accuracy must be better than the third of the width of the taxiway.

The accuracy limit requirement (95%) may be calculated from the width of the taxiway because the apron has no specific width. The runway is larger than taxiway so the taxiway width is more stringent.

The taxiway width is different from an airport category to another so the accuracy required for guidance systems will depend on the airport category where the aircraft is navigating. Table 7 introduces the accuracy required for the guidance application.

	Airport cat D	Airport cat E	Airport cat F
Accuracy (95%)	18/3 = **6 m**	23/3 ~ **7.5 m**	25/3 ~ **8 m**

Table 7: Accuracy (95%) required for guidance application

These values are independent of the operational phases and represent the NSE limit for guidance applications.

HAL

The HAL (Horizontal Alert Limit) represents the maximum position error, which results in a safe operation.

The HAL is different according to the operational phases. It is not the same on the runway, on the taxiway as on the apron.

With guidance systems, the main risk is that pilot may take a wrong taxiway. So, the HAL on the runway, taxiway and high-speed taxiway must be lower than half of the taxiway minimum separation distance.

The taxiway minimum separation distance, defined in [3], is introduced in table 8.

	Airport cat D	Airport cat E	Airport cat F
Minimum separation distance (m)	66.5	80	97.5

Table 8: Minimum separation distance

Similarly as was done for accuracy, HAL is defined according to airport category (because the taxiway minimum separation distance is not the same from an airport to another). Table 9 shows the proposition of HAL for guidance application for runway, taxiway and high-speed taxiway.

	Airport cat D	Airport cat E	Airport cat F
HAL	66.5/2 ~ **30 m**	80/2 ~ **40 m**	97.5/2 ~ **45 m**

Table 9: HAL for guidance systems for RWY, TWY and HS TWY

On the apron, the aircraft is displayed on a uniformly colored surface. Aerodrome mapping database accuracy is about 5m [19] so the estimated position accuracy is not required to be better than the accuracy introduced in table 7. Nevertheless, the HAL cannot be computed as for taxiway. The HAL for apron phase must be equal to 7.5m which corresponds to the minimum clearance between an aircraft using the stand and any adjacent building, aircraft on another stand and other objects [3].

The Time To Alert (TTA) may be defined by the TTA used for Category I, precision approach (Approach operations with vertical guidance). This value, 6 seconds [8], is sufficient for guidance application.

Continuity risk

When the function is used for guidance, if the function is lost the pilot knows in the worst case that he has to stop the aircraft. The requirement of 10^{-3}/h may be sufficiently low to be considered as useful.

Moreover, 1000h corresponds to 41 days. The value 10^{-3}/h is equivalent to less than 1 loss of continuity per month if the system is used 24h/24h. A taxi phase on an airport surface is roughly 15 min so we can consider the system will be only used 1 hour per day. This value of continuity risk seems correct for this application.

The continuity retained for guidance systems (10^{-3}/h) is more stringent than guidance continuity on visibility condition IV ($1,5.10^{-3}$/h) defined in [4] and introduced in table 10. Nevertheless, it can be noted that it is of the same order.

Visibility condition	I	II	III	IV
Guidance continuity	3.10^{-3}/h	3.10^{-3}/h	3.10^{-3}/h	$1,5.10^{-3}$/h

Table 10: Guidance continuity for guidance systems [4]

Integrity Risk

To define the integrity risk, the consequences of a missed detection are examined using the FHA-method. The examined function is the aircraft location. To do this, we focus on the consequences of the failure cases previously identified.

The phases to consider in our FHA analysis are the operations on the different airport area described in Figure 1. For each of these phases, the following sections describe the logical to derive the Integrity Risk values using FHA methodology.

It can be noted that the consequences will not be the same according to the visibility conditions and where the aircraft is located.

In good visibility condition (GVC), visual references (ground marking, lights, traffic sign, etc) can help the pilot checking the integrity. He can see that he makes a navigation mistake (he realizes it by himself or he is alerted by the control tower), particularly if he passes too close to other vehicles (mobile or stationary), if the display of the airport situation is not correlated with the reality or if there are unexpected obstacles.

In low visibility condition (LVC), only poor visual references are visible for the pilot. It will be more difficult for the pilot to realize he makes a mistake, as it will be more difficult to correlate the partial visual references with its actual situation. The consequence is a risk classification higher than in GVC unless speed reduction is considered to decrease the risk associated to a loss of integrity.

Such mitigation is assumed for guidance and steering applications. No map matching is considered for mitigation in system implementation. Probability of detection of a localisation error through map correlation is too much dependant on the airport configuration and the trajectory followed by the aircraft.

Departure/Arrival on the Apron

At departure, the pilot can take a wrong taxiway. In GVC or in LVC with reduced aircraft speed the consequence is a significant reduction in safety margin. This risk may be classified as **Major**.

In LVC with non-reduced aircraft speed, when the pilot goes on a wrong taxiway, the consequence is a large reduction in safety margin. The higher speed along with the pilot's longer reaction delay due to LVC may provoke more serious damages, especially on the passengers. That is why this risk may be classified as **Hazardous**.

Arrival at the Gate

The pilot can approach several obstacles before reaching the gate (airbridge, fix objects). In GVC or in LVC even if the aircraft speed is not reduced, the speed being already low, the consequence is a significant reduction in safety margin due to the presence of obstacles in the safety area that could lead to a collision. This risk may be classified as **Major**.

Departure/Arrival on the Taxiway

The pilot can take a wrong taxiway. In GVC, the pilot can monitor the indicated situation with visual references, and detects the navigation error and/or potential presence of obstacles. The effect is a reduction in operational capabilities and is classified **Major**. In LVC with reduced aircraft speed, the risk is the presence of obstacles in the safety area that could lead to a collision. It may be classified as **Hazardous** due to the medium speed of the aircraft.

In LVC with non-reduced aircraft speed, the non-adapted speed can provoke serious damages on aircraft (due to the low reaction time of the pilot caused by the low visibility condition) and loss of passenger's life. This risk may be classified as **Catastrophic**.

Arrival on the High-Speed Taxiway

The pilot may go on a wrong HS-TWY. This error can provoke a collision with another aircraft already in the HS-TWY. This collision may cause damage on the aircraft and hurt passengers. This risk may be classified as **Hazardous** in GVC and in LVC in case of reduced aircraft speed.

The non-adapted speed can provoke serious damages on aircraft (due to the low reaction time of the pilot caused by the low visibility condition) and loss of passenger's life so the consequence may be classified as **Catastrophic** in LVC with non-reduced aircraft speed.

Departure/Arrival on the Runway

The pilot may go on a wrong runway. In the arrival case, this error can provoke other aircraft in approach to perform an emergency go-around.

Due to aircraft high speed in this phase, the consequence is a large reduction in safety margin. In the worst case, the proximity can be with another aircraft and provoke a collision. This risk may be classified as **Hazardous** in GVC.

In LVC, the reaction time of the pilot is increased so the consequence may be classified as **Catastrophic**.

Exposure time
The integrity risk proposed previously about the feared event is defined for an exposure time.

For guidance applications, the exposure time corresponds to the time elapsed from the onset of a failure and the detection of this failure by an external alert (control tower, A-SMGCS systems). An approximation of this time is made: about 30s. This value is a proposition and must be validated through study (taken into account the inattention of the controllers, the radar errors, etc, which can imply a higher value for the exposure time).

IV.2   STEERING APPLICATION

HUD is one of the way envisaged to support steering application. It is assumed in this paper that a HUD will be employed to display information to the pilot.

Accuracy
The 95% accuracy must be better than one meter. In fact, above this value, the display of the real environment in the HUD can be deteriorated and the indication cannot be usable by the pilot.

The accuracy is defined according to where the aircraft is situated. To enable safe aircraft maneuvers on the airport, the accuracy of the system must be as defined in table 11.

	RWY	TWY	Apron	Gate
Accuracy	1m	1 m	1 m	0.5 m

Table 11: 95% accuracy requirement on the TSE

Today, to park the aircraft a person on the ground assists the pilot and helps him. The aircraft is parked with an accuracy of at least 50cm. The system must have the same performance so an accuracy requirement of 0.5 meter at the gate is retained.

These values correspond to the TSE (Total System Error) because the system controls the aircraft. Table 12 introduces the proposition of requirements onto NSE for the steering application.

	RWY	TWY	Apron	Gate
TSE	1m	1 m	1 m	0.5 m
FTE	0.57m	0.28m	0.28m	0.28m
NSE	0.82m	0.96m	0.96m	0.41m

Table 12: Requirements onto NSE for the steering application

HAL
For airport categories D, E and F, the HAL must be below 7.5 meters because the minimum separation margin necessary between two aircraft is 7.5 meters [3].

If the application is used in low visibility, the risk is to have the landing gear run off the taxiway. So, the HAL may be derived from the width of the taxiway and the main gear wheel span. Moreover, the taxiway edge safety margin is defined in [4] and is given in the table below.

	Airport cat D	Airport cat E	Airport cat F
Taxiway edge safety margin	4.5m	4.5m	5m

Table 13: Taxiway Edge Safety Margin [4]

The risk is also associated to the corresponding phase. There is not the same HAL on the runway that at the gate.

On the runway, on the high-speed taxiway and on the taxiway the HAL can be considered as the same. It is deduced from the taxiway width. The following table shows the margin according to the airport category:
- ❑ The first line is calculated from the taxiway width and the minimum wheel track,
- ❑ The second line is calculated from the taxiway width and the maximum wheel track,
- ❑ The third line is the taxiway edge safety margin defined in [4],
- ❑ The fourth line corresponds to the value retained.

These margins correspond to the HAL for the runway, the high-speed taxiway and the taxiway phases. The HAL considered for the apron phase is 7.5m (the minimum separation margin) because the run off pavement is not envisaged on the apron.

Airport cat D	Airport cat E	Airport cat F
(18-9)/2 = **4.5 m**	(23-9)/2 = **7 m**	(25-14)/2 = **5.5 m**
(18-14)/2 = **2m**	(23-14)/2 = **4.5m**	(25-16)/2 = **4.5m**
4.5m	**4.5m**	**5m**
4.5m	**4.5m**	**5m**

Table 14: Margin for steering application

At the gate, the HAL is reduced owing to the step. It is derived from the minimum distance between the platform and the body of the largest aircraft whose the bridge is adapted for. This distance is about 1.2 m [9], so the HAL must be equal to or better than 1.2 m at the gate. It is the same value for all airport categories.

Continuity risk
The continuity risk for aircraft steering application is the same as for guidance application because in the worst case, the pilot (or the system in case of autotaxi) can stop the aircraft and he is able to drive without the function.

TTA
The time-to-alert allocated to aircraft control systems is the time-to-alert corresponding to a catastrophic event. The time-to-alert retained is between 1 and 2 seconds. It is the same TTA as for Cat III approaches [21].

Integrity Risk
To define the integrity risk, the consequence of non-detection failure is examined from FHA-method as same as for guidance application.

Departure/Arrival on the Apron – Arrival at the Gate
At the gate and on the apron, the aircraft is close to obstacles (fix or mobile in the apron).

At the gate whatever the visibility condition and on the apron, only in GVC and in LVC with a reduced aircraft speed, the risk is a significant reduction in safety margin. It may be classified as **Major** due to the aircraft low speed in these phases and the pilot capability to identify a dangerous situation particularly in GVC.

On the apron in LVC with a non-reduced aircraft speed, it is not easy for the pilot to see that the navigation system commits an error. The consequence is a large reduction in safety margin. The non-adapted speed can provoke serious damages on passengers (due to the low reaction time of the pilot caused by the low visibility condition). The risk may be classified as **Hazardous**.

Departure/Arrival on the Taxiway
In GVC, the pilot can monitor the automatic driving of its aircraft through visual references, and detects anomaly in the control. The effect is a reduction in operational capabilities and may be classified **Major**.

In LVC, the risk is a large reduction in safety margin or the run off pavement of the aircraft, with medium speed. A run off pavement with a medium speed can provoke serious damages on the aircraft and can hurt passengers.

In LVC with a reduced aircraft speed, the risk may be classified as **Major/Hazardous**.

In LVC with non-reduced aircraft speed, it may be classified as **Catastrophic** due to the high speed in this phase.

Departure/Arrival on the Runway – Arrival on the High Speed Taxiway
On the runway or on the HS TWY, the risk is a large reduction in safety margin or the run off pavement of the aircraft, with medium/high speed. A run off pavement with high speed can provoke serious damages on the aircraft and can hurt passengers.

On the HS TWY, this risk may be classified as **Hazardous** in GVC and in LVC with reduced aircraft speed and **Catastrophic** in the other case.

On the runway, the risk may be classified as **Catastrophic** whatever the weather conditions due to the high speed of the aircraft in this phase.

Exposure time
For each operational phase, the considered operation duration is the exposure time defined in [4] (see table 2). Contrary to guidance systems, the operation durations are not of the order of a few seconds because the control tower (or the A-SMGCS systems) does not have a sufficient accuracy to detect that the aircraft runs off pavement (not managed with guidance systems).

Comparison between the two applications
A comparison of the integrity risk per operation (/op) duration for the two applications is done in table 15.

	GVC	LVC with aircraft speed reduced	LVC without aircraft speed reduced	Operation duration for steering application	Operation duration for guidance application
Gate	10^{-5}/op	10^{-5}/op	10^{-5}/op	6 min	30 s
Apron	10^{-5}/op	10^{-5}/op	10^{-7}/op	6 min	30 s
TWY	10^{-5}/op	10^{-7}/op	10^{-9}/op	3 min	30 s
HS TWY	10^{-7}/op	10^{-7}/op	10^{-9}/op	30 s	30 s
Runway	10^{-7}/op	10^{-9}/op	10^{-9}/op	~ 10 s	~ 10 s

Table 15: Integrity risk comparison between guidance and steering applications

The comparison of the time-to-alert and loss of continuity is described in the following table.

	Guidance systems	Aircraft control systems
Time To Alert	6s	1s
Continuity	$10^{-3}/h$	$10^{-3}/h$

Table 16: Comparison of time-to-alert and continuity for the two systems

The comparison of the level of accuracy and HAL for the two applications is shown in table 17.

	Guidance Application		Steering Application	
	Accuracy [m]	HAL [m]	Accuracy [m]	HAL [m]
RWY	6-8m	30-45m	1	4.5-5m
HS TWY	6-8m	30-45m	1	4.5-5m
TWY	6-8m	30-45m	1	4.5-5m
Apron	6-8m	30-45m	1	7.5
Gate	6-8m	30-45m	0.5	1.2

Table 17: Accuracy and HAL comparison between guidance and steering applications

To conclude, the two applications have the same level of integrity with an exposure time different and a different level of accuracy.

V   OTHER ALLOCATION PROPOSITIONS

Since no standard deals with aircraft localization requirements on airport surface, some studies have been conducted about aircraft localization, such as EMMA2 (European airport Movement Management by A-SMGCS, part 2) [10], ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) [11], and currently SESAR (Single European Sky ATM Research) [12] and ALICIA (All Conditions Operations and Innovative Cockpit Infrastructure) [13].

Requirements for navigation system performance are introduced in results of these studies [14] or on few papers [15]. More recently, W. Schuster and W. Ochieng [16] have published a paper that analyses the navigation system performance requirements for airport surface movement. Navigation system continuity and integrity risks elaborated in their paper are presented in table 17.

Operational phases	Continuity risk	Integrity risk	Exposure time
RWY	$2,5.10^{-5}$/op	$2,5.10^{-9}$/op	30s
TWY	$2,9.10^{-4}$/op	$2,9.10^{-9}$/op	360s
Apron	$7,25.10^{-5}$/op	$7,25.10^{-9}$/op	90s
Gate	$7,25.10^{-5}$/op	$7,25.10^{-9}$/op	90s

Table 17: Navigation system continuity and integrity risk [16]

The continuity risk is of the same order as our allocation. The integrity risk for the operational phases runway and taxiway is also in the same order as our requirements. The main difference is for the apron and gate phases where the value proposed in [16] is more stringent. It was assumed in [16] that the integrity risk cannot be mitigated by the pilot because there is no external visual reference (under zero visibility conditions). In this paper, we assumed that due to the low speed of the aircraft at the gate, a catastrophic or hazardous event is prohibited. In the apron phase, the aircraft speed can be reduced and thus it may be sufficient to consider an integrity loss is hazardous.

The most stringent alert limit proposed in [16], 1.4m, is in the same order as the most stringent alert limit assumed in this paper (1.2m). The SIS (Signal In Space) accuracy requirement (95%) is the same in the two cases (0.5m) as well as the TTA (1s).

CONCLUSION

In this paper, requirements for guidance applications and steering applications have been proposed for the different airport categories, using a FHA method. The aircraft control systems requirements are more stringent than guidance systems requirements and these requirements depend on where the aircraft is situated.

The accuracy and HAL requirements are totally different from a system to another. For guidance systems, they are defined according to the airport category. For aircraft control systems, they are defined according to the operational phases. In general, the system accuracy is more stringent for aircraft control systems than for guidance systems.

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