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Detection, Tracking and Classification of Vehicles and Aircraft based on Magnetic Sensing Technology

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***Abstract*—**Existing ground movement surveillance technologies at airports are subjected to limitations due to shadowing effects or multiple reflections. Therefore, there is a strong demand for a new sensing technology, which will be cost effective and will provide detection of non-cooperative targets under any weather conditions. This paper aims to present a new intelligent system, developed within the framework of the EC-funded ISMAEL project, which is based on a new magnetic sensing technology and provides detection, tracking and automatic classification of targets moving on the airport surface. The system is currently being installed at two European airports. Initial experimental results under real airport traffic demonstrate the great potential of the proposed system.

***Keywords*—**Air traffic management, magnetic sensors, multi-tracking, A-SMGCS.

I. Introduction

Air traffic control has become an increasingly complex task due to increasing traffic, airport complexity and the number of operations that take place even under low visibility conditions. Recent research has shown that traffic volumes at European airports will continue to increase leading to at least a doubling in traffic every 12 years [1][2]. Furthermore, statistics from Eurocontrol (the European organization for the safety of air navigation) and FAA (Federal Aviation Administration) reveal that the highest risk portion of a flight refers in fact to ground movements [3]. Specifically, runway incursion is considered as one of the most critical safety issues for all airports (e.g. the incident at Linate airport in Milano in October 2001 [4]).

This problem is increasingly addressed by advanced systems, called A-SMGCS (Advanced Surface Movement Guidance and Control Systems) [5], whose main goal is to provide maintenance of uninterrupted traffic capacity under any weather conditions. A-SMGCS systems are mainly based on surface movement primary radars (SMR). However, this technology suffers from limitations e.g. shadowing effects or multiple reflections. Thus, most of the large airports are equipped with additional sensors, e.g. multi-lateration systems, whose function relies on signals from Mode-S transponders on board aircraft. Nevertheless, even multi-lateration systems are subjected to limitations. For instance, multi-lateration is subjected to interference caused by reflections, while non-cooperative targets (e.g. vehicle or aircraft either without or with switched-off Mode-S transponder) cannot be detected by the system increasing so the risk of a runway incursion.

For these reasons, a new sensing technology is required in order to improve safety and efficiency of ground movements at airports. The EC-funded research project ISMAEL [6] aims to determine whether recent advances in magnetic sensing can provide improved surface movement surveillance at airports. The resulting system can either be used as an additional sensor to cover blind spots in an existing A-SMGCS system at major airports or as a cost-effective alternative to SMR (Surface Movement Radar) for smaller airports. A survey carried out with approximately 500 European airports revealed that around 80% of the responding airports are based on tower outside view only to perform surveillance and guidance of airport ground traffic. In addition, 40% of the airports are affected by low visibility, which is defined as a runway visual range of less than 400m for more than 15 days a year. Without any technological aid, airport operation has to shut down in this case, thus significantly limiting an airport's general

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capacity. This lack of infrastructure at a large part of European airports along with frequently occurring low visibility conditions results in a strong demand for a low-cost detection alternative such as the ISMAEL system.

The proposed solution uses a network of magnetic sensors to detect ferromagnetic materials, classify targets according to their signal level and provide tracking information using a multi-target tracking algorithm. The final data can then be sent in ASTERIX format (a standard for the exchange of radar data) to any A-SMGCS system.

The structure of the paper is as follows: In Section II the proposed magnetic sensing technology is described, while in Section III the module used for target tracking is presented. Section IV and V present the automatic classification of targets and some initial experimental results respectively. Finally, conclusions are drawn in Section VI.

II. Target Detection

The detection of targets moving on the airport surface is achieved by detecting their ferromagnetic parts such as vehicle motors or aircraft engines and gears, based on their interaction with the earth's magnetic field. The earth's field acts as a biasing magnet, resulting in a magnetic signature (fingerprint) from ferromagnetic objects [7]. The local change of the earth's magnetic field is often extremely small – less than 1 μT - but the new proposed detector is able to detect it reliably. This property can be used to detect and locate the objects, either using a single point detector or an array of detectors.

Fig. 1 The magnetic detector is within its housing. Various housing shape can be applied to fit different detector locations and applications

Based on the experiences obtained during early stage development of the project, the design of detector has several improvements. The detector now uses a processor with Digital Signal Processing (DSP) functionality. It, shown in Fig. 1, has three equal channels (magnetoresistive (MR) sensors) for the three-dimensional detection of earth magnetic field changes. The three-axis-signal is sampled and mathematically filtered inside the controller. Different filtering techniques are used to filter out ambient noise. The detector's firmware reacts on changes of the sum of the (unsigned) magnitudes of the three axes and currently signals on demand the binary states "Field disturbed" and "Field not disturbed" or the three-axis-signal via RS485. The current approach of the detector has certain advantages accounting for the risks involved in applying laboratory results to real life conditions. Core functions of detectors inclusive sensitivity and noise level have been tested under well-controlled laboratory conditions. Especially, the output shift of the detector caused by the temperature coefficient of the resistance of the complete sensor and by the change of its sensitivity to magnetic fields has been discovered. The most promising approach to this problem is a local compensation of the magnetic field at the sensor's position. This compensation is realized via a control loop. In this setup, there is a compensation coil which can produce a magnetic field reverse to the external magnetic field by adjusting the current through the coil. Therefore, the magnetic sensing element always works in zero magnetic field conditions.

Field tests of the detector at test site of Saarbruecken airport, Germany, have been applied to bring valuable insights for detector performances at real field applications. Detector prototypes were installed at different locations of Taxiway A of Saarbruecken airport: two prototypes were buried inside one tunnel crossing the taxiway. This tunnel is two meters before the stop bar (one meter below the taxiway surface). The location is in the middle of the taxiway. The other three prototypes were installed at the edge of taxiway (11 meters away from centreline of taxiway).

Various tests have been taken on passing by aircraft. A typical test result is presented in Fig. 2: A DHC-8311 plane was detected by the detector prototype which is buried inside the tunnel and 1 meter underneath taxiway centreline. In this test, sensing element in x-axis is parallel to aircraft moving direction, meanwhile y-axis is perpendicular to moving direction and parallel to ground, and z-direction is perpendicular to ground.

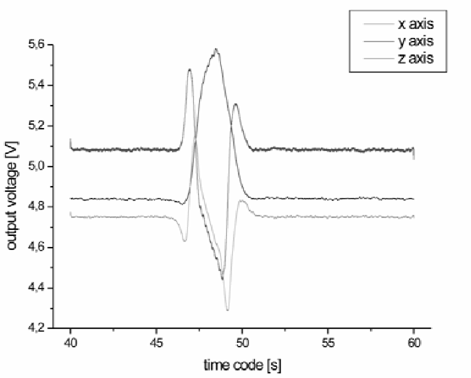


Fig. 2 Magnetic profile of one DHC-8-311 which is detected by magnetic detector prototype. The prototype is one meter underneath taxiway centerline. Three detection channels are presented here

Based on the field test results, the detectors have following features which can be used for airport applications:

- The detectors performed reliably in a variety of environmental conditions. Temperatures ranging from -10 °C to +35 °C as well as fog, rain and snow did not affect detector performance.
- There are no indications for electromagnetic interference emanating from magnetic detectors and influencing airport or aircraft equipment due to its passive detection principle.
- The only interference encountered emanating from airport systems and influencing detectors is 50 Hz magnetic noise generated by airport ground lighting. This noise can be mostly removed by simple digital signal processing procedures.
- Very low frequency signals could be observed as aircraft of certain types (Cessna 525, Embraer ERJ-135, Embraer ERJ-145) stopped overhead a detector. The most likely source of those signals is a thermostat-controlled electrical pitot tube heating.
- Other periodic signals, especially 400 Hz AC, can only be found at very close range, e.g. inside an aircraft. Thus, only static signals can be used for detecting aircraft.

III. Target Tracking

Signals from all magnetic detectors are sent to a central server called SDF (Sensor Data Server). The primary goal of the SDF is to process the data from magnetic detectors to estimate plots (observations), which are used to generate and update target tracks. The ISMAEL system tracks multiple targets moving on the airport surface using the Multiple Hypothesis Tracking (MHT) algorithm. MHT starts tentative tracks on all observations and uses subsequent data to determine which of these newly initiated tracks are valid. Specifically, MHT is a deferred decision logic in which alternative data association hypotheses are formed whenever there are observation-to-track conflict situations. Then, rather than combining these hypotheses, the hypotheses are propagated in anticipation that subsequent data will resolve the uncertainty. Generally, hypotheses are collections of compatible tracks. Tracks are defined to be incompatible if they share one or more common observations [8]. MHT is the only statistical data association algorithm that integrates all the capabilities of:

- Track Initiation: The automatic creation of new tracks as new targets is detected.
- Track Termination: The automatic termination of a track when the target is no longer visible for an extended period of time.
- Track Continuation: The continuation of a track over several frames in the absence of measurements. Thus, the algorithm provides a level of support for temporary occlusion.
- Explicit Modelling of Spurious Measurements
- Explicit Modelling of Uniqueness Constraints: A measurement may only be assigned to a single track and a track may only be the source of a single measurement per polling cycle.

The Multiple Hypothesis Tracking algorithm of ISMAEL system was based on an efficient implementation by Cox [9]. In this approach various motion models can be used to describe the motion of each target. Since only position measurements are available in ISMAEL a simple two-state (position and velocity) target manoeuvre model, in which the target acceleration is modeled as white noise (constant velocity-CV motion model), was initially selected. A drawback of this motion model is that it allows each target to move freely within the ground plane. On the other hand, detectors have to be installed along pre-defined paths (forming detectors chains), in other words their allowed trajectories belong to pre-defined curves. Therefore, it would be useful if a constraint is applied to force the target to move exclusively on this pre-defined curve. Then, a 1-D Kalman filter may be used to provide the position and the velocity of each target along this predefined path. An additional advantage of this approach is that the computational costs associated to MHT algorithm are significantly decreased, since a 1-D Kalman filter are used for each target instead of the standard 2-D Kalman filter.

For this reason, a novel motion model has been designed and implemented. Initially, a polynomial interpolation approach between all available sensor positions, belonging to the same chain, was used to define the allowed path. However, even for a relatively small number of detectors (e.g. N=8, which was the number of sensors installed at Thessaloniki airport) the high degree of the polynomials resulted to abnormal path shapes, which were undesirable. For this reason, cubic spline interpolation was finally used to define the allowed path of the target, for each chain of detectors. This approach is more robust (since it correctly constraints the target estimates on a fixed path curve), yields smooth trajectories, is computationally efficient and is suitable for any fixed-track application.

More specifically, let $c_i(x_i,y_i)$, $i=1,\ldots,N$ be the centre of a detector in a chain. A parametric form $(f_x(s),f_y(s))$ of the allowed path is defined using two functions that define a curve that passes through all N points of the chain i.e. $f_x(i)=x_i$ and $f_y(i)=y_i$. These two functions are both defined as natural cubic splines [10]. It was decided to use cubic splines, which have significant advantages:

- efficient implementation, since fast methods to solve for the coefficients of the interpolating functions can be used,
- the first and the second derivatives of the functions are continuous at all points of the path.

Two sets of coefficients corresponding to each cubic spline are computed using the spline function described in [10], assuming that $f_x(s)=x_i$ and $f_y(s)=y_i$ for s=i. Furthermore, the second derivatives of $f_x(s)$ and $f_y(s)$ are set to zero for the first and last points (detectors of the chain) 1 and N (natural spline). Then, the MHT algorithm is used as before, however, this time, a 1-D Kalman filter is used to track each target. More specifically, t=[s, v_s] is used as the sole state variable, while the corresponding measurement *z* is now a real number from the space interval [1,*N*]:

$$t_{k+1} = At_k + v \quad (1)$$

$$z_k = Ht_k + w \quad (2)$$

where A, H, v and w represent the transition matrix, measurement matrix, process noise and measurement noise respectively.

The final results of the MHT algorithm are the position and velocity estimates t_k of each target, which can be easily translated to ground (x, y) coordinates:

$$(x, y) = (f_x(t_k), f_y(t_k)) \quad (3)$$

$$(v_x, v_y) = (\frac{dx}{dt}, \frac{dy}{dt}) = (\frac{dx}{ds}, \frac{dy}{ds})\frac{ds}{dt} = (f_s^{'}(t_k), f_s^{'}(t_k))v_s \quad (4)$$

This tracking mode, is more robust (since it correctly constraints the target estimates on a fixed path (curve), computationally efficient and very suitable for any fixed-track application.

The final data (plots or tracks) are then coded in ASTERIX format (a standard developed by EUROCONTROL for the exchange of radar data and extended to any kind of surveillance data) and thus they can be sent to any A-SMGCS system via a UDP/IP communication. The SDF server also provides a real-time display window for the surveillance of traffic on the airport surface. The display of the application provides target tracks (crosses) moving on the airport's map and the state of each magnetic sensor (green in case of activation and red if the detector is off) as well as the position and the range of each sensor.

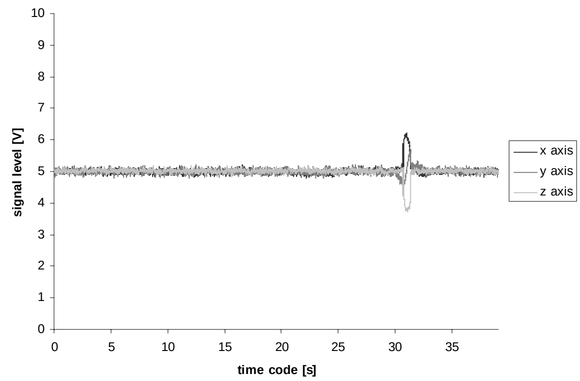
IV. Target Classification

One of the main advantages of the proposed system is its ability to classify detected targets into two main classes i.e. aircraft and cars. This targets classification is based on different signal levels produced by cars and aircraft respectively. Specifically, initial tests (Fig. 3) revealed that cars produce stronger signals than aircraft. This fact is due to two main reasons:

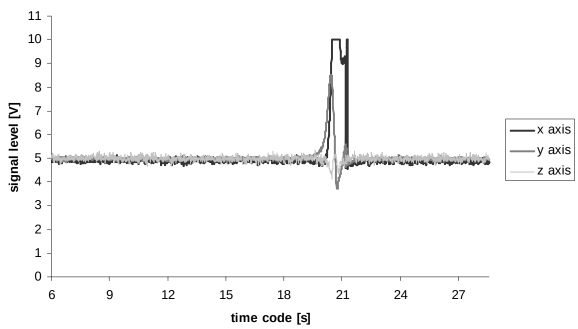
- cars are made of a larger amount of ferromagnetic materials and
- they also pass closer to detectors

In each polling cycle SDF server collects x, y and z components from each detector. The maximum of the three components observed at the time of detector activation is associated to corresponding observations and tracks. The decision of whether a target is a car or aircraft is based on threshold the maximum level signal associated with this track. The class of each target is presented by SDF's display as labeling information associated to each target.

Apart from the maximum magnitude of the signal, further investigation is still required for the determination of all those parameters that contain significant information about the passing target leading so to a type identification and classification. Until end of May, 2006, 154 magnetic profiles of 66 individual aircraft and 30 types and relevant subtypes of aircraft have been recorded in Saarbruecken airport test site. All aircraft encountered so far could be detected by the detectors placed 1 m underneath the taxiway centreline. In addition, only a few aircraft can be detected by the detectors at the edge of taxiway. Test results on same aircraft, but



(a)



(b)

Fig. 3 (a) The magnetic signature of an aircraft Jet AVRO RJ 100 and (b) the magnetic signature of a car

in different time with time difference up to 7 months have proved the reproducing ability of the detector. That is, magnitude and shape of those profiles were found to be typical for a type of aircraft, allowing discrimination between aircraft types. One database, which contains signals from all tested aircraft, is currently under construction. Further analysis of these data is expected to lead not only to discrimination of aircraft and cars, but also to an automatic identification of aircraft class or even type.

V. Experimental Results

After an extensive analysis of user requirements, three applications were identified as most promising areas to be targeted by the ISMAEL project: a) airport surveillance, b) runway incursion prevention and c)gate management

To investigate the three identified airport applications, adequate detector locations have been defined at two European airports (Frankfurt airport and Thessaloniki airport). Detector positions and numbers have been optimised based on detector features as well as airport application requirements. Communication aspects between detectors and servers have been defined and the first system level tests have proven the successful communication among these components. Currently, first tests are being performed with the established detector array at Thessaloniki airport to validate the expected performance. Additional tests with a different detector configuration at Frankfurt airport will also be conducted providing more information about the functionality of magnetic detectors in a major airport environment. At Frankfurt airport, gate B46 has been selected for evaluating the aircraft parking application. Taxiway S will be used for evaluating runway incursion protection and airport surveillance.

The first prototype system for airport surveillance has been installed at Thessaloniki airport in Greece, where eight magnetic detectors have been installed along the centreline of the main taxiway (Taxiway A) before the stop line of Runway 16. The distance between the magnetic detectors is 30 metres, except for the last detector (under the stop line) that has been installed 20 metres away from the previous one for better monitoring of the stop line. The monitoring of the stop line is considered as being of great importance since aircrafts enter the runway (prevention of runway incursion). The central SDF server computer was installed at the tower and connected with the magnetic detectors network. First tests at Thessaloniki airport have shown the great possibilities of the proposed system. Indicatively, in Fig. 4 the magnetic signal of an Airbus A320 is presented, while Fig. 5 shows the change in magnetic field caused by a Boeing 747-400. These two types of aircraft are the most common at Thessaloniki airport.

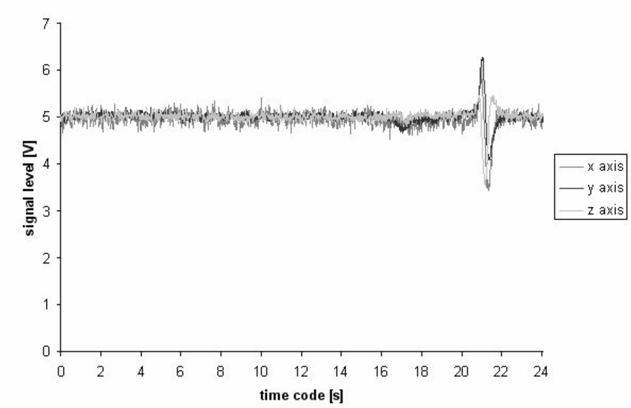


Fig. 4 The magnetic signature of an AIRBUS A-320

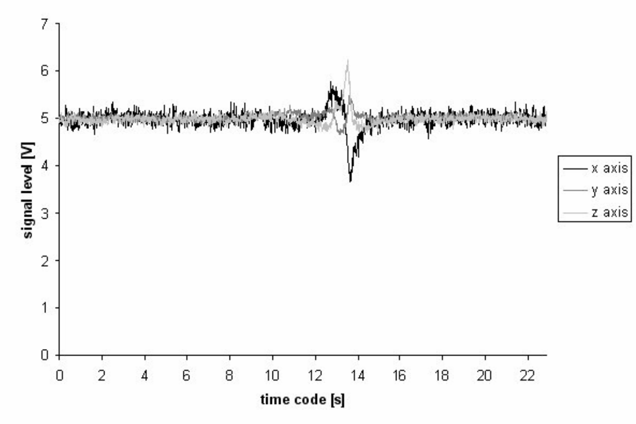


Fig. 5 The magnetic signature of a BOEING 737-400

VI. Conclusion

First development steps and feedback from potential user groups have shown that the magnetic sensing solution developed within the ISMAEL project seems to be a reasonable and promising aircraft location detection system to be incorporated in existing and future A-SMGCS or to be applied as stand-alone alternative for smaller airports. The major benefits of the planned solution are derived from the fact that it constitutes an efficient low-cost complementary position technology to be included in existing A-SMGCS. Furthermore, it is easy to implement due to small detector size allowing for installation at almost any location, such as integration in existing ground lighting systems. Unaffected by weather conditions, interferences and shadowing effects the system provides reliable position, velocity and direction information. In addition, a broad classification of passing vehicles is intended. Moreover, the system does not rely on secondary transponders or other on-board equipment, such as multi-lateration or ADS-B (Automatic Dependant Surveillance Broadcast). Based on a passive detection principle, the system does not interfere with other systems like aircraft radios. In general the solution is characterized by low energy consumption and a modular architecture that allows for easy system upgrades and extensions accounting for the heterogeneity of different airports. In this context another strong argument for this new detection technology is its flexibility. The system can be integrated into existing A-SMGCS and serves as efficient augmentation for special areas and/or special tasks.

Additional benefits may be derived from the applicability of the magnetic sensing technology to other fields of application such as the management of road traffic or the occupancy of parking blocks. Regarding the former case, research results on the magnetic properties of different classes of vehicles, their unique magnetic signature, obtained within the scope of ISMAEL may significantly contribute to optimize highway utilization. Furthermore, due to its ability to also detect stationary targets the proposed magnetic detector well suited for stop line monitoring at airports or traffic light controls at highways. Unlike existing loop systems which depend on a changing magnetic field due to a moving targets, the new magnetic detector will detect the presence of a target regardless of whether it is moving or not.

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