RUNWAY INCURSION PREVENTION: CONCEPT FOR AN ONBOARD SURFACE MOVEMENT AWARENESS & ALERTING SYSTEM

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1. OVERVIEW

Increasing traffic density on the aerodrome surface due to the continuous worldwide growth in the number of flight operations does not only cause capacity and efficiency problems, but also increases the risk of serious incidents and accidents on the airport movement area. Of these, Runway Incursions are the by far most safety-critical. In fact, the worst-ever accident in civil aviation, the collision of two Boeing B747s on Tenerife in 1977 with 583 fatalities, was caused by a Runway Incursion.
Therefore, various Runway Safety programs have recently been initiated around the globe, often focusing on ground-based measures such as improved surveillance. However, as a lack of flight crew situational awareness is a key causal factor in many Runway Incursion incidents and accidents, there is a strong need for an onboard solution, which should be capable of interacting cooperatively with ground-based Air Traffic Management (ATM) systems, such as the Advanced Surface Movement Guidance and Control System (A-SMGCS) where available.

This paper defines a concept of preventive and reactive Runway Incursion avoidance and describes a Surface Movement Awareness & Alerting System (SMAAS) designed to alert the flight crew if they are at risk of infringing a runway. Both the Synthetic Vision System (SVS) flight deck displays and the corresponding alerting algorithms utilize an ED-99A/RTCA DO-272A compliant aerodrome database, as well as airport operational, traffic and clearance data received via ADS-B or other data links, respectively. The displays provide the crew with enhanced positional, operational, clearance and traffic awareness, and they are used to visualize alerts. A future enhancement of the system will provide intelligent alerting for conflicts caused by surrounding traffic.

2. INTRODUCTION

In order to maintain safe operations on the runway, strict procedures and rigorous surveillance are employed. Current operating procedures on the ground require explicit clearances to cross or enter the runway surface and its associated protection zone, and additional clearances are required for line-up and takeoff. Outside the United States, landing clearances to arriving aircraft may typically only be issued if all other traffic has vacated the runway. A violation of these procedures results in Runway Incursions, which constitute the most dangerous type of surface movement incident, with the potential to cause many fatalities if they lead to an accident.

Furthermore, Runway Incursions are exemplary of surface movement incidents in terms of the underlying causes. Therefore, various national and international research programmes on Runway Incursions and Runway Safety have been initiated in the European Union, Canada and the United States in recent years.

While it is unquestionable that any collision of two aircraft – or an aircraft and a vehicle – on the runway surface constitutes a Runway Incursion accident, there are still various diverging definitions of a Runway Incursion in general. In its most recent Runway Safety Report, the Federal Aviation Administration (FAA) gives the following definition (FAA, 2005):

> *A runway incursion is any occurrence in the airport runway environment involving an aircraft, vehicle, person, or object on the ground that creates a collision hazard or results in a loss of required separation with an aircraft taking off, intending to take off, landing, or intending to land.*

This definition is based on the concept of a protection zone ("*bubble*") around any aircraft entering the runway, the size of which corresponds to the required separation from other aircraft and any other objects. In this concept, any penetration of this protection zone is regarded as a Runway Incursion, and the depth of penetration serves as a measure for the severity of the incursion (FAA, 2001).
However, this definition is not unproblematic, because it requires a loss of separation or collision hazard. If a pilot enters a runway without clearance and there is no other aircraft in the vicinity, this will not constitute a Runway Incursion according to the FAA definition, but merely be considered as a surface movement incident. Many accident reports and studies, nevertheless, clearly indicate that a vast number of incursions are eventually caused by errors on the flight deck. As an example, 57% of all Runway Incursions in the US between 2000 and 2003 were caused by flight crews erroneously disobeying or misunderstanding a clearance to cross an active runway, to line up, take off or to land (FAA, 2004). An erroneous runway entry, and not a loss of separation, is the crucial step leading to a Runway Incursion, because the presence of and the distance to any other aircraft – and thus the collision hazard – is largely determined by chance, especially in low visibility conditions. In other words, the collision risk is the ultimate consequence of a Runway Incursion, not the cause.

Since November 2004, therefore, a more global definition of Runway Incursions by the International Civil Aviation Organisation (ICAO) is effective (Eurocontrol, 2004):

> *Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take off of aircraft.*

The wording chosen here clearly shows the influence of the FAA definition. However, with the use of the phrase "*incorrect presence*" instead of "*collision hazard*" and "*loss of separation*", the ICAO definition emphasizes the main cause of Runway Incursions (albeit at high level), whereas the FAA definition is merely descriptive of the incursion symptoms. It is also noteworthy that, in contrast to the ICAO definition, the FAA definition of a Runway Incursion (FAA, 2005) includes foreign objects on the runway as well. Although the consequences of foreign objects on the runway can be dire, as the loss of the Air France Concorde near Charles de Gaulle airport in 2000 (BEA, 2000) shows, this type of runway incident will not be considered here, as it has almost nothing in common with Runway Incursions caused by aircraft, vehicles or persons, which are generally the result of erroneous surface movement operations. Consequently, the more recent and internationally accepted ICAO definition will be applied in this paper, all the more as even the FAA intends to change its definition to comply with ICAO in 2006 (IATA, 2005).

3. CAUSES OF RUNWAY INCURSIONS

In its first Runway Incursion Report (FAA, 2001), the FAA suggested a subdivision of Runway Incursions into three error types:

- Operational errors / deviations [i.e. ATC error]
- Pilot deviations
- Vehicle / pedestrian deviation

However, the identification of a Runway Incursion according to this scheme is not necessarily an indication of its actual cause, because this classification by error type typically refers to the last event in a chain of controller, pilot, and/or vehicle operator actions that eventually led to the Runway Incursion (FAA, 2004).
Aviation accidents and incidents, though, usually have no single cause, but result from an unfortunate combination of several technical and/or procedural failures, often in conjunction with deviations from Standard Operating Procedures (SOP). Thus, the series of events that usually leads to Runway Incursions cannot be reflected by the FAA classification, as only the last element is considered. Furthermore, it gives no indication *why* the corresponding party deviated or made an error, and thus the true reasons for the incursion mainly remain in the darkness.
Instead, the complete chain of events leading to an incident or accident has to be analysed, focusing on factors contributing to procedural deviations and errors. Furthermore, standard operating procedures themselves have to be scrutinized for systemic errors (Vernaleken *et al*., 2006).

It is out of the scope of this paper to give an exhaustive analysis of various Runway Incursion accident and incident reports. However, crew disorientation due to a lack of situational awareness played a substantial role in two recent fatal Runway Incursion accidents in Milan and Taipei. In both cases, crew disorientation was at least partially caused by adverse weather conditions and the non-conformance of airport lights, signs or markings to ICAO regulations (ANSV, 2004; ASC, 2002). Controllers erroneously clearing two aircraft for the same runway were the key causal factors in both the 1991 Los Angeles and the 2000 Paris accidents. In the latter case, the use of two different ATC languages prevented the crew of a British Shorts 330 from noticing the controller error (BEA, 2001).

From an onboard perspective, however, the focus should naturally be on Runway Incursions eventually caused by Pilot Deviations. In view of the brief analysis above, one can safely assume that the crews fail to obey ATC instructions because of:

- a lack of situational awareness, which in turn might result from poor visibility or other adverse weather conditions,
- high crew workload, e.g. due to checklists, last-minute runway changes
- inefficient communication between controller and flight deck,
- insufficient familiarity with the airport, fatigue and lack of concentration,
- airport infrastructure deficiencies, e.g. missing or non-standard markings, signs and lights

or any arbitrary combination of these factors, which are not fully independent, because all of them influence crew situational awareness, and a lack thereof may impair the efficiency of communication with ATC. With this in mind, a lack of crew situational awareness on the aerodrome surface can be subdivided further into:

- **Lack of positional awareness.** The crew is either not sure of the position on the airfield and gets lost, or believes the aircraft to be elsewhere on the airport, particularly in situations of poor visibility. Especially the latter case can lead to inadvertent entry into the runway (e.g. entering or crossing the wrong runway, e.g. 30L instead of 30R).
- **Lack of operational awareness.** The crew lacks awareness of the operational configuration of the airport, i.e. they are not aware of closed runways or taxiways, or of the runways in use.
- **Lack of clearance awareness.** The crew is not fully aware what the current clearance mandates or allows them to do, or whether the appropriate clearance has been requested or issued. This includes the crew being in the wrong 'mindset' and failing to request clearance for the manoeuvre; having a false impression of being cleared for the manoeuvre (e.g. to enter runway, to land or to take-off) and failure to correctly execute the ATC sequencing instruction.
- **Lack of traffic awareness.** The crew lacks awareness of the position, intention and cleared manoeuvres with respect to relevant traffic in the vicinity of the aircraft.

Thus, the main goal to be achieved from an onboard perspective is a global increase in crew situational awareness, supplemented by alerting in situations where the enhanced awareness is not sufficient to avoid hazardous situations. This is in line with the European Action Plan (Eurocontrol, 2004) and the main rationale behind the concept for a Surface Movement Awareness and Alerting System (SMAAS) outlined in the following section. In this context, the potential of such a system to enhance situational awareness above the required level should not be underestimated. This would allow the crew to detect errors and deficiencies resulting from other factors, such as errors in ATC clearances and missing, non-standard or obscured aerodrome markings.

4. CONCEPT FOR A SURFACE MOVEMENT AWARENESS AND ALERTING SYSTEM

4.1. Why onboard systems?

To reduce the number of Runway Incursions, both U.S. and European programs on runway safety propose a variety of ground-based measures from improved surveillance technologies such as multilateration to perimeter taxiways. Furthermore, novel cooperative ATM systems such as A-SMGCS and the Airborne Separation Assistance System (ASAS) are emerging, using both ground-based and onboard technologies.
However, there are various good reasons to consider standalone and largely autonomous onboard systems as key technology for Runway Incursion Avoidance, and the idea of onboard systems for the prevention of Runway Incursions is anything but new. Nonetheless, a holistic concept for an onboard functionality encompassing all aspects of situational awareness relevant for Runway Incursions is still missing. A brief review of the state of the art can be found in (Vernaleken *et al.*, 2006).

The main advantage of an aircraft-based solution is that it is available and usable everywhere, providing crew support independently of systems on the ground. Although limitations to the autonomy apply, this design approach is fundamentally different from looking at onboard systems from an ATM perspective as with A-SMGCS, where the perception of aircraft-based technology is more that of an onboard front-end of the global air-ground infrastructure.
After all, airlines have only very limited influence on airport infrastructure outside their major hubs, and it is likely that several more decades will pass until the airports of developing nations will be equipped with advanced ATM systems like A-SMGCS.
In addition to this, there is currently an interesting trend in aviation (FAA, 2003): more and more low-fare carriers, regional airlines and charter operators push onto the market, and their business model usually includes offering point-to-point travel to small airfields close to the tourist regions or to reliever airports (as opposed to large hub airports) in order to save airport fees. It is unlikely that these airfields will be among the first A-SMGCS equipped aerodromes, as one may argue that only large and complex airports will significantly benefit from A-SMGCS. Smaller airfields with low traffic density and a simple structure, in this line of thought, are not too prone to surface movement incidents, and will not be equipped with priority, if at all. However, the Tenerife events suggest that the potential for Runway Incursions is lurking everywhere, even if the risk is admittedly higher at large hubs (FAA, 2004).
Furthermore, as the Tenerife accident and the closure of US airspace following the terrorist attacks of September 11 show, even carriers shuttling between fully A-SMGCS equipped hubs may suddenly find themselves diverting to small airfields due to ATC strikes or terrorist threats. Moreover, weather hazards and a medical or technical problem aboard the aircraft might also cause such a diversion.
In the event of a mass-diversion to a small airfield, there is subsequently a high risk that neither airport infrastructure nor controllers will be able to handle this sudden increase in traffic properly. After all, controllers working at a very small airport with typically 1-2 aircraft per hour will gradually lose their capability of handling 40 a/c per hour, even if their original training covered high-density airports. Even if advanced ground-based technology is available, the site-specific tailoring may not cover the mass-diversion case, which could lead to incomplete surveillance, nuisance alerts or complete outages.
Consequently, for Runway Incursion Avoidance, airline aircraft cannot rely on enhanced ATC surveillance in all visibility conditions and ground-based alerting tools everywhere in the world. Likewise, taxi routes and other Controller-Pilot Data Link Communications (CPDLC) services as well as fused traffic data broadcast by Traffic Information Services (TIS-B) might not be available.
Furthermore, and more importantly, there are safety implications with ground-based alerting as well: The airline, represented by the captain, is ultimately responsible for the safe conduct of the flight. From this perspective, up-linking alert information from the ground (derived from a system with potentially unknown certification) to the aircraft avionics is a major certification issue, particularly when it comes to the prioritisation of potentially contradictory onboard and ground-generated alerts. To avoid this problem, ATC will have to continue to alert crews via conventional radiotelephony (R/T), but this might lead to the loss of valuable seconds required for conflict resolution.
Another benefit of onboard systems is that the situational awareness they provide with respect to position and other traffic may enable the crew to detect potential threats and conflicts proactively, maybe even before the controller does. In addition to this, there might even be a chance to detect controller errors.
Nevertheless, air-ground interoperability with various A-SMGCS and other ATM ground installations and procedures is a crucial requirement for onboard systems (and a main driver for standardization), as well as the capability to operate if only a reduced number of A-SMGCS services/packages are supported on a certain airport, i.e. if the aircraft's avionics supports more services/packages than the corresponding installation on the ground. This last point illustrates once more the necessity to ensure that onboard systems are capable of operating in a more or less autonomous standalone mode (although a potentially reduced functionality in this case might be acceptable), because from an economic point of view, airlines are unlikely to invest in a system that is only usable at a limited number of airports and additional ballast elsewhere, especially in view of increasing fuel prices.
Last but not least, interoperability with similar onboard systems in other aircraft should be considered. At non-towered airports or in areas with no or insufficient ATC coverage, equipped aircraft could form a cooperative network, exchanging safety-relevant and operational information via data link. Taxi routes might be exchanged or negotiated. Today, this exchange between aircraft is limited to radio telephony. Furthermore, as with the Airborne Collision Avoidance System (ACAS), conflict avoidance manoeuvres could be coordinated automatically.

4.2. Preventive and Reactive Runway Incursion Avoidance

The insight that Runway Incursions are not primarily, but only in last consequence, a traffic conflict problem enables a fresh look on the subject focusing on rigorous ownship surveillance with special respect to the operational context, particularly clearances. Before describing the elements of the Surface Movement Awareness and Alerting System (SMAAS) in the next subsection, it seems appropriate to outline the underlying concept of Preventive and Reactive Runway Incursion Avoidance.
Flight crews can be involved in Runway Incursions in two principal ways: First of all, they can actively cause a Runway Incursion by entering a runway or the associated protection zone without the required authorization.

The second possibility to be involved in Runway Incursions is that another aircraft or vehicle enters or fails to vacate the runway protection zone while the flight crew is cleared to line up, take off or land on the same runway. In this case, the crew's involvement is passive, but immediate awareness of this potentially very dangerous situation is essential, and appropriate countermeasures are crucial to avoid accidents. Conceptually, this second case includes Runway Incursions due to controller errors as well – the flight crews see themselves confronted with a Runway Incursion they have not caused.

SMAAS must be able to provide awareness and alerts for both cases. In this context, it seems therefore appropriate to introduce the concept of Preventive and Reactive Runway Incursion Alerting or, more generally, Runway Incursion Avoidance.
Conceptually, Preventive Runway Incursion Avoidance is the first logical and main step to reduce the number of Runway Incursions and thus the number of accidents by fighting the underlying causes. In a first stage, it intends to provide the crew with adequate situational awareness with respect to position, operational environment and clearances. If this is still not sufficient to prevent erroneous surface movement, a timely and adequate alerting concept catches the crew's attention when they are at risk of causing a Runway Incursion and prevents the crew from entering the runway protection zone. Certainly, it is much easier and safer to prevent Runway Incursions at a stage before they result in a risk of collision.

However, there have to be provisions for the case where a flight crew encounters a Runway Incursion caused by others. This is where Reactive Runway Incursion Avoidance is required. Mainly based on fused traffic data – using sources such Automatic Dependent Surveillance-Broadcast (ADS-B), TIS-B and ACAS – it surveys the traffic environment and relates it to ownship position and the airport. If an obvious or potential Runway Incursion caused by another mobile is detected, appropriate alerts and, in a second step, conflict resolutions, can be given to the crew, enabling them to react to this dangerous situation. Furthermore, when displaying relevant traffic on the airport moving map, crews may be able to anticipate potentially hazardous situations themselves before alerts are necessary.
When generalizing this concept to all kinds of airfield incursions, one has to take into account, however, that the runway is a special case where virtually no collision can occur that is not preceded by an incursion, as the access to the runway is usually limited to one aircraft at a time. While the concept of protection zones can be extended to all airport elements, a risk of collision might exist independently of an incursion, especially in the case of aircraft on the apron or aircraft queuing for takeoff. Therefore, the more generic term "conflict alerting" seems more appropriate for the taxiway system and the aprons.

4.3. Elements of the Surface Movement Awareness and Alerting System

The Surface Movement Awareness and Alerting System (SMAAS) aims at improving safety and efficiency of aircraft movements on the aerodrome surface, i.e. during taxi, takeoff and landing, and on final approach. The main purpose of this system is the avoidance of Runway Incursions by:

(a) Preventing the own aircraft, by enhanced situational awareness and alerts, from entering, crossing, taking off or landing on runways without a corresponding clearance, and

(b) providing traffic awareness and giving timely alerts if other vehicles or aircraft infringe the protection zone of a runway that is used or has been cleared for own-ship operations.

Generally, the SMAAS supports the aircrew during all ground operations, takeoff and final approach by providing enhanced situational awareness and, if necessary, timely alerts in case of potentially dangerous situations. This functionality is also envisaged as a potential enhancement of the ASAS Package 1 application "Enhanced Traffic Situational Awareness on the Airport Surface" (ATSA-SURF).

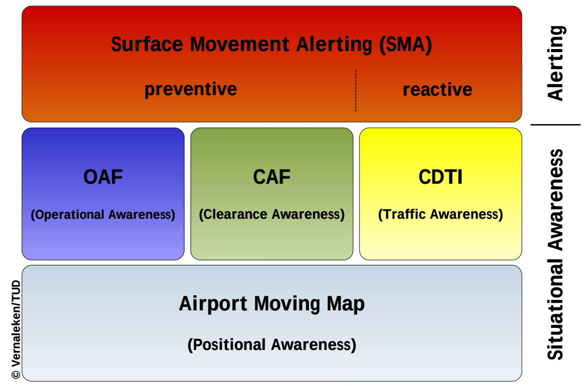

Figure 1 Elements of the Surface Movement Awareness & Alerting System (SMAAS)

The SMAAS consists of two complementary parts (see Figure 1), one aimed at maximizing crew situational awareness in the various domains identified in Section 3, and the other part dedicated to alerting in case this is not sufficient to prevent a hazardous situation. The core element of the SMAAS encompasses an airport moving map based on an ED-99A compliant aerodrome database, which is intended to provide the crew with enhanced positional awareness to avoid disorientation on the airfield, a common precursor of Runway Incursions.
The basic airport moving map can be enhanced by three further situational awareness functions. By displaying traffic on the ground and in the takeoff or landing phases in relation to the airport moving map, Cockpit Display of Traffic Information (CDTI) [1] functionality can be added to the basic airport moving map to increase traffic awareness.
In addition to this, the Operational Awareness Function (OAF) processes and presents relevant information on the operational configuration of the airport, such as runways in use, runway closures, whether Low Visibility Procedures (LVP) are in force and other information typically contained in Automatic Terminal Information Service (ATIS) transmissions (voice or digital) or Notices to Airmen (NOTAM). Furthermore, the takeoff or landing runway used in the FMS flight plan is highlighted on the airport moving map to remind the crew of the FMS settings, which is intended as another measure to prevent takeoff and landing operations on the wrong runway.
Last but not least, the Clearance Awareness Function (CAF), mainly by presenting the assigned taxi route, raises the crew's clearance awareness. While it is obviously preferable to obtain the data required for OAF and CAF in a machine-readable format via data loader and data link, there are provisions to enter

[1] The term CDTI is used here for an enhanced display of traffic information beyond current ACAS in the cockpit. While this may include an additional, separate cockpit display, the preferred solution is an ND-integrated traffic display.

these data manually using the MCDU, the MFD or a dedicated hardware control panel to ensure that the system can work independently of ground infrastructure.

Only if the pure display of all this information fails to prevent a hazardous situation, the second part, the Surface Movement Alerting subsystem, which builds on the same information as the awareness part, comes into play. It can be subdivided into two integral parts, a preventive and a reactive one. The first goal of the Surface Movement Alerting system is to ensure that ownship does not cause a Runway Incursion, i.e. Preventive Surface Movement Alerting. To achieve this, the alerting part is armed using the same airport, operational and clearance data as the awareness part of the SMAAS. This enables specific alerting tailored to the particular operational situation, which is by itself a prerequisite for preventive alerts up to Master Warning level (Level 3). Without operational and clearance information, it would, for example, be impossible to alert the flight crew specifically when they enter a runway that is completely closed due to heavy construction, or when they enter or try to take off from a runway without the appropriate clearances.
In parallel to this rigorous ownship surveillance, relevant surrounding traffic will continuously be monitored to alert the crew if a Runway Incursion caused by others poses a significant collision hazard (Reactive Surface Movement Alerting).

Nonetheless, the main idea behind the SMAAS is not to create additional alerts on the flight deck. Rather, the intention is to enable the crew, by means of improved situational awareness, to avoid potential conflicts proactively at a strategic or pre-tactical level, and to provide alerts only for last resort conflict avoidance. Like the tactical alerts from safety net functions such as ACAS or the Terrain Awareness and Warning System (TAWS), the alerting part of the SMAAS has to be seen as a backup or safety net function for those situations where the pure awareness functions are not sufficient to avoid a hazardous situation.

4.3.1. Airport Moving Map including Cockpit Display of Traffic Information (CDTI)

Because a lack of crew situational awareness[2] is a key causal factor in Runway Incursions and other surface movement incidents and accidents, it is of paramount importance to increase situational awareness on the flight deck. In the context of a standalone onboard system, the obvious initial solution is a moving map display of the aerodrome with a depiction of other ground traffic, mainly aircraft, relevant vehicles and aircraft under tow. Furthermore, a corresponding solution is envisaged by both A-SMGCS and ASAS Package 1 (ATSA-SURF), and thus, an airport moving map in combination with a CDTI forms the backbone of the SMAAS and the basis of all additional awareness and alerting functionality.

In a first step, the airport moving map display is intended to improve positional awareness, because the crew needs to be aware of their position on the airfield at all times, especially in adverse weather conditions, as crew disorientation on the aerodrome surface is a common precursor of Runway Incursions. Secondly, awareness of other traffic is crucial to understand the traffic situation and to anticipate potential traffic conflicts; this also enables a verification of ATC instructions and is not limited to the runway. Therefore, the surrounding surface traffic has to be presented, and the obvious place for this is the airport moving map, as it provides the unique opportunity to display traffic both in relation to ownship and the aerodrome. Otherwise, it is very difficult, if not impossible, for the crew to identify the exact position of surface traffic presented on the display if visibility is reduced. Therefore, it is not surprising at all that a US study by CAA and NASA concludes that efficient surface traffic awareness is hardly possible in the absence of an airport map (Battiste *et. al.*, 2000).

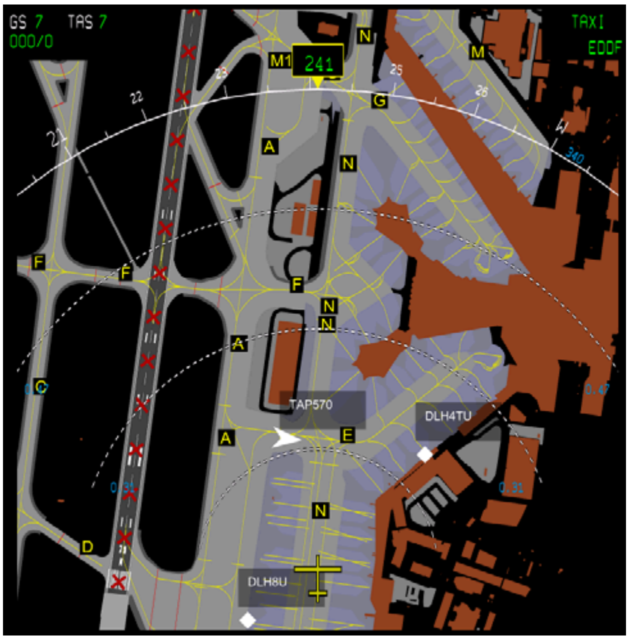

Figure 2 Airport moving map display with ground traffic and display of closed runway.

The concept proposed is that of a dedicated taxi mode for the classic Navigation Display (ND) with all the usual modes, ARC, ROSE and PLAN. The reason for this choice is quite simple. In order not to extend the pilot's scanning pattern to further displays, which might be associated with additional workload, airport and traffic information should be displayed on the Electronic Flight Instrument System (EFIS) displays, all the more as the airport moving map forms the basis of the SMAAS. In particular, this means that there have to be provisions to display high level alerts, as Runway Incursion alerts, for example, are highly safety-critical and will certainly use Level 2 (Caution) and Level 3 (Warning) alerts. Apart from a connection to the Flight Warning System to ensure appropriate display and prioritisation of alerts, this also requires a high-level certification of the display hardware and software employed.
While a side display like the Electronic Flight Bag might be suitable as a retrofit taxi display, it is clearly not desirable to display Runway Incursion and other surface movement alerts on this type of display, which is usually installed at sub-optimum locations and not aligned with the aircraft axis, which in turn might be problematic if an ownship symbol and heading information are displayed. Even if the required certification level to display alerts could be achieved with a side display, this is highly questionable from a cockpit design philosophy point of view. In case of an aural alert, the crew would have to be trained to look primarily at the side display on the ground and at the flight deck displays in the air. Moreover, with respect to the traffic displayed, consistency issues might rise if, especially in case of retrofit, only ACAS traffic is displayed on the ND, while

[2] Of course, there are numerous cases where ATC errors (often also due to a lack of controller situational awareness) led to Runway Incursions as well, but the focus of this thesis is the domain of onboard systems, and thus the analysis concentrates on flight deck causal factors.

the side display potentially features ADS-B traffic including alerts for a particular target that might not be visible on the ND.
Naturally, the ownship position is displayed on the airport moving map, using generally the same symbol as for the airborne mode, to provide position and heading information. For the lowest ranges, a more realistic symbol using the actual dimensions of the aircraft is envisaged. This enables intuitive conflict detection in high traffic density areas, such as the apron, stand areas or when queuing for takeoff. The key issues associated with the display of the position of the own aircraft are navigational precision and integrity.
While an airport moving map on an ND-type display is crucial for SMAAS, this does not preclude the display of aerodrome mapping and traffic data on other display formats such as Primary Flight Display (PFD) or Head-up Display (HUD).

As a general rule, the display of traffic has to be crew-selectable, to allow the pilots to de-clutter the display manually by de-selecting traffic information. However, with the display of traffic simply switched off, the crew might miss a highly safety-relevant traffic alert, and could be confused or react with delay if there is a mere aural alert (e.g. callout) without a corresponding indication on the display. Therefore, in case of a conflict, there have to be provisions for an automatic pop-up of at least the conflicting aircraft, irrespective of display settings. The display of aircraft other than the intruder causing the conflict could be helpful in this situation to aid the crew in planning and executing the conflict resolution manoeuvre.
Furthermore, for reasons of HMI consistency, the traffic symbology used for the representation of aircraft on the ground should be identical, or at least visually and functionally similar, to the symbology used for airborne CDTI applications. If the traffic data source contains heading/track information, a traffic symbol with unambiguous directionality is used. Otherwise, standard ACAS symbology can be applied. Supplementing conventional symbols with additional heading or track vectors is not desirable, as this leads to complex symbols and display clutter. As for the ownship symbol, the lowest moving map ranges from an exception, because a representation of intruder aircraft in their actual size and geometry should be used, provided that accuracy and integrity of traffic data are sufficient. This will allow an intuitive traffic conflict avoidance while taxiing. Based on the ICAO 24-bit Mode S address (e.g. 383E7A for the first A380, F-WWOW), data on precise aircraft type, wingspan, length etc. can be obtained from an onboard database to achieve this, as ADS-B transmits only the wake vortex category of aircraft (RTCA, 2000)[3].

Traffic symbols definitely have to be accompanied by a traffic label which, on the ground, should at least consist of the aircraft callsign or registration. Further information should be available on pilot request. The traffic label display policy is currently subject to research.

As the number of aircraft simultaneously operating on large hub airports is large, traffic de-cluttering is definitely an issue, especially when airport vehicles are also taken into account. For vehicles, the display policy has to consider whether the vehicles are allowed on the manoeuvring area or not, and whether they typically move outside stand areas and vehicle roads on the apron, because an indiscriminate display of all airport vehicles would result in tremendous display clutter. Obviously, vehicles need to be displayed with a different symbol. The underlying assumption is that at least all airport vehicles allowed on the manoeuvring area are equipped with ADS-B, or at least covered by ground surveillance (A-SMGCS) and part of the TIS-B transmission.
Of special concern, from a human factors point of view, is whether parked aircraft should be displayed, while this is unquestionable for aircraft under tow, especially in view of a recent serious incident at Schiphol, where a B767 had to abort a takeoff as a B747 was towed across the runway by accident (RVTV, 2001). For both issues, this is of course connected to the availability of the corresponding data.

Generally, for the display of traffic on the airport moving map, SMAAS is dependent on the availability of traffic data, which is by no means trivial. There is a fundamental difference between ADS-B/TIS-B and ACAS traffic data: accuracy and integrity of ADS-B and TIS-B data depend on the equipment installed aboard 3rd party aircraft or on the ground, while ACAS data (bearing/range) are calculated onboard from transponder interrogations. For ACAS to provide traffic data, all that is required aboard the surrounding aircraft is a working transponder, i.e. equipment that is already mandatory. While TIS-B and ADS-B provide much better positional accuracy than ACAS, ADS-B is not (yet) mandatory, i.e. both equipment and adherence to the published ADS-B standards are voluntary.

4.3.2. Operational Awareness Function

Awareness of the operational status of an airport is crucial for safe and efficient surface movement operations. In particular, it is essential that the crew is aware of the runways in use and potential runway closures or restrictions to avoid Runway Incursions. The goal of the Operational Awareness Function (OAF) is to provide the flight crew with this information in electronic form, and there are at least two approaches to motivate this function:

- to compensate for the disadvantages of the airport moving map compared to paper charts
- to facilitate the creation of a mental picture of the airport including short-term changes and other operationally relevant information by pre-processing and combining this information with the airport moving map[4]

Along with the greater variety and configurability of airport views enabled by range and mode selections, which can be supplemented by panning functionality, the improved positional awareness provided by airport moving map displays is believed to be a huge advantage over conventional paper charts. However, the airport moving map display is limited to quasi-static airport information, because the underlying aerodrome database is envisaged to be updated only every 28 days with the regular AIRAC cycle (Arinc, 2006) that also applies to paper charts. However, when it comes to short-term and/or temporary changes[5] typically conveyed by NOTAM, such as runway or taxiway closures, this limitation turns out to be a major disadvantage compared to paper charts, on which pilots can combine this additional information with the airport representation simply by sketching or writing the changes on the paper, a method

[3] There is no need to sacrifice valuable airborne data link bandwidth for these data, which essentially remain the same as long as an aircraft is not re-registered. The traffic database could be updated along with FMS and airport databases within the AIRAC cycle.

[4] This particularly important for airports that the crew is not very familiar with, i.e. airports they visit only once every few months.

[5] Short-term changes are alterations that occur between AIRAC effective dates; the changes may be either of temporary or permanent nature.

practiced by many flight crews today. The basic airport moving map display does not have any comparable provisions. Introducing these requires extensive considerations on data sources and human factors, but should eventually lead to a by far superior solution[6].

Today, information on short-term changes such as closed runways is typically conveyed by publication via the following services, depending on the available ahead-warning time (shortest to longest):

- **ATC:** Short-term notification of the crew via conventional R/T or CPDLC, e.g. in case a runway is closed because of snow clearing activities, urgent repairs, accidents etc.
- **(D-)ATIS**: notification of runways currently in use (or closed runways) and other information relevant to operational environment, e.g. weather conditions etc.
- **NOTAM:** notification of all relevant short-term changes (temporary or permanent), typically as Pre-flight Information Bulletin (PIB)[7] during the pre-flight briefing.
- **AIP Supplements:** temporary changes of longer duration (3 months and beyond), e.g. runway closure for several months due to pavement replacement

If temporary changes are valid for three months or longer, they are published as an Aeronautical Information Publication (AIP) Supplement. Alternatively, in case extensive text and/or graphics are required to describe an information with shorter validity, an AIP supplement is used as well. AIP supplements often replace NOTAMs and then reference the corresponding serial number of the NOTAM (ICAO, 2004). The information from the services above, the first three of which are routinely directly available to flight crews, is complementary and partially redundant, as e.g. runway closure information might be reported by all of the services listed above.

With the exception of some AIP supplements, all of these services provide textual (or, in the case of ATC, verbal) information only. In this context, however, one of the lessons to be learned from the Taipei disaster is that conveying runway closure information in this textual form is not the optimum solution. In fact, the flight crew of SQ006 had reviewed NOTAM information and was aware that RWY 05R was closed (ASC, 2002), but the disorientation leading to the assumption that they were on RWY 05L while they had, in fact, lined up on RWY 05R rendered this information useless.

In order to prevent crews from taking off from or landing on a closed runway, it is therefore essential to display a closed runway on the airport moving map. Moreover, a conventional NOTAM package for an intercontinental flight typically consists of some 30 printed A4 pages, and the time the crew commonly has for the briefing is not sufficient for a detailed review of all this information. Thus, there is a small, but not vanishing risk that runway closure information is simply overlooked. Furthermore, with just textual information available in both NOTAM and D-ATIS, the crew has to merge this information with their mental picture of the airport. They can be greatly aided in this process by a closed runway representation on the display, which also reduces the risk of error and confusion.

Therefore, to overcome these limitations and to improve the crew's operational awareness, the airport moving map display is used to visualize the FMS runway, runways in use, information on closed runways, closed taxiways, restrictions of either runways or taxiways and temporary obstacles on as well as in the vicinity of the aerodrome. Optionally, further information, such as Low Visibility Procedures (LVP) status, Runway Visual Range (RVR), braking action and other relevant meteorological data, can be indicated to the crew in textual form.

While it is clearly preferable that these data are available in a machine-readable format, thus enabling the automatic display of this information without pilot interaction, there has to be a back-up to enter these data manually.

4.3.2.1. Data Handling and Operational Concept

In order to extract the data required for the Operational Awareness Function (OAF) directly from D-ATIS or NOTAM, several pre-requisites have to be fulfilled. First of all, the corresponding messages must be machine-readable, but a machine-readable format alone is not sufficient, because the data have to be transferred to the aircraft somehow. For D-ATIS information, an implementation via the Airborne Communications Addressing and Reporting System (ACARS) is already widely available, which, together with a machine-readable D-ATIS format, could be used to convey information on the runways in use. A first concept for a machine-readable xNOTAM format based on the Aeronautical Information Exchange Model (AIXM) for NOTAM relating to airports has recently been demonstrated by TUD in cooperation with Eurocontrol to show-case the extended possibilities of AIXM 5.0 (TUD, 2006). Furthermore, there are already live trials for uplinking of enroute NOTAM in plain text (D-OTIS).

For NOTAM information, there are, irrespective of the industrial format eventually chosen, at least three scenarios to achieve this transfer from the ground to the aircraft:

1. The dispatcher compiles NOTAM information in electronic xNOTAM form (as well), and this information is transferred to the aircraft before flight, using either non-volatile data storages (such as flash memory, CD-ROM…) or data links such as gate-link or ACARS.
2. There are dedicated xNOTAM services available via a specialized aeronautical data link, such as ACARS, VDL or SATCOM. The providers could be either the Air Navigation Service Provider (ANSP), the Airline Operation Control Centre (AOCC), or the Aeronautical Information Service (AIS) unit in charge of providing these data.
3. xNOTAM services are available from either ANSP, AOCC or AIS Centre (AIS-C) via an encrypted connection using the onboard Internet, and a fraction of the bandwidth of Internet services for passengers is reserved for the transfer of operational information.

The most likely combination of these scenarios is outlined in the following sub-sections.

Pre-Flight

The responsible dispatcher compiles an (additional) electronic, machine-readable version of the Pre-flight Information Bulletin (PIB), which is transmitted to the aircraft avionics prior to the flight, using either data loaders, e.g.

[6] The use of touch-sensitive devices in the cockpit, which would enable quasi-natural writing of annotations on cockpit displays, cannot be recommended, as it will most likely lead to significant certification concerns (reliability, usage during turbulence etc.) and would additionally require complicated recognition software to make the pilot annotations "known" to the avionics system.

[7] According to current ICAO regulations, a compilation of current NOTAM and other information of urgent character shall be made available to flight crews in the form of plain-language Pre-flight Information Bulletins (ICAO, 2004).

- Ethernet connection to crew laptop or portable Electronic Flight Bag (EFB),
- CD-ROM,
- Compact Flash,
- USB Stick or other non-volatile storage media

or data links such as Gate Link/WLAN or ACARS. At remote airfields, and on suitably equipped aircraft even through on-board internet, the crew can also download this information from their Airline Operation Control Centre (AOCC) using their crew laptops or EFB. The main idea behind this is that, at least for flights of short duration, the majority of applicable NOTAM is already available prior to the flight.
An index file supplied with this electronic version of the PIB, keeping track of the NOTAMs contained, will facilitate subsequent updates in flight and helps to ensure that all relevant information is uploaded during an update, whereas the time filtering window concept proposed by the CASCADE OSED (Bousmanne & Tonea, 2005) cannot fulfil this requirement with certainty.

NOTAMs and other important information contained in the electronic PIB are then processed by the Operational Awareness Function (OAF) and displayed on the airport moving map. This can be achieved either in an integral representation, i.e. with a dedicated symbology for e.g. runway closures as part of the moving map application, or as an overlay in a separate display layer.
Initially, the explicit display of NOTAM information on the airport moving map would have to be limited to temporary and permanent status changes (e.g. runway or taxiway closures, restrictions or renaming) of elements already contained in the Aerodrome Mapping Database (AMDB), because it is, in view of the certification effort and associated costs, highly unrealistic that there will be a certified onboard application processing changes to the airport geometry, such as new or broadened taxiways, directly into the AMDB (or a copy thereof), and there are – with few exceptions such as new parking positions on an already existing apron – several severe issues, both in terms of human factors and certification, with displaying changed geometries as an overlay to the original AMDB. Simple additional non-AMDB geometries like new or temporary obstacles form an exception. Likewise, complex restrictions would be merely indicated by an attention-getting symbol on the moving map and the serial number of the associated NOTAM at this first stage. Interactively or using the MCDU/MFD, pilots could then review the associated text of the NOTAM as on paper. Generally, the crew must be able to review all NOTAM contained in the electronic PIB in plain text, as this is an ICAO requirement on the PIB in general (ICAO, 2004).

As a first enhancement of this basic ePIB process, the dispatcher could check in the process of compiling the electronic PIB, most likely aided by software tools, whether applicable NOTAMs contain changes to the airport geometry. If this is the case, he could verify with the AMDB provider whether an off-cycle update (i.e. a new version) of the relevant AMDBs already containing these changes is available. Alternatively, database providers could submit changed AMDBs to subscribing airlines (or airplanes) as soon as they are available. If this is the case, the corresponding new AMDB is acquired and uploaded to the aircraft together with the electronic PIB. If not, the geometry changes are indicated as before.
If the crew has access to the Internet, either on the ground or through an onboard internet service, updated AMDBs could be downloaded from the AOCC, and even a direct connection to the AMDB provider could be envisaged. Currently, however, airlines, who have the ultimate responsibility for the safety of their aircraft, validate all data received from database vendors before they are deployed to aircraft, which would rule out the latter solution.

Further improvements to the OAF processing should then focus on complex restrictions. Wherever possible, these could be evaluated using ownship data and then presented as tailored usability criteria for the airport element that the restrictions refer to. For example, if a taxiway is temporarily restricted for A380-size aircraft, but there are no limitations for A320 family aircraft, the A380 crew would see the taxiway marked as unusable, optionally with a reference to the corresponding NOTAM if they request additional information on the element, while the A320 crew would not be bothered with information not relevant for them; nothing would be displayed.

The electronic PIB solution has the huge advantage that it is, in principle, completely independent of any advanced AIS functions or formats. Therefore, it could be realised and introduced by an individual manufacturer or airline for a particular aircraft type (or all), and is, in that sense, an autonomous onboard function. Of course, it is preferable that NOTAM information etc. is already provided by the AIS-C in machine-readable format, but this conversion step could very well be performed by the airline itself, or the provider of the corresponding databases.

To ensure that aircraft are always deployed with up-to-date airport geometries in the future, pursuing the way of processing temporary or permanent geometry changes into the AMDB directly from NOTAM at the airline or even onboard the aircraft is both highly unrealistic and inefficient. Rather, the solution should be sought in amending the regulations pertaining to these geometry changes, as they do not occur "out of the blue", but are usually planned a comparatively long time before they become effective.
Therefore, by regulation, airport geometry changes should be announced 5 days in advance and must be notified no later than 72 h before they become effective[8]. The time values given are initial suggestions and assume that efficient and partially automated update processes at database providers ensure together with shift operations that updated AMDBs can be made available within 12 h, such that airlines would routinely have sufficient time to deploy aircraft on ultra-long-haul flights (up to 18 h duration) with AMDBs containing up-to-date airport geometries. Otherwise, the time values given above have to be increased. Generally, the geometry changes are then automatically activated at the effective dates or, in case of delays, by digital NOTAM or CPDLC messages. Prior to that, the corresponding airport elements are represented as closed or under construction.

In-Flight

For initial implementations, if NOTAMs are cancelled while the aircraft is airborne, the crew is advised of this either by ATC or by the AOCC via ACARS. Using the MCDU/MFD, the crew then cancels the corresponding NOTAM manually.
Runway closures and other short-term changes not contained in the onboard NOTAMs that are transmitted to the crew in-flight via conventional ACARS (from AOCC), D-ATIS or directly by

[8] These comparatively short periods of time have been chosen to have a chance take into account temporary geometry changes as well, e.g. a provisional taxiway if a major taxiway is closed for reconstruction on short notice, potentially after an accident.

ATC can be entered manually using the MCDU/MFD. On aircraft with an interactive Cockpit Display System (CDS), pilots can set runways and taxiways or taxiway segments as closed by direct interaction with the corresponding moving map elements. As stated above, this manual interaction with the OAF is necessary to prevent the display of erroneous, outdated information, and to arm the Surface Movement Alerting part with the correct data.

For more advanced implementations, the transfer of NOTAM in machine-readable format via airborne datalink or onboard Internet can be envisaged, either via the AOCC, which could consolidate and pre-select information, or directly from the ANSP or AIS-C. At any rate, the ePIB index file will be used to determine which additional NOTAMs have to be transferred to the aircraft, and whether NOTAM cancellations are necessary. If this process takes place at the AOCC, there is even no need to downlink the index file, as it is already available to the dispatcher, who can then send the files for the required additional NOTAMs, along with an updated index file, to the aircraft[9]. For other solutions, the update process would be initiated by downlinking the ePIB index file to the NOTAM provider. Generally, the policy of having one NOTAM per file, with the file name containing the serial number of the corresponding NOTAM, would allow an incremental update of the ePIB with minimal risk of corrupting the data already available on board. The cancellation of NOTAMs could be realised by removing the associated NOTAM file entries from the index file, while leaving the file itself in storage. This avoids the problem of sending file deletion commands via data link and enables the crew to switch back to previous versions of the ePIB in case an obviously corrupted or erroneous new index file is received.

At any rate, though, the manual data entry and cancellation option must still be maintained to ensure that information given to the crew on very short notice is available to the avionics.

4.3.3. Clearance Awareness Function

The Clearance Awareness Function (CAF) enables the display of the taxi route assigned by ATC and further clearances. This requires that CPDLC clearances are machine-readable. Alternatively, the taxi route can be entered manually as a series of taxiway identifiers, and the CAF computes the associated route. As many crews use the scratchpad of the MCDU already to write down the taxi clearance, a solution using a dedicated MCDU page for a manual entry of the clearance would not create too much additional workload. Of course, for both the Operational Awareness Function and the Clearance Awareness Function, the risk that the entry of incorrect data by the crew poses, has to be considered versus the benefits.

Obviously, CPDLC clearances are the preferred solution. Next to the taxi route, line-up and takeoff clearances can be presented to the crew visually and, as an option, aurally. The basis of traffic and aerodrome mapping data on the display also provides fully new opportunities to visualize clearances involving other aircraft, for example "You are No. 2 after Lufthansa 123…"

Furthermore, a technology for broadcasting CPDLC clearances to all parties involved can be envisaged. CPDLC-B might be a powerful enabler for advanced clearance awareness. First of all, it could be used to display the clearances assigned to another aircraft or mobile on pilot request. Furthermore, CPDLC-B could compensate for the missing party line effect when using CPDLC as envisaged today. Pilots could choose to follow the clearances issued for others on an ECAM or MFD screen as in an online chat, optionally. Even more, this could help to reduce problems due to language proficiency, as the crew could choose their preferred ICAO or even local language to display clearances. Last but not least, access to the clearances of other traffic could help to make alerting more specific and decrease the number of nuisance alerts.

4.3.4. Surface Movement Alerting

Cockpit alerts can be sub-divided in two major categories: alerts addressing the internal (system) state of the aircraft and alerts linked to the external environment. Examples of alerts concerned with aircraft systems are e.g. engine fire or brake overheating alerts, conveying information on abnormal or critical system states to the crew. ACAS and TAWS provide, in addition to basic situational awareness functions, mainly tactical alert information on external threats like terrain and traffic. By nature, SMAAS is an onboard surveillance function like TAWS or ACAS.

However, although the design approach should be an independent onboard system, provisions for interacting with ATM systems have to be made. This includes basic A-SMGCS surveillance data services such as TIS-B and CPDLC as well as alerts transmitted by high-level A-SMGCS systems. This requires an onboard alert consolidation and prioritisation function for cases where simultaneous ground-generated and onboard-generated alerts are present.

A crucial point in the design of both Preventive and Reactive Runway Incursion Avoidance systems is the question whether these systems should be limited to the detection of potential runway incursions, or whether they should also provide the flight crew with a suggestion for conflict resolution. Regarding safety net functions, pilots usually expect instructions what to do in case of a master warning (Level 3) alert. As an example, current TAWS implementations like the EGPWS urge the pilot aurally and textually to "PULL-UP" or to "AVOID TERRAIN", as per TSO-C151. ACAS provides the crew with similar instructions in case of a traffic conflict and might advise a climb or a descent.

Naturally, such resolution advisories are also desirable for systems designed to avoid Runway Incursions. However, the fundamental underlying question is whether a universally valid conflict resolution exists for each imaginable Runway Incursion scenario. For obvious reasons, it is furthermore of utmost importance to prove to the certification authorities that the conflict resolutions provided by the system do not lead to hazardous or catastrophic situation (FAA, 1988). As a further complication, in the rare event that the system creates false or nuisance alerts, it has to be warranted that the crew obeying these erroneous alerts does not lead to major or catastrophic failures, either.

In the case of incursion avoidance functions for airborne aircraft, preventive or reactive, the situation is comparatively easy. If a Master Warning alert occurs on final approach, the crew can initiate a go-around without endangering their and the passengers' lives. Although this might lead to increased fuel consumption and economical disadvantage in case of a nuisance or premature alert, the application of the missed approach as a standard procedure can be considered as safe – it is already applied as a runway incursion conflict resolution today if the pilot detects an incursion visually or is advised of the imminent danger by the controller. Of course, there might be rare situations, e.g.

[9] To ensure that the ePIB index files are sent to the correct aircraft, an index file naming convention containing the flight number, date and UTC time could be applied, e.g. `LH4679_20060608_1230.PIB` for a Lufthansa flight on June 8, 2006, with the PIB created at 12:30 UTC. This way, the onboard systems can double-check whether the received files are determined for them or not.

an emergency landing due to an engine fire, or an aircraft low on fuel, where this manoeuvre might lead to disaster, but in these cases, the runway is usually reserved for the landing aircraft, thus minimizing the risk of an additional Runway Incursion. Furthermore, the alert could be inhibited in case of an engine fire or insufficient fuel resources. It can, thus, be regarded as proven that a valid conflict resolution exists for most cases of runway incursion alerts for airborne aircraft.

The situation is completely different for Runway Incursion Avoidance functions for aircraft manoeuvring on the ground, and especially for the reactive case. Naturally, the severity of the conflict and feasible resolutions depend on the relative positions, speeds and closure rates of the two mobiles. For conflicts involving low closure rates, e.g. in case a Runway Incursion is detected before the crew commences the takeoff roll or very shortly after, bringing the aircraft to a full stop on the runway and/or vacating the runway at one of the nearest exits can be assumed to be the most advantageous conflict resolution.
However, with higher closure rates and decreasing distance, conflict resolution becomes more complicated. For example, during take-off, as the speed approaches V_1 and as the remaining distance to the intruding mobile decreases, there might be no margin left to resolve the conflict in this conventional manner (if at all).
Under these circumstances, even unorthodox conflict resolutions, like vacating the runway into the grass, and their consequences have to be considered very carefully. After all, above a certain speed, the system would thus be mandating an action resulting in injuries to passengers/crew and at least substantial damage to the airframe, if not a total hull loss. Close to V_1 the consequences of leaving the runway anywhere could be equally serious for passengers and crew as colliding with the intruder. While it is obvious that the safety of passengers and crew is the first concern in these considerations, there is clearly an ethical problem: To what level are injuries and even fatalities resulting from such manoeuvres acceptable to avoid a more serious collision? What if an aircraft vacating the runway to avoid a collision gets completely out of control and hits another aircraft on an adjacent taxiway or runway? This issue is particularly important in the light of certification, especially with regard to the possibility of false alerts. Generally, it is questionable whether a system that proposes conflict resolutions potentially leading to injuries and significant airframe damage will be accepted by regulators, operators and pilots.
Therefore, eventually, the difficult and complex decision on how to react to a detected Runway Incursion caused by others could still be left to the crew in the end.
Irrespective of the previous discussion, the system could be endowed with coordination functionality and interact with other similarly equipped aircraft, much in the same way conventional ACAS coordinates resolution advisories.

5. OUTLOOK

The first validation results for the Surface Movement Awareness and Alerting System (SMAAS) reported in (Vernaleken, 2006) indicate that the approach taken is a valid solution to the problem of Runway Incursions, as it supplies pilots with operationally relevant and desired information at different levels, ranging from the mere display of information to Master Warning (Level 3) alerts. Future work will focus on the enhancement of the current system to include Preventive Runway Incursion Alerting, and on the design of novel human-machine interfaces for CPDLC technology.

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