2012 International Conference on Indoor Positioning and Indoor Navigation, 13-15th November 2012

Hybrid indoor/outdoor localization system to improve aeronautical maintenance works

Nelly de Bonnefoy, Yohann Dugua, Samir Torki, Jean-Pierre Jessel
"Visual Objects: from Reality To EXpression" Team
Computer science research institute of Toulouse (IRIT)
Paul Sabatier University, Toulouse, France
nelly.de-bonnefoy@irit.fr, yohann.dugua@gmail.com, torki@irit.fr, jessel@irit.fr

Bernard Ordy
Research and Technology
AIRBUS
Saint-Martin du Touch, France
bernard.ordy@airbus.com

***Abstract* — This research work is carried out in the framework of a project focusing on the future of aeronautical maintenance. One of our main objectives is to localize continuously technicians in relation to the aircraft on which they intervene during maintenance session. This module will be part of a context-aware application that will deliver several services to maintainers. The challenge is hard, the expected precision is around a centimeter and constraints are numerous. As for examples, the system must work inside and outside a hangar, inside and outside the aircraft, whatever the hangar configuration, the weather, the luminosity are. This paper presents the early stages of our research methodology. It first provides initial steps that were dedicated to a study of the operational context and a discussion of the results of a state of art of available technologies for localization. They allowed us to concentrate our choices on a Hybrid Localization System (HLS) combining an Inertial Measurement Unit (IMU), a 3D model of the aircraft and a third technology that will be integrated later (optical or radio wave). Next, this document depicts methods that have been implemented and tested. Depending on the way covered by the technician during the maintenance session, the obtained error rate is around 5-10%. The 3D registration offers an interesting gain inside the aircraft or in the vicinity of binding elements. In this difficult context, the research path taken to design the HLS looks already promising. Localization will be improved when the vision module, on which we are still working, will be integrated.**

Keywords - Hybrid localisation system; IMU pedestrian navigation; zero-velocity update; 3D registration; context aware application.

I. Introduction

In the framework of a project focusing on the future of aeronautical maintenance, research works are made to design a context-aware application that will deliver several services to maintainers. Its main objectives are to improve work conditions and quality, to save time, to increase safety and to improve information availability, access and understanding.

One of our main objectives is to localize continuously technicians during a maintenance session. This will allow offering various services to support maintenance technicians as:

- Locate quickly aircraft part or zone.
- Make "Path planning": offer the way to reach another place in the aircraft, a component, etc.
- Locate structural damage on an aircraft.
- Make "geographical filtering" of the available information (e.g. documentary source).
- Provide an augmented view of the aircraft to the technician (e.g. see what is behind a panel).

Even if the localization in zones can be sufficient for some services, the long-term precision is expected to be around a centimeter. It will be particularly useful for augmented reality applications and structural damage localizations.

This paper presents the early stages of our research works. It first provides information on initial phases of the project. So, a presentation of the study of the operational context is made. It allows us to highlight numerous constraints inherent of the aeronautical maintenance context. It is then followed by a discussion of results of a state of art on available technologies for localization. Thanks to these first steps, the choice on different technologies to design a Hybrid Localization System (HLS) was made. They are inertial, optical and/or radio wave (UWB). In a first time, we decided to focus our work on an approach combining an inertial navigation system (INS) and a 3D model of the aircraft. The rest of this document is dedicated to this combination INS/3D. First, we depict our approach. The inertial navigation and particularly pedestrian dead-reckoning methods are presented briefly. They are followed by a description of the use of a 3D model to correct the drift of the INS, to register the localization. Then, a section is dedicated to the prototype. It presents the global functioning, algorithms and methods implemented for the combination INS/3D, and the interface. To finish, the last section presents tests that have been performed and obtained results.

II. Study of the operational context

This section introduces briefly the aeronautical maintenance domain. It also highlights some important features and inherent constraints that will influence the design of the localization system design.

978-1-4673-1954-6/12/$31.00 ©2012 IEEE

A. The aeronautical maintenance

From the beginning of the international civil aviation, free-market economy and maintaining a high level of security were the main objectives of the states around the world. For this, various international, European and national authorities are responsible to certify, supervise and regulate all areas of this sector, and therefore, aircraft maintenance. In order to exist and operate in the field of aircraft maintenance, each organism or airline must imperatively conform to these regulations. In addition, in order to maintain the airworthiness requirements of their aircrafts, and therefore, to use them, the owners and aircraft operators are obliged to comply with initial programs imposing the periodicity of preventive maintenance tasks, but also, with data and technical instructions designed by the manufacturer.

Generally, aircraft maintenance consists of line maintenance that is performed when the aircraft is in service, and base maintenance for which the aircraft is usually taken out of service. Each of these categories has different activities, scheduled maintenance (preventive) and unscheduled maintenance (corrective), and they consist of different types of task as for example inspections, troubleshooting, removal/installation, etc. Line maintenance activities are performed on a parking area or at a gate of an airport. They are done between two flights or during night stop. The available time for the intervention is approximately 40 to 60 minutes between flights. During this time, a scheduled "*pre-departure visit*" (around 20 minutes) and some unscheduled tasks must be carried out. Note that the staff, infrastructure and resources necessary to perform unscheduled tasks are not necessarily quickly available. Base maintenance activities can be characterized by the fact that the aircraft is grounded for a certain period of time. Depending on the scheduled maintenance check, it can range from a few days to several weeks. Moreover, these activities are done in an appropriate infrastructure, as hangar and/or workshop, and the personnel, equipment and resources needed are usually available. However, for reasons of immobilization costs, the organization and the schedule of work is usually very tight, leaving little space for unforeseen tasks. Either in base or in line, maintenance activities are organized in shifts covering 18 hours (2 shifts without night) or 24 hours (3 shifts with night). Maintenance technicians are the heart of the aeronautical maintenance system. To do their job they must follow official data and procedures from the technical documentation (TD) of the manufacturer. The entire TD dedicated to maintenance can reach forty manuals of several hundred of pages. Generally, at the beginning of their shift technicians receive a job card that contains tasks to perform. Depending on the company, this job card contains more or less details. Some have only the list of tasks to do, and the technician must search in the TD how to do tasks. Some have tasks to carry out and how to do them (copy of the TD). Moreover, maintenance technicians are mobile and nomad. Indeed, some tasks require reaching several zones of the aircraft, others necessitate to stay in the same zone or to walk around the aircraft. The time spends in one zone is variable.

The aeronautical maintenance is dependent on the composition and the evolution of the ever-increasing world fleet. The latter is composed of a large proportion of aircraft entering their period of "aging" and of aircraft "new generation" taking advantage of the rapid development of new technologies; thereby the aeronautical maintenance is an activity that becomes increasingly multidisciplinary and complex.

Furthermore, the aircraft maintenance is also influenced by the increased competition between airlines. Indeed, in order to offer competitive rates companies increasingly tend to minimize their operational costs while complying with safety recommendations. This directly affects the maintenance activities, which represent 10 to 15% of direct operational costs [1]. As a consequence, they must be carried out in ever shorter time limits to stop the aircraft on the ground as less time as possible.

In conclusion, aircraft maintenance is a significant and inevitable operational cost for airlines. Maintenance technicians must deal with numerous constraints and the mental pressure linked to get the aircraft available in the shortest time, at the lower cost while insuring the greatest safety level. Aircraft manufacturers must ensure to meet needs of airlines by offering ever more maintainable aircraft while minimizing downtime. One of investigated ways is to design a system that will support maintenance technicians by offering them contextualized information in real-time. This will improve the accessibility, the availability and the understanding of technical information, and then, reduce time of information search, numbers of mistakes, etc. This contextualization depends on several parameters and the localization of the technicians in relation to the aircraft is one of them.

B. Different aircraft maintenance environments

Mentioned in the last subsection, maintenance activities consist of two categories base maintenance and line maintenance. Both of them have different environments of work, and their characteristics will influence the design of the localization system.

In base maintenance, activities are generally carried out indoor, in a hangar. It allows being sheltered from climatic elements (as rain, wind, snow, etc.), but not from temperature and humidity. Indeed, the hangar is not a model of isothermal construction; it is generally constructed with metallic materials, which are good drivers of heat. That is to say, in summer the hangar becomes quickly an oven and in winter a fridge. And because of its volume, its lack of insulation and its use, as for example when doors are opened to take out an aircraft or equipments, it is difficult to warm or to air-condition a hangar. Consequently, from the point of view of heat and humidity, the environment is changeable and inconstant. In case of line maintenance, activities are carried out on an aircraft parked outdoors whatever the weather. Of course to a certain extent, but if the aircraft can land and take off, the aircraft must be maintained. The environment is thus fickle. It depends on the climatic conditions and of the moment of the day/night. With rain, snow or fog the visibility is quite reduced.

Particularly, in case of aircraft maintenance activities performed indoors, the metal is present everywhere in the vicinity of the aircraft. Indeed, building materials of the hangar are mainly metallic. In addition, to support technicians in their job there are numerous infrastructures, equipment and tools in the hangar, as for example scaffoldings, ladders, mechanical platforms, nacelles, etc. Their number and their place can vary during the maintenance session.

In base maintenance, the luminosity level is generally quite low. It depends on the hangar architecture and on the lighting installations. In all cases, dedicated lights are fixed on the ceiling or at least to a height high enough so that aircraft can be parked safely below. Consequently, the light sources are generally away from the aircraft, and so from the working area. In addition, the aircraft and some equipment (as scaffoldings or platforms) create zones of shade. Moreover, because they are difficult to reach, lights are full of dust and they are not replaced immediately when they break down, making light of the global environment less efficient. For example, recommendations are a minimum of 807.3 Lux (75ft.c) to perform maintenance normal tasks and 1021.25 Lux (95ft.c) for certain "special" inspection tasks. Nevertheless, in a study made by Colin G. Drury it has been measured an average of 548.25 lux (51ft.c). In addition, according to a study made by the Federal Aviation Administration (FAA), it is worst in areas that are not directly accessible by light. Indeed, under wings or in cargo hold, the luminosity varies from 10.75 Lux to 150.5 Lux (1ft.c to 14ft.c) [2]. In line maintenance, the luminosity level is changeable and inconstant during the day. It depends mainly on the weather, the airport configuration, and on the working area. The aircraft or airport infrastructures can also create zones of shade. In night work, it is worst because the light infrastructure of airports (parking area or at gate) are not design for maintenance work.

C. Requirements

We have to design a localization system that must track the maintenance technician during his job, and therefore, deliver the relative location of the technician in relation to the aircraft in real time.

There must be a single system that must work anywhere in the world whatever the maintenance activity (base or line). This means that the system should work in any climatic environments including temperature, humidity and climatic elements (rain, fog, wind, snow, etc.). The system must deliver the localization wherever the operator is: outside the aircraft, in the cabin, in cargo hold, etc.

As mentioned in the introduction, in the long term the expected accuracy for the continuous localization of the maintainer is around one centimeter. This accuracy is strong to allow services as augmented reality views or damage localization. Other service as "geographical filtering" of the technical documentary source does not require as precise localization. Moreover, the response time might be less than two seconds, because it is essential for the aircraft technician comfort and acceptance and, for the system regularity particularly for the coherence of given results. The localization system must be as non-intrusive as possible. No bulky additional hardware has to be carried by technicians and installed in the vicinity of the aircraft. Moreover, no modification of the aircraft design must be made (additional hardware installation). The software application must be as transparent as possible and its use as intuitive as possible.

III. STUDY OF TECHNOLOGIES OF LOCALISATION

The first step of our research work methodology was to make a survey on available technologies to track technicians. In the first instance, the main technologies employed to develop localization sensors actually used in the virtual reality and motion capture domains were investigated. Indeed, with robotics these domains are precursory in localization systems, and it seems important to us to take an interest in these technologies. In the second instance, technologies used for large-scale location systems and in Ubiquitous Computing or Ambient Intelligence domains to locate people in indoors environments were studied. So technologies referenced and studied were: mechanical systems, gravimetric and inertial systems, electrical field sensing systems, magnetic field sensing systems, radio-wave systems (Wi-Fi, Bluetooth, RFID, UWB, Zigbee, etc.), optical tracking systems, acoustic systems, localization systems with satellites, and localization system with terrestrial networks. Furthermore, the main objective of this paper being not to present a state of the art of technologies available for localization, a discussion on them in relation to our context and requirements is presented in this section.

In spite of their interesting accuracy, localization systems based on infrared (IR) (some millimeters), ultrasound (some centimeters) and magnetic sensors are not conceivable. Firstly, the infrastructure of such systems must be installed in the working environment. Because of the low range of such technologies, the number of sensors will be too large and their installation will be too tedious and restricting. Secondly, several environmental characteristics will cause many perturbations. Indeed, as mentioned upper, working environments are essentially composed of metal that creates strong magnetic perturbations and multipath effects. Moreover, ultrasound waves are sensitive to variations of temperature and IR to light. In consequence, these technologies have not been chosen for the system.

Large-scale localization systems as GPS or telephony networks do not offer an interesting accuracy to satisfy our requirements. In addition, particularly inside the hangar or the aircraft, errors due to the quality of the signal reception, to the low number of visible satellites and to the multipath effects do not allow us warranting desired performances.

Localization systems based on an existing wireless networks infrastructure, as Wi-Fi, are interesting for most of applications. They allow reaching a reasonable accuracy of results without necessitate a specific hardware installation. However, the diversity and the quantity of maintenance zones in the world do not permit to affirm that they will be equipped with necessary network access points.

More generally, the radio wave technology necessitates installing an emission/reception infrastructure. In addition, depending on the wavelength and on the frequency on the wave category, this kind of technology is relatively sensitive to metal, which generates reflections and multipath. But it is also sensitive to water that may be presented on various forms in the maintenance environment (humidity, rain, snow, ice, etc.). Moreover, the use of such technology can cause acceptation problems in term of security particularly on airport where several radio wave types are used for communications or radars for example. So, the use of radio wave can be difficult to implement. However, among all radio-waves systems studied, the Ultra Wide Band (UWB) category has retained our attention. It has a good precision and this kind of wave can propagate through several types of material.

Optical localization systems have an interesting accuracy, with markers it is around 0.5-5mm and without markers 0.1-5m. However, they have several drawbacks. In case of use of markers, the precision depends on the number of them presents in the working environment and on their visibility. In our case, this imply placing exactly several markers on and in the aircraft, in its vicinity and in the hangar or on the tarmac. Their number must be sufficient to manage occlusions generated by maintenance infrastructures, equipments, tools and people that are in the working area. Moreover, localization systems based on video are very sensitive to variations of luminosity and to occlusions. This is difficult to manage in maintenance environments where lighting varies from one area to another and throughout the day. In addition, particularly without markers, an optical localization system necessitates complex image processing and vision algorithms. Even if, this technology has several drawbacks, its use remains interesting because no heavy infrastructure is required and video cameras can be small enough to be wear by maintenance technicians without disturbing them in their job.

The inertial navigation technology, through an inertial measurement unit (IMU), is interesting because it gives acceleration, attitude and gravitational forces of the object on which it is attached. Moreover, no infrastructure has to be installed in the environment. The IMU is small and light, it is then possible to place it on the technician. However, this technology is sensitive to gravity and is subject of drift.

The use of a unique technology to localize maintenance technicians in relation to the aircraft is not possible. The solution will be to implement a hybrid localization system that will combine different technologies in order to have technologies advantages and to overcome drawbacks and limitations of a single one. In our context, the best solution seems to be the use of a localization system without infrastructure, and that will be hold by the maintenance technician. The appropriate technology in this case is the inertial navigation. However, if it is used in an autonomous way, it is subject to drift that causes a low accuracy. This technology necessitates to be coupled with another technology, as in [3] [4], and/or to use a registration technique that will allow improving the precision of the localization.

IV. Our approach

To design the hybrid localization system we decided, in a first time, to exploit the major advantage of our context: the general work place is known. In other words, the aircraft dimensions and configuration are known. For that, we decide to use a 3D model of the aircraft to correct the localization results that come from the processing of the IMU data. The general principle in illustrated in the Fig.1 and the referential of the localization system ($\mathcal{R}$) is presented in Fig.2. The localization process starts at an initial position in the referential ($\mathcal{R}$).

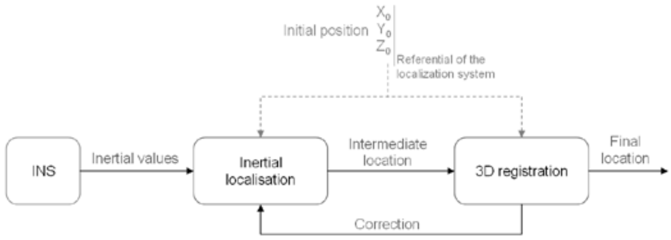

Figure 1. General principle of the hybrid system INS/3D

A. *Inertial navigation system*

1) *Basic inertial navigation system*

The basic inertial navigation uses an algorithm called “Dead Reckoning” which consists in calculating the new position from the previous position by adding to it the distance made since the last measurement. The amount of displacement at time (t) is calculated through a double integration of the acceleration vector provided by the inertial measurement unit (IMU). It is important to note that it is assumed that the user starts stopped, its initial velocity and initial position is 0 at time t=0. The IMU does not provide a continuous signal but samples of the signal at a certain frequency (up to 120 Hz for inertial sensors MTi and MTi-G). It is therefore necessary to use a method of numerical integration in discrete time to process the sampled signal. The numerical integration used is an approximation of the integration in continuous time. For that, rectangles or trapezoids methods are commonly used, and several algorithms can be implemented: Euler, Velocity Verlet, Runge-Kutta, etc.

Nevertheless, the double integration method causes a large drift between the calculated position and the real one. As mentioned [5], this phenomenon is due to two main causes. Firstly, the process of numerical integration generate itself errors because it approximates the continuous real signal. Secondly, the process also integrates the noise that is in the signal acquired by the sensors. These errors, repeated along time, accumulate because of the “Dead Reckoning” principle. As illustration, the drift of a calculated position from a sinusoidal velocity was tested; after one minute of simulation the position has drifted about three meters. To overcome this major problem, two solutions are possible. First, it is possible to couple the inertial navigation system with another navigation system as the GPS [6], and secondly, to improve the « Dead Reckoning » algorithm by using a dedicated approach to the pedestrian navigation.

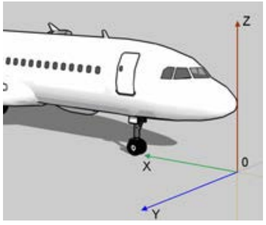

Figure 2. Referential of the localization system ($\mathcal{R}$)

2) Inertial Navigation System: Pedestrian Dead Reckoning (PDR)

a) Principle of pedestrian navigation

To reduce the drift caused by the double integration, some scientists have looked at improving the algorithm of "Dead Reckoning" by adapting it to the particular case of pedestrian navigation. During the last decade, several methods have been proposed to localize a person effectively with low-cost inertial sensors. Among the main we can cite: [7] [8] [9] [10] [11] [12] or [13]. These methods are commonly called “Pedestrian Dead-Reckoning” (PDR). They allow estimating the motion of a person based on the step detection, the estimation of the step length and the direction of the motion. They use the principle of “Zero Velocity Update” (ZVU). Its principle is to contain drifts of the inertial navigation by forcing a reset of the parameters of the integration algorithm. More precisely, the velocity vector is put to zero periodically. The drift due to the numerical integration and noise of sensors is then contained. Algorithms based on ZVU are considered as the most reliable and the most multipurpose with regard to different types of moving: walking, running, lateral movement and the rise and descent of stairs [7]. It is therefore necessary to determine a recurrent event in human walk to reset the velocity vector.

So, in order to apply the ZVU principle to the pedestrian navigation it is necessary to analyze the mechanical movement of a pedestrian. This consists of a repetition of movement (stride) that is called the “walking cycle”. It is the movement exerted by the two legs between two supports (stances) on the same foot [14]. It consists of two steps, and each step is made of a swing phase and a stance phase. They are illustrated in the Fig. 4. During the stance phase, usually about 0.1 – 0.3 s [15], the step’s velocity is zero. So, this phase will be used in the ZVU method as a reset event of the velocity vector and then of the velocity error. The main difficulty of the PDR algorithms will be to detect the stance phase, i.e. the zero velocity intervals.

b) Pedestrian Dead Reckoning (PDR) algorithms

The use of the ZVU principle to make PDR algorithms is illustrated in the Fig. 3. As shown in [8], a PDR algorithm consists of three main stages: the step detection, the length step estimation, and the attitude estimation and location calculation.

For the step detection stage, most of algorithms are based on technical analysis of basic data such as filtering, amplitudes, local variances or threshold. In addition, most of them use linear accelerations provided by the accelerometers, angular velocities or orientations provided by the gyroscopes. A minority uses magnetometers. A current problem with these methods is the detection of wrong positives. Most of time, they appear during static change of direction, when the user makes a change of direction on itself. Two solutions can be used, take into account moving of some centimeters or analyze accelerations while the step is detected. Another solution to detect a step can be to use an additional sensor to improve the detection of the stance phase; in [16], a high-resolution pressure sensor place under the sole (heel area) of the shoes has been used.

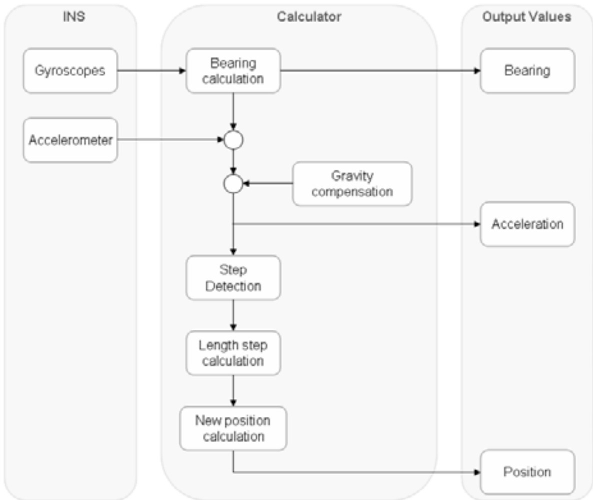

Figure 3. Functioning of the inertial navigation system based on PDR

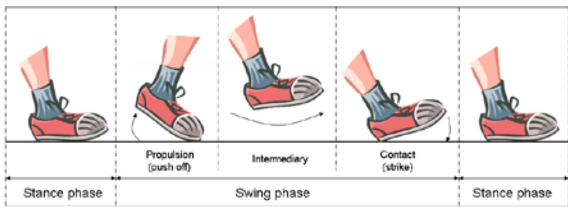

Figure 4. Phases of a step

Once the step detected, it is then necessary to estimate the length of the step in order to calculate the total moving of the user during his walk. It depends mainly on the morphology of the user, on the velocity and the frequency of the walk. Based on this postulate, several algorithms are available. There are: the fixed step length algorithm, the modeling of the human walking algorithm, and the algorithm of integration of inertial values and ZVU. The method based on a fixed length of step is basic. The number of step is calculated and it is multiplied with the length of a step. It is known thanks to a constant value given by the user or to a result of a calibration step. Next, as underline [14], the study of the human walking shows that the leg is outstretched from the beginning to the end of the stance phase. During this period the displacement can be compared to an inversed pendulum. The distance traveled during this period is comparable to the size of the step, and a simple geometric property of isosceles triangles can be used to calculate it. The third method is based on the integration of inertial values with ZVU application during stance phase. This method from [11] is the closest method to the basic inertial navigation with two differences. First, it combines the method of ZVU with the classical algorithm. Then, the integration is not performed over the entire acquired signal, but over periods of time corresponding to each step.

The first two methods do not allow determining the moving on the Z axis. Or in our case, this kind of moving is possible in particular when the maintenance technicians climb stairs. As shown in [17], it is possible to detect correctly the ascent of stairs by analyzing gyroscopic data on the Y axis. However, it is not possible with this method to differentiate a walk flat and stair descent only by the analysis of these values. In our case, the estimation of displacement on the Z axis doesn't need to be very efficient since we can easily readjust the height with respect to the traversing elements of the 3D model. Nevertheless, we must still detect the proximity of the user with one of these elements. For example, if the user takes the staircase to enter the cabin through the access door, we must detect the climb of stairs to differentiate the situation where the user is under the access door on the ground level from the one where the user is at the same level. In case of the user exits the cabin through the same access door, the problem does not arise because one only needs to register the position at ground level.

Concerning the phase of estimation of the attitude and the position, in the basic inertial navigation, it is necessary to change the benchmark of accelerations vectors acquired by the inertial measurement unit (IMU). This action is feasible by the use of the attitude of the IMU expressed in the navigation benchmark thanks to the "Cardan angles", the "Direct Cosine Matrix" or the quaternion. In the case of "Pedestrian Dead-Reckoning" (PDR), the principle is the same. It is necessary to project the displacement vector previously calculated by the successive stages of step detection and length step estimation. For this, the orientation representing the direction of movement must be known. In the case of using a single inertial sensor, usually positioned on the foot of the user, this information is difficult to know. Indeed, when a person walks, his feet are not perfectly aligned with the axis of his shoulders and the direction of the movement. In addition, during the swing phase of the cycle, angles describing the attitude can vary by +/-10°. It is therefore necessary to establish a strategy to better estimate the average attitude of the user during a step making. A first solution consists in taking into account the initial angle provided by the inertial sensor during an initialization phase. Then, this angle must be subtracted to the mean angle calculated during the swing phase constituting the step. A second solution is to use a second inertial measurement unit (IMU) mounted on the upper body (lower back or torso). This solution assumes that a user, in the case of a normal walking forward, always directs his shoulders in the direction it moves. Thus, by looking at the attitude of the second IMU at the time of step detection, it is possible to know the direction in which the step was made.

B. 3D correction and registration

Our proposition is based on the study of constant environment features to correct and make a registration of the results delivered by INS. For that we use a 3D model of the aircraft. In this version of the prototype, two kinds of constraints are used: non-traversing objects and traversing objects.

Non-traversing objects represent most of the objects in the 3D scene. However, the main non-traversing object is the fuselage. It is used to detect movements so implausible that the user would exit the aircraft through its middle. In this case, the application considers that there is an error in the orientation of the displacement induced by a drift of the gyroscopes. The information of the orientation of the "non-traversing element", which is traversed, is used in order to estimate a correction value of the orientation. This value is communicated to the INS in order to recalculate a new location and take it into account when calculating future displacements. Fig. 5 illustrates the orientation registration principle using the detection of intersections with "non traversing" elements. The green route represents the section of the path for which no need of registration was detected. The red segment represents the segment in which an intersection with the fuselage was detected, and then a need of registration. The blue segment represents the moving once the registration made.

Traversing objects allow passing from inside the aircraft to outside and vice versa. They are for example access doors, hold doors, etc. They are illustrated below in Fig. 6. This kind of constrain allow a second registration type, the location registration (on the three axes x, y, z). So, when the application detects that the user moves in the vicinity of a traversing object with a directional vector parallel to the normal of the traversing object, the position is modified in order to coincide with the center of the bottom segment of the traversing element (c.f. Fig. 7).

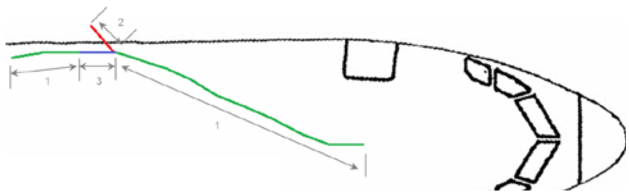

Figure 5. Registration principle using "non traversing" elements: 1 – Sections with no need of registration, 2 – A segment in which an intersection with the fuselage was detected, 3 – The moving once the registration is made.

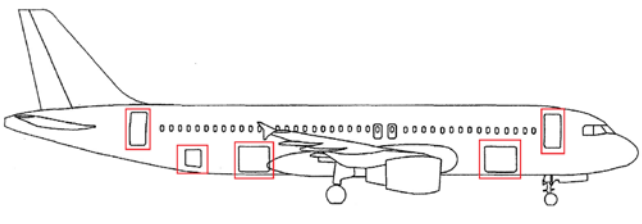

Figure 6. Traversing elements

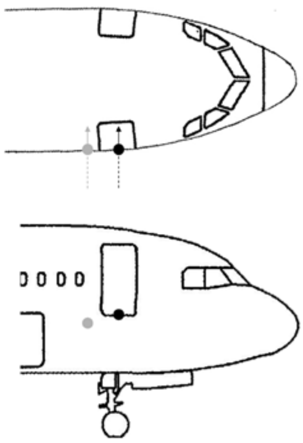

Figure 7. Registration principle using traversing elements: the grey point is the location before registration, the black point is the location after registration, arrows are direction vectors, the black dotted line is the normal of the traversing object (NTO) and the grey dotted line is a parallel of the NTO.

V. PROTOTYPE

A. Global functionning

1) Operation modes and main functions

At this step of our research work, the main objective has been to evaluate a hybrid localization system using the combination Inertial Navigation System (INS) / 3D registration. Moreover, taking into account that we have no aircraft available for testing every day, we have identified the necessity of two operation modes. The first one is the real time localization that must track the user while performing a real path inside and/or outside the aircraft. And the second one is the simulation post-acquisition which is an operation mode that must enable to replay pre-recorded data sets in order to evaluate, compare and optimize algorithms. For that, main seven functions have been defined, they are:

– Configure the inertial sensors

– Acquire inertial data

– Localize thanks to the PDR algorithm chosen

– Visualize digitally the current position of the user

– Visualize in real time the location of the user graphically (2D and 3D)

– Record acquired inertial data

– Replay pre-recorded data

2) Global prototype architecture

The prototype consists of six objects; their organization is presented in Fig. 8. First, the object "parameters selection screen", allows the display and the selection of parameters necessary for localization. It includes the configuration parameters of the inertial sensor, the parameters necessary for the INS and the display settings. Then, the object "IS interface" is used for the connection, the set-up and the acquisition of inertial data. The object "INS" is the inertial navigation system itself. It implements classical inertial navigation algorithms and "Pedestrian Dead Reckoning" (PDR) algorithms. The object "3D engine", as for it, is responsible of the registration of the calculated position by the INS. It estimates its validity and, when appropriate, it calculates the correction applicable to INS.

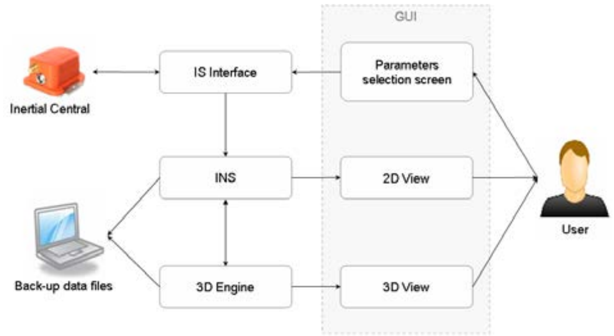

Figure 8. Global prototype architecture - Rectangles represent objects and arrows show data flows between objects and their directions.

Then, the object "2D view" is responsible of the display on the 2D map of the intervention zone. It displays both actual and registered successive positions. And to finish, the object "3D view" is responsible of the display on the 3D map of the intervention zone. An effort was made to separate and share out functionalities consistently between the different parties. This design allows easily envisaging the replacement of an object by another. For example, functionalities of processing and display are completely dissociated. It will allow reusing algorithms of interfacing and localization for another application that will not need to display the user's position but simply to know its position (location of damage, augmented reality, etc.).

3) Materials

Following the survey of available technologies for localization and the choice made for the hybrid localization system, a study on "*Commercial Off-The-Shell*" (COTS) inertial sensors was made. Main objectives have been to find sensors that were light, not very bulky and sufficiently precise, and also with an easy and rapid implementation. We were particularly interested on two products designed for virtual reality and motion capture. The first one is the MTi-G of the Xsens Company. It consists on the combination of 3 accelerometers, 3 gyroscopes and 3 magnetometers. And the second one is the IS1200 of the Intersense Company. It combines an inertial sensor (with 3 accelerometers and 3 gyroscopes) and a video camera. Nevertheless, the sensor IS1200 could not be tested because the furnished server version at the time of tests did not allow us having directly access to the inertial data. So, the inertial sensor used for this project is the MTi-G.

B. Combination Inertial Navigation System / 3D model

1) Inertial Navigation System

At this stage of our research works, the main objective was to evaluate the 3D registration principle and its influence on results of a pedestrian inertial navigation system. So, at the moment, no innovative ways were investigated to improve performances of the pedestrian inertial navigation system.

Three different algorithms have been implemented for the step detection phase. They use linear accelerations as presented in [8], angular velocities as presented in [7], and the angular velocity on the Y axis. The last consists in making a threshold on the angular velocity on the Y axis (ω_{yi}). A step is made at each transition between an oscillation phase (ω_{yi}>1rad/s) and a stance phase (ω_{yi}<1rad/s).

Three different algorithms have been implemented for the length step calculation phase. They use the principle of a fixed length, the human walking modeling as presented in [14] and the integration of linear accelerations with the ZVU method as presented in [11].

Concerning the estimation of the moving on the Z axis, useful for climbing stairs, a detection method based on the analysis of inertial measurements and the work of Brian Coley in [17] was defined. It is based on the analysis of the angular position around the axis Y. Indeed, when the user use a stair this angle is positive throughout the step, while in a flat displacement, it varies equally between -40° and 60°.

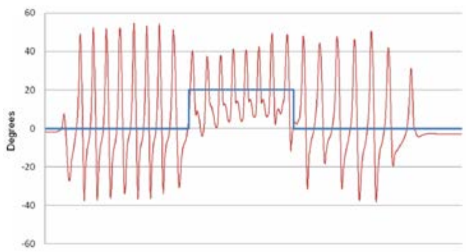

Figure 9. Angular position on the Y axis during stair climbing

Fig.9 shows this phenomenon. The timing blue indicates the period, during which a climb of stairs is done, the red curve represents the angular position on the Y axis.

In order to estimate of the attitude and the position, we saw in IV.A.2)b) that the orientation representing the direction of movement must be known. Because a single inertial sensor is used, we have implemented the solution consisting in subtract the initial angle (obtain during the initialization phase) to the mean angle calculated during the swing phase of a step.

When different algorithms are available for a same phase, the choice is made by the user at the beginning of the application.

2) 3D registration

a) Scene graph and 3D Library

To implement the 3D registration module the scene graph of the 3D model is used. A scene graph is a way of representing a 3D scene as form of a descending tree. Each tree node corresponds to an element of the scene. The interest of this representation is to have a coherent structure of scene that allows displaying the 3D scene in an efficient way (parent elements are displayed before their children) and facilitating the handling of elements constituting the scene. Indeed, each handling on a node of the tree is automatically updated in the child nodes without having to travel all the elements. Moreover, from a software point of view, this representation is also interesting because it is consistent with the paradigms of the "Object Oriented Programming" (OOP).

There are many 3D libraries to use and display a 3D scene. Among the "open sources" ones we can quote: GLC_lib, Ogre3D or Irrlicht. Important characteristics have been taken into account in the choice. First, we haven't looked for the 3D library that has the best quality for the display of the 3D scene. Indeed, given that the main function of our virtual environment is to realign the inertial data, the display of the scene is only secondary. Secondly, it is essential to be able to easily connect the 3D library with the part of the prototype managing the acquisition and the analysis of inertial sensors data. It is therefore necessary that this library is compatible with development in C + + and integrable with Qt. Thirdly, having a 3D model of an aircraft in the 3DSMax format, the library must allow easily loading this model. Then, another important feature that must take into account is the availability of functions managing the detection of collisions. It will facilitate the implementation of algorithms that calculate intersections.

TABLE I. RESULTS

Criteria	GLC_Lib	Ogre3D	Irrlicht
C++ Development	Yes	Yes	Yes
Collision detection	No	Yes	Yes
Integration to Qt	Yes	Yes	Difficult
3DS Max scene import	No	Yes	Yes
Documentation	Medium	Good	Good
Community	Poor	Very important	Important

Finally, the availability of a sufficient online documentation is also a criterion to analyze. Indeed, the functioning of a 3D engine is often difficult to grasp. So, the presence and the accessibility of documentation and of a large community of users can facilitate the implementation.

A comparative study by taking into account theses characteristics was made between the « open sources » 3D libraries: GLC_lib, Ogre3D and Irrlicht. Table 1 hereafter presents the results. Given the different assessment criteria, and because there is no functionality of collision detection in GLC_Lib and the integration of Irrlicht in Qt is difficult, the library Ogre3D was chosen.

b) Implementation of the 3D registration

To implement the software application of 3D registration, we seek to detect collisions of the avatar with elements of the 3D environment. For that, the principle of bounding box is used. Bounding boxes (BB) are symbolic cubes that include elements of a scene. They are calculated by taking the minimum and maximum of extremities of the elements on three axes (x, y, z). Fig. 10 shows in green the BB of the fuselage of the aircraft, and in red the BB of the access door to the cabin. Our application detects if the segment corresponding to the last detected step intersects an edge of a BB. However, the 3D model consists of more than three hundred elements and then as many BB. So, it is not possible to make the test on all. The technique of "ray tracing" is used to perform a filter to know bounding boxes that have to be tested. This functionality is provided and optimized by the library Ogre3D. It consists in simulating a ray and returning a list bounding boxes present in the ray alignment. For that, a ray is created, its origin is at the initial position of the moving, and its orientation is the same as the last detected step. Then, a function of Ogre3D returns the first element corresponding to the closest BB, and an intersection test is performed.

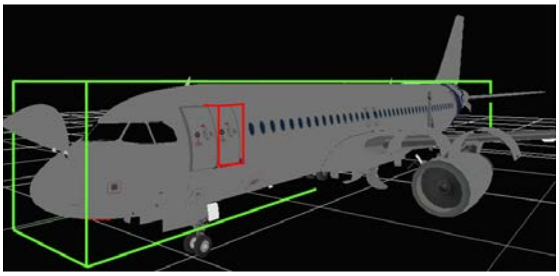

Figure 10. Example of bounding box

This technique has a problem because the implementation of the "ray tracing" of Ogre3D don't return a BB if the origin of the ray is in it. This is potentially our case for our application, in particular when the user is in the cabin. So, an additional test of intersection on the BB of the fuselage has been added. It is executed each detected step. When an intersection is detected, two actions are possible. First, if the origin of the moving is outside the BB and the finish point is inside the BB, or conversely, then a registration angle is calculated. This consists in calculating the difference between the orientation of the moving and the orientation of the BB. The obtained angle is then transmitted to the inertial navigation system (INS). And it will be taken into account in the rest of the route. Secondly, if the origin of the displacement is outside the BB and the finish point is outside the BB then a simple registration of the position is made.

C. *Prototype Interface*

The graphical interface of the prototype is designed with the tool "QtDesigner". It consists of several zones in a same main screen. Fig. 11 hereafter shows the interface.

In the top left-hand corner there is the configuration zone (surrounded in green). It allows selecting parameters of acquisition, localization and display. In the bottom left-hand corner of the interface there is the 3D display zone (surrounded in red). It allows displaying the 3D model of the scene and an avatar of the user. It is interesting to emphasize that two views of the 3D scene are available. The first one is a "third person view" on which the evolution of the avatar can be seen thanks to a video camera placed in the 3D scene. It is possible to move this video camera by using arrows of the keyboard. The other view is a "subjective view" that shows what the user has is his field of view. In the middle at the bottom, there is the 2D display zone (surrounded in yellow). It presents a 2D map of the aircraft in which real and registered locations will be progressively traced. In the bottom right-hand corner there is the digital display zone (surrounded in purple). It presents digital values of the localization and some data coming from inertial sensors. In the top right-hand corner there is the command zone (surrounded in blue). It consists of four buttons that allow beginning or stopping the localization. Finally, a progress bar at the bottom of the screen informs the user about the status of the calibration phase. The last is necessary at the beginning of the localization process, and the user must remain as motionless as possible during it.

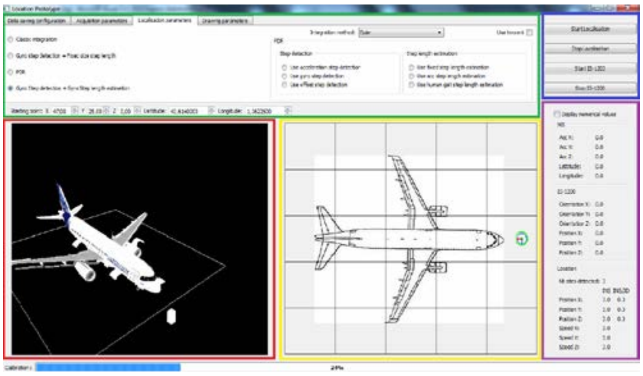

Figure 11. Interface of the prototype

VI. EVALUATION AND RESULTS

As mentioned in [18], the recurrent problem of the evaluation of pedestrian localization systems is the absence of known reference localization systems. Indeed, there is no easily accessible system supplying data for a reliable comparison. Nevertheless, there are methods that allow supplying results without investing in complex and costly equipment. In our case, several parts of the application must be evaluated. There are: the step detection algorithm, the algorithm of length step estimation and the 3D registration. For each of them, evaluation method consists in realize a way and analyze calculated results compared with real data. This kind of method is commonly used in projects of localization or navigation in large-scale or middle-scale.

A. *The step detection phase*

In order to assess the algorithm of step detection, a straight path must be covered, the number of steps must be counted and this value must be compared with the result given by the system. So, we have made several ways with different lengths (7, 10, 16, 20 and 40 steps) and two different positions for the inertial sensor (on the heel and on the foot).

All results have been analyzed for each implemented algorithms that are the use of linear accelerations (LA) [8], the use of angular velocities (AV) [7] and the use of the angular velocity on the Y Axis (AV_y) presented in V.B.1). The more efficient and robust algorithm is the one based on LA, with a mean error rate (R_p) of 2.7%. The use of AV or AV_y obtains a mean R_p of 5.4%. In addition, the LA is less sensitive to the sensor position.

B. *Length step estimation phase*

In order to assess the algorithm of step length estimation, the same way was used by covering different lengths of straight path (10, 20, 40 steps). All results have been analyzed for each implemented algorithms that are: the use of fixed length (F), the use of linear acceleration with ZVU (A_{ZVU}) [11] and the use of the human walking modeling (HMW) [14]. Results are presented in the Table III. There are rates of: the mean error (*Mean*), the standard error (*SE*), the minimum error (E_{min}) and the maximum error (E_{max}).

TABLE II. COMPARATIVE RESULTS OF ALGORITHMS OF LENGTH STEP EVALUATION

Step detection			**Length of step calculation**			**% Error**			
LA	***AV***	***AV_y***	***F***	***A_{ZVU}***	***HWM***	***Mean***	***SE***	***E_{min}***	***E_{max}***
X			X			10.99	30.4	2.00	32.40
X				X		16.94	28.25	2.65	30.90
X					X	5.92	12.51	0.35	12.86
	X		X			10.52	32.20	0.20	32.40
	X			X		16.65	35.38	2.17	37.55
	X				X	3.79	9.55	0.35	9.90
		X	X			8.53	11.66	2.00	13.66
		X		X		28.57	46.20	10.00	56.20
		X			X	9.88	21.55	3.80	25.35

The algorithm based on the HWM seems to be the more efficient. Indeed, coupled with the method based on LA or on AV, in some cases the combination reaches an accuracy of 0.35% of the distance. However, it is important to notice that its use is more reliable when it is coupled with the algorithm based of the angular velocities. Note that this combination can be improved by the use if an additional inertial measurement unit on the thigh to improve the accuracy of the calculation of the angular amplitude of a step.

C. *Combination of the INS with the 3D registration*

1) *Context of tests*

Tests sessions were performed on an aircraft parked on a tarmac. The technician was equipped with an inertial measurement unit (IMU) and a webcam on the cap. Moreover, several IMU positions were tested: on the torso, the right ankle (inside of foot), the instep, the tibia, the heel. First, inertial data acquisitions were performed through static measurements in order to evaluate the influence of the operational context on inertial sensors. Secondly, several paths were made with different positions of the IMU on the technician: geometric path around the aircraft, ascent and descent of the platform access, ascent, visit and descent of the cargo hold with a platform access, and typical walk around (Daily). Moreover, video acquisitions during the different paths were made in order to evaluate the possible interest of its use to improve the hybrid localization system. In this paper, we present results for three paths with the IMU placed on the heel of the technician.

2) *Description of paths*

The path P1 consists in a starting position in front of the nose of the aircraft on the tarmac, then the ramp is used in order to enter in the cabin through the front left door. Once inside, the middle of the cabin between two rows of seats is followed to reach an open area behind. The path P2 is a round trip from the front of the cabin to the back avoiding a zone with several calculators. The path P3 is a geometrical path around the aircraft, starting from the nose and passing through the right wing tip, the tail, the left wing tip, and return to the nose.

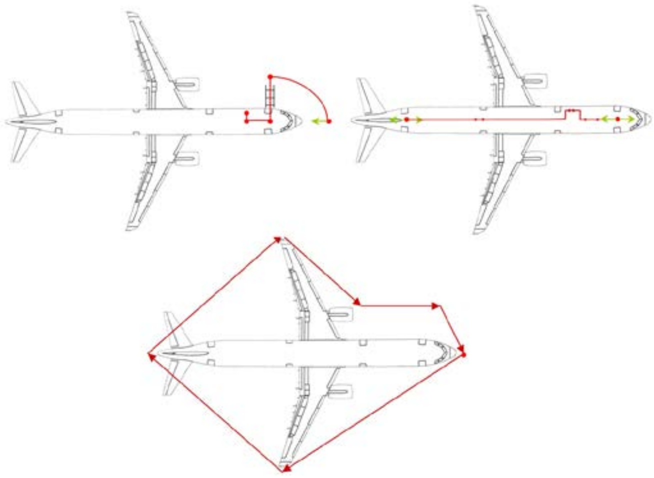

Figure 12. Paths illustration: P1 in the top left-hand corner, P2 in the top right-hand corner and P3 at the bottom.

A detour has been made because of the presence of a maintenance equipment in the front left of the aircraft. These paths are illustrated in Fig. 12.

3) *Initialization phase*

Before each localization process, an initialization phase must be done. It consists in reaching an initial location and remaining static during 20 seconds. So, the localization process starts from a known position in the referential of the localization system illustrated in Fig. 2.

4) *Paths with INS alone*

Paths have been made with the INS alone. Results are shown in Fig.13. For P1, there is a gap of 0.50m on the X axis, 1m on the Z axis and 0.50m on the Z axis. For P2, the final position on the X axis has a gap of 0.8m. And the about-turn at the back of the cabin caused a big gap on the Y axis: 10.25m. For P3, the final calculated position is very far than the real one. There is a gap of 3.5m on the X axis and 7.6m on the Y axis.

5) *Paths INS with 3D registration*

Paths P1 and P2 are interesting because they are made mostly around and inside the aircraft. The 3D registration is fully utilized thanks to the proximity of binding elements of the environment. Fig. 14 presents the contribution of 3D registration for paths P1 and P2 within the aircraft. In case of the path P1, we notice that there are no major improvements on the X and Y axes, the INS is sufficiently efficient, but the 3D registration has corrected the deviation of the position on the Z axis during the passage of the access door. In case of path P2, we notice that the 3D registration allows correcting the gap of initially 10m to a gap of less than 50cm on the Y axis. Nevertheless, the gap on the X axis has increased from 80cm to 2m. This allows us to diminish the percentage of error from 28% of the global path to less than 6%.

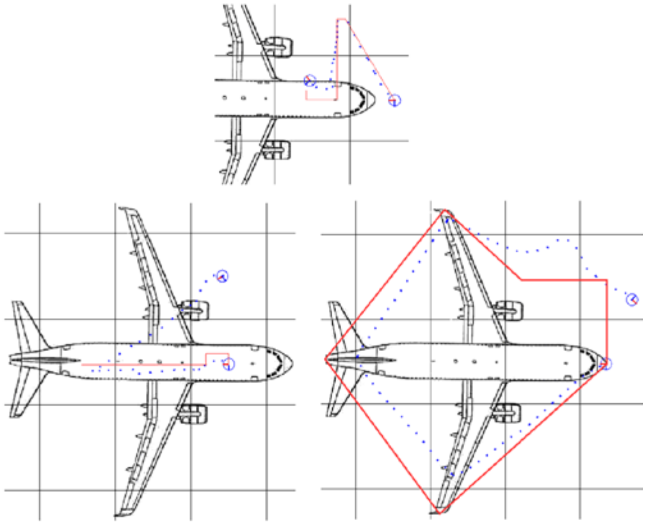

Figure 13. Paths with the INS alone – Red path is the real one and blue path is caculated by the INS.

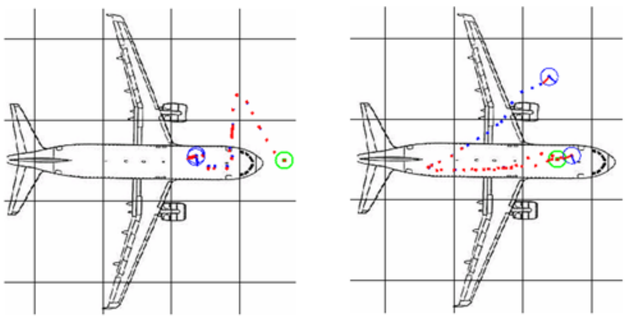

Figure 14. Results on P1 and P2 - Red path is combination INS/3D, blue path is INS alone.

VII. Conclusions and Perspectives

A hybrid localization system based on the combination of a pedestrian inertial navigation system (PINS) and a 3D registration was implemented and tested. In spite of the "naïve" implementation of the PINS [19], results obtained are quite good. Indeed, depending on the way covered by the technician during the maintenance session, the obtained error rate is around 5-10%. The 3D registration offers an interesting gain inside the aircraft or in the vicinity of binding elements. In this difficult context, the research path taken to design the hybrid localization system (HLS) looks already promising. Moreover, our implementation of the pedestrian inertial navigation system must be improved by implementing and assessing the Kalman filter, the extended Kalman filter and the particles filter. In addition, other aircraft characteristics can be taken into account in the 3D registration module. The HLS will be also improved when the vision module, on which we are still working, will be integrated. Several methods without markers have been tested as SIFT [20], SURF [21] and FAST [22]. The use of the SLAM principle from the robotics domain, which is well presented in [23] and [24], is currently in study. However, this last technology can't be used in all situations, as in case of fog or night work for example. So, we are also studying the possible use of an "Ultra Wide Band" radio-wave module.

References

[1] Transport Studies Group of Westminster London, "Dynamic Cost Indexing". In the framwork of Inovative Cooperative Actions of R&D in EUROCONTROL Programme CARE INO III, Technical Discussion Document 9.0, "Aircraft Maintenance – Marginal delay costs". June 2008.

[2] G. Eason, B. Noble, and I. N. Sneddon, "On certain integrals of Lipschitz-Hankel type involving products of Bessel functions," Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955. (references)

[3] M. Zhu, K. Zhang, W. Cartwright, G. Retscher, Q. Fu, "Possibility studies of Integrated INS/RFID Positionning Methods for Personnal Positionning Applications," Proceedings of International IGNSS Symposium, Qld, Australia, 1 – 3 December, 2009.

[4] A.R. Jiménez Ruiz, F. Seco Granja, J.C. Prieto Honorato, J. I. Guevara Rosas, " Pedestrian Indoor Navigation by aiding a Foot-mounted IMU with RFID Signal Strength Measurements," in the International Conference on Indoor Positioning and Indoor Navigation (IPIN), 15-17 September 2010, Zürich, Switzerland.

[5] Y. K. Thong, M.S. Woolfson, J.A. Crowe, B.R. Hayes-Gill, D.A. Jones, "Numerical double integration of acceleration measurements in noise," ScienceDirect, vol. 36, pp 73-92, April 2004.

[6] H. Weinberg, "Accelerometers – Fantasy & Reality,"in Analog Devices, vol. 43, pp 13-14, 2009.

[7] R. Feliz, E. Zalama, J. Gómez García-Bermejo, "Pedestrian tracking using inertial sensors," Journal of physical Agents, Vol. 3, n°. 1, January 2009.

[8] A.R. Jiménez Ruiz, F. Seco Granja, J.C. Prieto Honorato, J. I. Guevara Rosas, "Comparison of pedestrian Dead-Reckoning Algorithms usin low-cost IMU," in the 6th IEEE International Symposium onn Intelligent Sinal Processing, Budapest, 2009.

[9] S. Beauregard, "Omnidirectional Pedestrian Navigation for First Responders," 4th Workshop on Positioning, Navigation and Communication (WPNC '07), pp.33-36, 22-22 March 2007.

[10] J. Won Kim, H.J. Jang, D. Hwang and C. Park, "A step, stride and heading determination for the pedestrian navigation system," Journal of Global Positioning Systems, vol. 3 (1-2), pp.273-279, 2004.

[11] R. G. Stirling, "Development of a pedestrian navigation system using shoe mounted sensors," Master of Science, University of Alberta, 2003.

[12] R Stirling, J. Collin, K. Fyfe and G. Lachapelle, "An Innovative Shoemounted Pedestrian Navigation System," in GNSS 2003, Graz, Austria, pp. 1-15, 22-25 April 2003.

[13] H. Weinberg, "Using the ADXL202 in Pedometer and Personal Navigation Applications", Analog Devices AN-602 application Note, 2002.

[14] V. Renaudin-Schouler, "Hybridation MEMS / UWB pour la navigation pédestre intra-muros", Thèse de doctorat, Ecole polytechnique Fédérale de Lausanne.

[15] S. K. Park and Y. S. Suh, "A Zero Velocity Detection Algorithm Using Inertial Sensors for Pedestrian Navigation Systems," Sensors, vol. 10, pp. 9163–9178, 2010.

[16] Ozkan Bebek, M. A. Suster, S. Rajgopal, M. J. Fu, X. Huang, M. C. Cavusoglu, D. J. Young, M. Mehregany, A. J. van den Bogert, and C. H. Mastrangelo, “Personal Navigation via High-Resolution Gait-CorrectedInertial Measurement Units,” IEEE Transactions on Instrumentation and Measurement, vol. 59, pp. 3018–3027, 11 2010.

[17] B. Coley, B. Najafi, A. Paraschiv-Ionescu, K. Aminian, “Stair Climbing Detection durig daily physical activity using a miniature gyroscope,” Gait Posture, Lausanne.

[18] M. Angermann, P. Robertson, T. Kemptner, and M. Khider, "A high precision reference data set for pedestrian navigation using foot-mounted inertial sensors," International Conference on Indoor Positioning and Indoor Navigation (IPIN), vol., no., pp.1-6, 15-17 Sept. 2010.

[19] C. Fisher, P. Talkad Sukumar, M. Hazas, “Tutorial: implementation of a pedestrian tracker using foot-mounted inertial sensors”, in IEEE Pervasive computing, 2012.

[20] Lowe, D.G.; , "Object recognition from local scale-invariant features," Computer Vision, 1999. The Proceedings of the Seventh IEEE International Conference on , vol.2, no., pp.1150-1157 vol.2, 1999

[21] H. Bay, A. Ess, T. Tuytelaars, and L. Van Gool, “Speeded-Up Robust Features (SURF),” Computer Vision Image Understanding 110, 3 (June 2008), 346-359, 2008.

[22] E. Rosten and T. Drummond, “Machine learning for high-speed corner detection,” in Proceedings of the 9th European conference on Computer Vision - Volume Part I (ECCV'06), Aleš Leonardis, Horst Bischof, and Axel Pinz (Eds.), Vol. Part I. Springer-Verlag, Berlin, Heidelberg, 430-443, 2006.

[23] H. Durrant-Whyte and T. Bailey, “Simultaneous localization and mapping (SLAM): Part I: The essential algorithms.” IEEE Robotics & Automation Magazine, 13(2):99-108, 2006.

[24] T. Bailey and H. Durrant-Whyte, “Simultaneous localization and mapping (SLAM): Part II: State of the art.” IEEE Robotics & Automation Magazine, 13(3):108-117, 2006.