Decision-support methodology to improve airport ground movements efficiency
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Ricardo Machado[1], Gabriel Pestana [2].

1) Instituto Superior Técnico, Lisboa, Portugal
ricardo.machado@ist.utl.pt

2) INESC-Inovação, Lisboa, Portugal
gabriel.pestana@inesc-id.pt

Abstract

In complex environments, as in the case of an airport, decision-makers need to be continuously informed about ongoing operations. Such service requires the implementation of a control mechanism capable of providing an effective support at managing traffic ground movements in real-time. Nowadays, technology became available for the implementation of different levels of location-based services aiming to ensure the safety and efficiency of airport surface traffic under all circumstance with respect to traffic density, visibility and complexity of the airport layout. The paper presents an in-depth analysis of a methodology that implements the routing and guidance requirements specified by the Advanced Surface Movement Guidance and Control System (A-SMGCS) defined by ICAO and EUROCONTROL. This includes the analysis and discussion of a site test implementation of the proposed methodology with traffic data from Lisbon airport, in addition to an algorithm to dynamically deal with conflicts and deviations from assigned routes.

Keywords: A-SMGCS, Location-based services, Routing, Guidance

1. Introduction

Improving the safety and efficiency of aircraft and vehicle movements in the European airports in all weather conditions is the main objective of the A-SMGCS strategy defined by the European Organization for the Safety of Air Navigation (EUROCONTROL) and by the International Civil Aviation Organization (ICAO). From a safety point of view, the A-SMGCS strategy is particularly relevant regarding the avoidance of incidents caused by traffic congestions or lack of synchronization. ICAO also defines the A-SMGCS as a "system providing routing, guidance, surveillance and control to aircraft and affected vehicles in order to maintain movement rates under all local weather conditions within the Aerodrome Visibility Operational Level (AVOL) whilst maintaining the required level of safety" [EUROCONTROL 2010].

A-SMGCS has four distinct levels of implementation, which include surveillance, automated monitoring and alerting functions, routing, and automated aircraft guidance functions, with increasing implementation complexity from level one to level four [ICAO 2004].

- **Surveillance** (level I): positioning of moving objects within the airside area of an airport.
- **Control** (level II): detection and resolution of safety hazards and other conflicts.
- **Routing** (level III): generate a route for each aircraft in the movement area of an airport, allowing adapting a possible path deviation.
- **Guidance** (level IV): indications to allow the pilots maintaining their assigned path.

The implementation of the A-SMGCS requires the combined use of accurate localization techniques, fast wireless communication networks in the airside, low cost embedded systems installed on-board the vehicles, centralized and on-board control services for surveillance and guidance, and geographical information systems enabling advanced graphical-user interfaces for mapping the airport environment. In recent years appropriate technology became available for implementation of the different levels of A-SMGCS. Indeed technological advances in wireless communication together with the progress in Global Navigation Satellite Systems (GNSS) and Real Time Locating Systems (RTLS) allow small electronic receivers to calculate the precise time and determine their location within a few meters [Casaca 2009].

In fact, the integration of location-based data collected from state-of-the-art wireless technologies with performing embedded systems enables, for instance, the transmission of data to a central system. This data includes the taxiing aircrafts identification, position and speed that is integrated with flight information to automatically determine the route from current position to the corresponding parking place [Casaca 2009]. During periods of low visibility, such location-based services would enable airport stakeholders to obtain valuable information about on-going surface movements without having to exclusively rely on radar data and radio communications to identify conflicts.

Along the last decades, the growth in air traffic caused an increase of the workload of both field and control personnel, which have to manage and coordinate ground movements to achieve tied schedules. Such complexity leads to the lack of resources and very often the pressure imposed by airline companies to reduce turnaround times, causes safety breaches, in particular those derived from human error. Despite of such stressing conditions, surface operations mostly rely on the principle of "see and be seen" to maintain a safety spacing between vehicles and aircrafts or even to identify intersections. However, relying on visual observations becomes complex and often misleading, particularly at rush hours when many operations must be managed simultaneously, sometimes under low visibility conditions [ICAO 2004].

Nowadays, only a limited set of airports are equipped with the first two levels of A-SMGCS, for instance Frankfurt Main (Germany) or Charles De Gaulle (France) have invested in new electronic means to provide accurate and reliable positioning information [EMMA 2005]. However, levels III and IV are only predicted to be implemented from 2015 onwards [Rees 2008]. This paper presents a solution that was implemented following the methodology proposed within an MSc thesis for creating a system capable to provide location-based services in compliance with the A-SMGCS requirements for levels III and IV. The methodological approach takes a graphical representation of all the airport taxiway segments, creating a graph with nodes and arcs, where each taxiway segment is represented as an arc and segments intersection as a node. A routing algorithm takes all the static information to generate the

shortest path between every pair of nodes. The conflicts resulting from dynamic information (e.g. conflicts derived from uncoordinated aircraft surface movements) are solved by a Mixed-Linear Integer Programming (MILP) solution that addresses the dynamic behaviour of the ground movements by re-routing the mobiles through alternatives or simply by defining a set of holding points.

The remaining of the paper is organized as follows. Section 2 presents the state-of-the-art concerning the location technologies and the static and dynamic algorithms. Section 3 starts by identifying the implementation requirements, followed by a detailed description of the methodological approach. Section 4 presents the business context used to evaluate the solution. The results of the site test are presented in Section 5. Finally, conclusions and future work are presented in Section 6.

2. Related work

Nowadays, the monitoring of airport procedures can be automated through the use of Location Based Services (LBS). Such services and related location technologies have evolved to a point that enables the implementation of business processes requiring a continuous surveillance of moving objects not only with a good precision but most of all with a higher accuracy to avoid false alerts. Such LBS start to be seen by airport stakeholders as a strategic tool help them better manage ground operations, minimizing safety hazards while enhancing operational efficiency. The following sections outline some technological issues to support the surveillance of ground movements in a critical infrastructure, as it is the case of an airport.

2.1 Location Based Services

In an airport environment, surveillance of moving objects can be handled by location-based services. It requires the coordination of multiple components, namely onboad units (e.g., vehicles) equipped with location-based technologies capable at transmitting their position continuously. Such onboad units are known as cooperative devices. The existence of a communication infrastructure responsible to transmit, in real-time, the reported position to a central system, together with a main application that centralizes the processing of all location-based information to detect any safety hazard situation or infringements to business rules. This typical architecture for the implementation of LBS is presented at Figure. The segmentation into a set of technological components is recommended not only to support the autonomy of the work to be performed by each component but most of all to cope with scalability requirements (e.g. in large airports).

A LBS is defined by the international Open Geospatial Consortium (OGC) as a "wireless-IP service that uses geographic information to serve a mobile user" [Steiniger 2006]. LBS systems provide services that are based on the current location of the monitored object. Besides positioning data, the service can operate with additional parameters such as destination, circulation direction or speed limit [Casaca 2009].

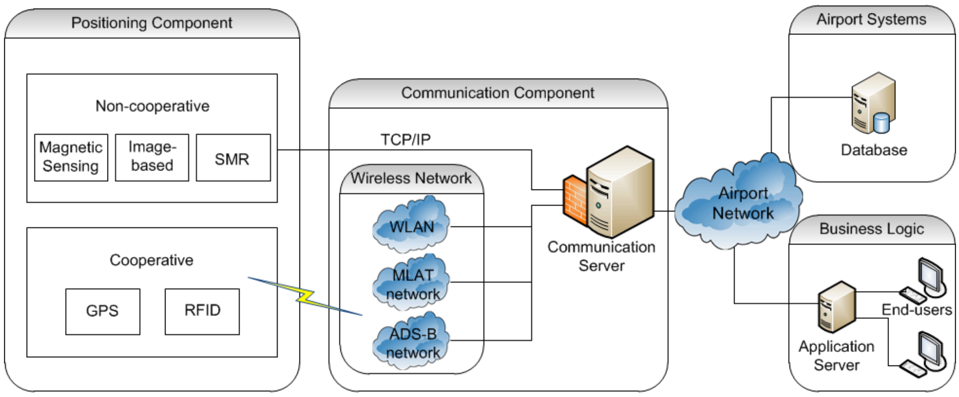

Figure 1 – LBS infrastructure[1].

The Positioning Component represented in Figure 1 is responsible for collecting positioning data related to moving objects. Cooperative vehicles are equipped with a transponder that is able to communicate its location to the service provider. But monitoring non-cooperative objects requires the ability to detect any mobile within the operational area without having the vehicle equipped with any location-based device [EUROCONTROL 2010].

The Communication Component is responsible to perform the validation and data fusion of all positioning data transmitted by each device through a wireless network or a TCP/IP data link [Casaca 2009]. The data fusion consists in transforming heterogeneous positioning data into a standard format that the application server understands.

The Business Logic Component is responsible for computing the positioning data against pre-defined business rules, as well as performing the data fusion with business data collected from existing Airport Systems, for instance mobile terminals, flight scheduling, operational tasks assigned to field workers and airport status. At the Application Server, the location of each object is presented as a moving point feature over a map-based layout, defined by a set of overlapped thematic layers which characterize the current status of the airport. The airport spatial context and point features are managed by a Geographical Information System (GIS) engine, described in more detail in Section 2.3.

2.2 Location Based Services technologies

The technologies that allow the interaction between the Positioning and the Communication Components are divided into two categories: location technologies to detect the geographic coordinates of a moving object and communication technologies to transfer the data throughout a network link for indoor/outdoor operational scenarios. An indoor environment relates to a place where the satellite signal can not be reached (e.g. inside a building), while an outdoor environment is all places where it is possible to maintain a continuous line-of-sight to the satellite. The transition between these two environments is another critical situation that might require location technology redundancies (e.g., GPS, RFID and Wi-Fi) [Qi 2008].

Table 1 summarizes the technologies used to test and validate the quality of the proposed solution for both environments taking into considerations their accuracy, reliability and range.

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[1] Based on [Casaca 2009].

Technologies		Cooperative	Indoor	Outdoor	Accuracy	Reliability	Range	Cost
Location technologies	Magnetic Sensing	No		✓	< 10m	High	< 20m	Low
	Image Based	No		✓	-	Medium	-	Medium
	SMR	No		✓	< 5m	Medium	2-3km	High
	GPS	Yes		✓	5-10m	High	-	High
	RFID	Yes	✓		5cm-5m	High	3cm-10m	Low
Communi-cation technologies	Wi-Fi	Yes	✓	✓	2-100m	Medium	50-100m	Medium
	ADS-B	Yes		✓	-	High	≈3km	Medium
	MLAT	Yes		✓	6-60m	High	-	Medium

Table 1 – Location Based Services technologies [Gao 2008] [Besada 2001] [Lukin 2008] [Roxin 2007] [EMMA 2005] [Muthukrishnan 2005] [Australian Government 2006] [Miyazaki 2009].

Although RFID is the more accurate technology, it only provides a very short communication range. However, it is the most promising one for indoor environments. On the other hand, ADS-B and GPS seems to be the most suitable technologies for the detection of aircrafts and vehicles, respectively. Besides their high reliability and large coverage range, these outdoor technologies achieve an accurate and cost-effective positioning. On the other hand, SMR is an expensive solution that captures every moving object in a large coverage area, with a medium level of reliability.

2.3 Geographical Information System

The previous sections described how LBS provide the position in real-time about every moving object within the airside of an airport. This information is required to improve situational awareness. To keep airport stakeholders, at the control centre, well informed about on-going operations it helps providing a map-based display with GIS functionalities enabling dynamic interactions with the map features.

This information is managed by a GIS engine that provides an abstraction of the layout complexity as a set of independent thematic layers, each one representing a specific operational area or providing particular features. These layers include taxiways, runways, stand parking areas, as well as traffic information labels that are refreshed every second. The airport layout is represented as a set of overlapped operational areas, each one with a specific meaning and metadata that are relevant to characterize events within the exact spatio-temporal instance thei occur. This means that the GIS engine the features of each layer are assigned with a set of metadata. For instance, taxiways have for each segment a length, traffic circulation rules and a specific speed limit [Casaca 2009]. This information allows generating a weighted graph that corresponds to a network of segments, where each arc has a weight associated. This weight is the length of the segment linking two nodes. The distance between every pair of nodes is stored in a two-dimensional adjacency matrix, each cell representing the length between two nodes [Roling 2008].

2.4 Routing algorithms

The metadata provided by GIS allows generating a weighted graph that is mainly used by the routing algorithms to solve the shortest path problem. This consists at finding the best path between a source node and a destination node. Metadata are quite relevant at this process because they enable, for instance, accurate definition of the cartographic position of each sub-element of the segment, the length of the segment and the circulation rules associated to a specific segment [Casaca 2009]. There are several algorithms providing static route planning, within the scope of this paper following three algorithms were considered.

- **Dijkstra** solves the shortest path problem by searching the minimum length from a given source node to all the other nodes in the network. The algorithm uses two vectors: one for the set of unprocessed nodes and a second vector with the shortest path distance found between the origin and each of the other nodes. Starting from the original node, each unprocessed node is processed individually in order to select the immediate successor that is closer to the current node. At the end, the second vector has the minimum distances values from the origin to all the other nodes in the network. So, the shortest path is determined by checking which nodes belong to the path, starting from the destination to the origin. This is possible because the length of each arc is known and the minimum distance between the origin and the other nodes is stored in the second vector. By comparing the value to the destination and the distance to its previous immediate successors, the node before the destination is determined. The same process is repeated until the origin node is achieved [Chao 2010].
- **A*** follows the same principle as Dijkstra, but uses a heuristic function that estimates the more promising node that will allow to reach the destination first. While Dijkstra have to check every node of the network to make a decision about the direction to follow, A* is based on a prediction that indicates which node is closer to the destination. The better the estimation accuracy is, the better the performance of the searching algorithm is [Yao 2010].
- **Floyd** was designed to provide the shortest path between each pair of nodes in a weighted network. The algorithm works in three sequential steps: first, it computes the shortest distance between each pair of nodes, then updates a route matrix that contains the intermediate nodes connecting each pair of nodes, and finally the optimal path is determined [Wan 2007].

The A* algorithm uses a heuristic function to estimate the node that will first lead to the destination. So, it solves the shortest path problem faster than Dijkstra, when considering the computational complexity. On the other hand, Floyd is more complex as it computes the shortest path between all pairs in the graph. However, Floyd is considered the most appropriate static path-planning algorithm for complex traffic environments. Although it has the highest computational complexity, it determines the shortest path between every pair of nodes with a single execution. On the contrary, Dijkstra and A* requires the analysis of almost all the nodes to compute a single path between two nodes.

2.4 Guidance programming models

Although the routing algorithms solve the shortest path problem, the static computation of routes for each aircraft must be enhanced with dynamic mechanisms in order to manage and coordinate all ground movements in real-time. Dynamic route planning implies that the assigned routes are rearranged according to the traffic situation over time [Xin-min 2010]. Two different approaches to the problem are addressed, namely a Colored Timed Petri Net (CTPN) model and a Mixed-Integer Linear Programming (MILP). In spite of being different, these guidance programming models follow the same principle: assign uncoordinated static routes for each moving object and then avoid the conflicts by re-routing the moving object to an alternative route or simply by holding it at a certain node.

- **Petri Net** is a particular representation of the weighted graph, modeling the system with three different components: places, transitions and arcs. A place represents a discrete element, such as a taxiway segment in the airport movement surface. The transition, as the name implies, is the passage from one input place to an output place. The transition is fired when a set of conditions are satisfied. The arcs are the connecting links between places and transitions. The CTPN is an improved Petri Net model, which provides a dynamic adaptation based on a set of constraints, where the state of the system is continuously verified in order to predict conflicts and provide a resolution. A constraint is defined as a condition that must be satisfied in order to fire the transition. For instance, an aircraft is not allowed to cross a transition until all the conditions are satisfied. In the case there is a conflict, the aircraft is retained a delay time that will assure the synchronization between all movements. Otherwise, the transition is fired and the token passes from the input place to the output place [Yu-ting 2009].
- **MILP** represents a traffic movement surface as a space-time network, where the occupancy of each node changes over the time. This model is divided in two main steps: first assigns an individual ideal route for each mobile target and then solves the conflicts caused by the uncoordinated paths. The first step allows scheduling, periodically, the ground movements in time. Such movements may involve conflicts, namely when there is more than one target using the same link at the same time or if there are two targets crossing each other. So, the conflicting routes are re-routed to an alternative path to the same destination or a delay is applied to avoid such conflict [Roling 2008].

In the Petri Net approach, the algorithm coordinates the movements by defining constraints that have to be validated whenever an operation takes place, whereas the MILP solution solves the conflicts by assigning alternatives routes or by defining a set of holding points. MILP is then the preferred dynamic path-planning algorithm since it provides a continuous guidance to moving objects with a simple and accurate mechanism.

3. Methodological approach

This section addresses the proposed methodology to implement levels III and IV of A-SMGCS. The main contribution consists at extending an existing A-SMGCS platform, named A-Guidance that already provides real-time positioning of aircrafts and vehicles. The A-Guidance also includes an alert mechanism to inform decision-makers and vehicle drivers about safety incursions or business rules infringements. This system is experimentally deployed in two airports in Portugal, where the ground movements are represented in real-time on a GIS display to airport stakeholders in order to improve their ability to manage surface movements [Casaca 2009]. Nevertheless, the system does not provide routing and guidance functionalities. The proposed methodology is therefore focused at implementing such functionalities, within the Business Logic Component of the LBS infrastructure presented in Section 2.1.

The methodological architecture is presented in Figure 2. It is divided into three main components, namely Surveillance, Routing and Guidance that actively interact with the Application Server. A-SMGCS control functions related to guidance procedures were embedded in the guidance component, where guidance conflicts are detected and resolved. As shown, the routing component manages the input data to be able to generate the weighted graph and compute the routes in run time. The required input data are mainly:

- Line segments extracted from the polygon shapes of the airport surface.
- Operational data with information about flight schedules.
- Business rules that mostly define the circulation rules.

The proposed routes are monitored by the Guidance component that is responsible for avoiding conflicts, at this phase only between aircrafts crossing the same taxiway intersection, a persecution or even a frontal collision [Li 2009]. Such situations will automatically trigger an alert procedure that must be resolved by the controllers, which have a set of alternative options provided by the guidance function. For instance, when a pilot fails a runway exit, the system automatically recalculates an alternative path to the same destination (i.e., stand position).

The Floyd algorithm was the routing algorithm that was implemented, since it provides the shortest path between every pair of nodes at any time without additional computation. This is particularly useful when there is a real-time requirement to compute alternative paths from anywhere to everywhere within a very short period. Therefore, the Floyd algorithm is the most powerful algorithm because, although it spends more time computing all paths at the beginning of the execution, it allows determining a path extremely fast during the execution.

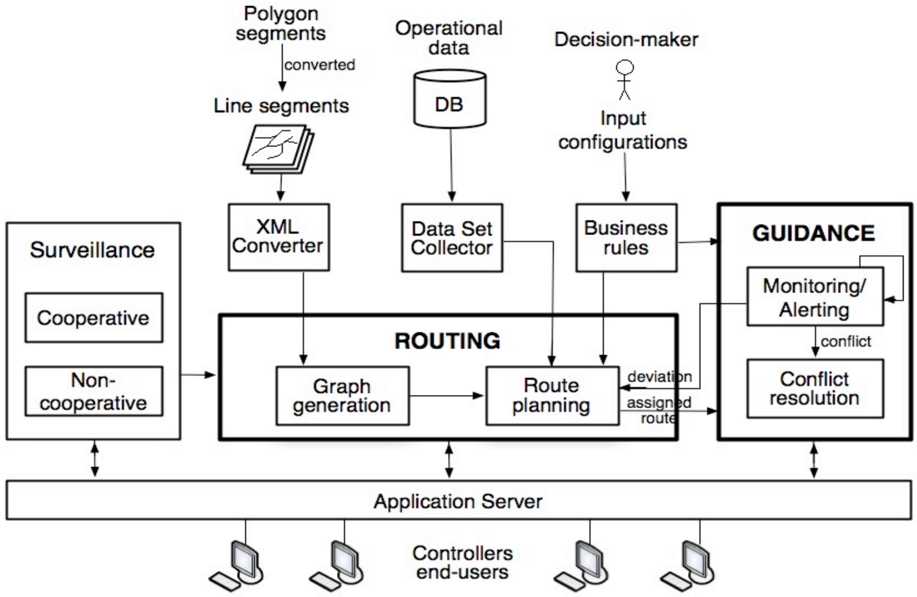

Figure 2 – Methodological architecture.

On the other hand, the guidance function was implemented based on the MILP model because it allows scheduling the surface movements in a very simple and effective way. Periodically, the guidance function assigns a path to each aircraft, while avoiding conflicts with the other movements. Then, it monitors the path followed by each pilot with the location data provided by the surveillance component and, if a conflict is detected, it reorganizes the pre-defined paths.

4. Case study

The case study focuses on the airport domain, more precisely on the movement area that is composed by the manoeuvring area and a restricted area called apron. The manoeuvring area is used by aircrafts for take-off or taxing ground movements. This area is organized by a set of taxiways and roadways used by aircrafts and airport vehicles, respectively. The apron area is the operational area of the airport used for parking aircrafts, boarding passengers, and where most of ground handling activities occurs. Aircrafts have to follow a route from the runway to the Stand area (or vice versa) [EUROCONTROL 2010]. Thus, there is a need to guide the aircraft along the route, while considering the location of other moving objects (people, vehicles and other aircrafts). Such need requires the application of the methodology described in the previous section, in order to take advantage from an LBS infrastructure to provide routing and guidance functionalities. The case study operates with data collected from the A-Guidance system that is installed at Lisbon airport extending its capabilities to cope with levels III and IV of the A-SMGCS requirements.

The A-Guidance software was developed by the INESC-Inovação (INOV) team, in collaboration with ANA-Aeroportos, the main airport management company in Portugal. This system is deployed at Porto and Lisbon airports, where several experimental tests have been performed in order to validate the safety and functional requirements of an A-SMGCS implementation. The current implementation relies on a LBS infrastructure where vehicles are

equipped with GPS/EGNOS receivers to transmit their position through a wireless network covering almost the entire movement area of the airport. Lisbon airport is equipped with a SMR enabling Aircrafts to be detected.

An airport is a very complex and regulated environment, where there are a set of business rules defining, for instance, circulation rules and conflict resolution rules. On the one hand, the circulation rules comprising for instance speed limits, traffic circulation rules, together with traffic signalling. Another rule is that aircrafts cannot move backwards or perform a tight turn (e.g. with an angle below 100º), forcing to re-route the aircraft through alternatives [Roling 2008]. The aircrafts must also maintain a safety distance from every obstacle, in order to avoid collisions. Conflict resolution requires the adoption of some rules related to aircrafts categories, the bigger the aircraft the higher the priority. In other words, the system must decide which aircraft has the highest priority. For instance, despite bigger aircrafts have circulation priority against smaller ones; departing aircrafts have circulation priority against any arriving aircraft. When a conflict takes place, the aircraft with lowest priority has two options: wait in a holding position until the other aircraft passes or find an alternative path to its target destination. At the current version the option that is less time consuming is selected.

5. Test and evaluation

The evaluation of the proposed methodology was based on a simulation environment applied to the Lisbon airport test bed, containing two runways and about 306 segments, including taxiways and stands. The routing and guidance functionalities were tested in this airport, with simulated flights and aircrafts. However, several tests were also performed with real historical data. The obtained results are presented in this section, evaluating how the system performs and how the ground movements' efficiency was improved.

5.1 A-SMGCS requirements

In order to evaluate the solution, the most relevant A-SMGCS requirements defined by ICAO were considered and are presented in Table 2 [ICAO 2004].

Type	Requirement
Operational	O1: Be able to compute a route for each authorized moving object within the movement area.
	O2: Allow for a change of destination or route at any time.
	O3: Minimize the length of computed paths.
	O4: Minimize the conflicts.
	O5: Provide guidance for every authorized moving object, for any assigned route.
	O6: Provide clear instructions to pilots to help them following their path.
Performance	P1: The initial route should be computed in less than 10 seconds.
	P2: Recompute the path for a moving object should not exceed 1 second.

Table 2 – A-SMGCS routing and guidance requirements.

5.2 Simulation environment

A test scenario with 7 aircrafts tested the routing and guidance functionalities, where there are different categories and types of aircrafts taxiing at the same time. The Table 3 presents the results obtained from this test, namely the taxi distance, the wait time and the number of conflicts. The taxi distance represents the length of the path followed by the aircraft and the wait time is the time spent in a holding point. The number of conflicts refers the number of conflicts detected and resolved. There are three categories of aircrafts' size: small, medium and large. Also, there are two types of aircrafts: arriving and departing. As shown in Table 3, 6 aircraft were involved in 4 conflicts (8 conflicts, 2 aircrafts for each). These conflicts forced the delay of 4 aircrafts, in order to avoid frontal collisions, persecutions and intersections. For instance, the main injured aircrafts were the aircrafts 2, 4 and 7 with a wait time of 18s, 19s and 20s respectively. On the contrary, the aircrafts with higher priority (1, 3 and 5) maintained their optimal path. Then, the system was able to coordinate the movements efficiently, giving priority to the largest and departing aircrafts, while the smaller and arriving ones had to wait a few seconds.

Aircraft	Category	Type	Start time	Taxi distance	Wait time	Number of conflicts
1	Medium	Departing	0:00:00	1390m	0s	0
2	Small	Departing	0:00:10	1732m	18s	1
3	Large	Departing	0:00:10	2167m	0s	1
4	Medium	Departing	0:00:30	2562m	19s	2
5	Large	Departing	0:01:20	1492m	0s	2
6	Small	Arriving	0:01:30	1385m	4s	1
7	Small	Arriving	0:01:35	1457m	20s	1

Table 3 – Test-scenario with 7 aircrafts.

Furthermore, the difference between optimal and alternative paths is represented in Figure 3, where the bold line is the shortest path from point A to point B and the dark line represents the alternative path computed by the routing algorithm. Other examples are presented in Table 4, where the first aircraft is relative to the Figure 3. These values prove that some alternative paths are almost twice longer than the optimal paths, which is the case of the aircrafts 1, 6 and 7. On the contrary, for aircrafts 2, 3, 4 and 5, the routing algorithm was able to find little longer alternative paths. This is particularly important when considering a deviation from the assigned path caused by a pilot's mistake, allowing finding alternative paths with almost the same length than the optimal one.

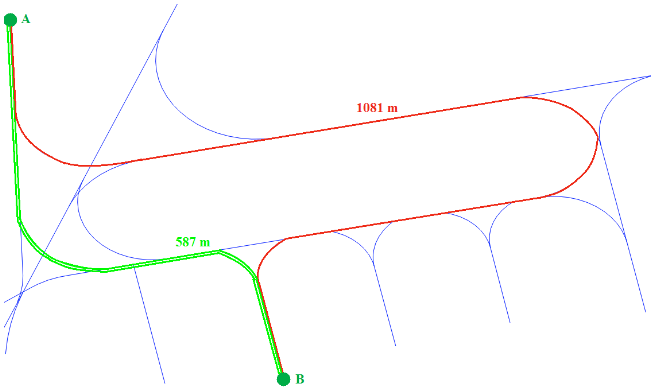

Figure 3 – Optimal path (bold) and alternative path (dark) representation

Aircraft	Taxi distance	
	Optimal	Alternative
1	587m	1081m
2	1454m	2223m
3	2113m	2562m
4	1020m	1134m
5	1952m	2002m
6	911m	1687m
7	545m	989m

Table 4 – Optimal and alternative paths' length.

Finally, the performance of the routing function was evaluated with respect to the execution times, depending on the number of segments of the computed path, for the first iteration of the routing algorithm. In other words, the path computation complexity was evaluated by measuring the execution times for paths with different sizes (number of segments). The results are represented in Figure 4, in which the execution time increases moderately with the number of segments of the computed path. As shown in the graphic, a path with 5 segments was computed in 20 ms. The same execution time was spent to compute a path with 15 segments and almost 20 segments. Even a path with 35 segments only spent 30 ms to be computed. So, it can be concluded that the algorithm is extremely fast and scalable, computing paths with 1 to 42 segments in less than 30 ms.

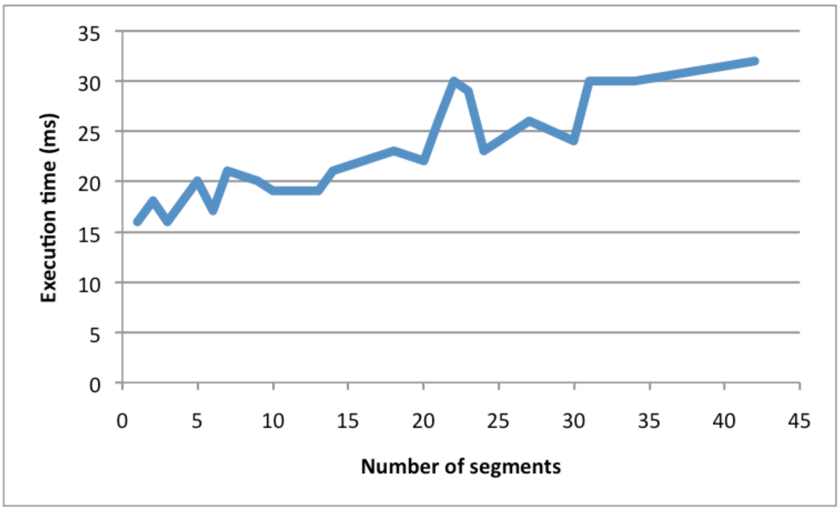

Figure 4 – Execution times for paths of different lengths.

5.3 Operational environment

The operational environment comprises the real historical data collected from February 2011 in the Lisbon airport, including the geographic coordinates of the path followed by each pilot. This data contains several gaps caused by interferences or other communication difficulties, for instance positions out of the taxiway guidance lines. These gaps force to implement a function that determines the real sequence of segments followed by the pilot, to enhance the guidance capability to detect conflicts and provide the guidance to the pilots.

From the data collected at the airport, relative to one operational day, about 23% were profitable. This means that the path followed by the pilot was identified was correctly monitored. The data presented in Table 5 represents the paths in which the A-Guidance system proposed a shortest path than the followed by the pilot. For instance, the difference between the real data and the A-Guidance proposal is 1099m for TAP741 and 477m for KLM1692, which would have saved several seconds in the taxiing time.

Aircraft	**Taxi distance**	
	Real data	**A-Guidance**
TAP741	2380m	1281m
TAP668	1625m	1601m
KLM1692	2069m	1592m
IBE31EW	1898m	1625m

Table 5 – Length of paths computed by A-Guidance, comparing to the real data at the airport of Lisbon.

5.4 Main outcomes

The test results proved that the operational A-SMGCS requirements were meet, since the optimal path (O3) was assigned to all aircrafts (O1), minimizing the conflicts with the other movements (O4). The pilots were also provided with an automated taxiway lighting system (O5) that turns on the lights relative to the segments n+1, meaning that a pilot is always guided by the lights of the current segment and the following one (O6). The guidance function also copes with path deviations, providing an alternative path in real time (O2).

On the other hand, the performance A-SMGCS requirements were also accomplished, since the routes are all computed within 30 ms (P1-P2). Furthermore, the Floyd spends approximately 9 seconds to initialize the matrices with the routing information. However, a mechanism was implemented to store the matrices in a file, in order to speed up the process. Then, the Floyd only spends 9 seconds when the airport layout suffers a modification that forces to re-computed the matrices. Otherwise, it only spends 70 ms reading from the file.

6. Conclusions and future work

The business case used to successfully test the proposed methodology was based on a LBS infrastructure supported by the A-Guidance system that copes with level I and level II of the A-SMGCS. The paper described how the methodology enabled the extension of the A-Guidance capabilities to provide routing and guidance functionalities. In fact, the integration of location-based data collected from wireless technologies with performing embedded systems enabled, for instance, to provide the required spatio-temporal context to the controllers. Such information improved the controllers' situational awareness, providing them with decision-support mechanisms to enhance the management of traffic ground movements more efficiently.

The results complies with the operational and performance A-SMGCS requirements, enabling the routing function to assign a path to every aircraft while minimizing the taxi distance as well as minimizing the risk of conflicts with other moving objects. Furthermore, the guidance function copes with dynamic changes to routing, enabling, for instance, to interact with the lighting system to guide the pilot from the current position to the assigned stand or runway. On the other hand, the performance goals were achieved since the routes are computed extremely fast and the system responds accurately to emergency situations.

The future work focuses on extending the proposed methodology to provide guidance assistance to airport vehicles. In this case the routing algorithm becomes more complex because vehicle drivers can have unpredictable driving behaviors. Such behaviors are extremely difficult to predict and introduces additional variables to the algorithm that might compromise its performance. Research is being done to respond to those challenges, namely to consider both forward and backward vehicle movements, tight turns, traffic rules and circulation priorities based on the type of vehicles as well as between vehicles and aircrafts.

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