

TERRESTRIAL MOBILE MAPPING BASED ON A MICROWAVE RADAR SENSOR. APPLICATION TO THE LOCALIZATION OF MOBILE ROBOTS

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KEY WORDS: Microwave Radar, Mapping, Localization, Robotics.

ABSTRACT:

Mobile robotics applications in outdoor environments now use intensively Global Positioning System (GPS). For localization or navigation operations, GPS has become an essential tool due to its ease of use, its precision, and its worldwide accessibility. The increase of autonomy level in mobile robotics implies a robust centimeter-level positioning, but the presence of natural (trees, mountains) or man-made obstacles (buildings) can degrade or prevent GPS signals reception. We present in this paper a solution for robots localization based on PELICAN microwave radar. PELICAN radar provides each second a panoramic image of the surrounding environment. These images are concatenated through a Simultaneous Localization And Mapping (SLAM) algorithm in order to build global maps of the traveled environments. The proposed solution computes the position and orientation of the robot through a real-time 3D matching between the current radar image and a pre-existing radar map constructed during an exploratory phase.

1. INTRODUCTION

Mobile robotics applications in outdoor environments has been transformed with the emergence of Global Positioning System (GPS). And today the majority of localization and navigation applications in outdoor environments uses intensively GPS-based solutions (Zhang, 2015; Li, 2010). The central question is now to know whether GPS is the better solution for localization tasks in mobile robotics applications. According to its impressive performances, it is very tempting to answer in the affirmative: GPS provides real-time localization, a worldwide accessibility, and the most sophisticated solutions offer centimeter-level positioning with more and more affordable costs. However, for mobile robotics applications requiring a high level of autonomy, several limitations can nuance these very positive results:

- the precision of GPS positioning is directly affected by the number of visible GPS satellites. Buildings, vegetation, hills and mountains, are some of the factors that can mask GPS satellites.
- the geometrical structure of GPS operational constellation varies throughout the day and affect GPS precision. GDOP (geometric dilution of precision) describes the error caused by the relative position of the GPS satellites.
- multipath effect is an important source of errors in GPS calculation, because GPS satellite signal bounces off of nearby structures (buildings, mountains, etc.).
- the troposphere and ionosphere can change the speed of propagation of GPS signals, and offset the GPS positions.

If one or more of these problems occurs, severe degradations of localization accuracy can be observed, with the risk of GPS receiver operating shutdown. Another problem is encountered if real-time centimeter-level positioning is required. In this situation, differential GPS (DGPS) has to be used, implying the periodical reception of correction signals (the repetition frequency is typically one second). The availability and the quality of these correction signals are limiting factors for this type of GPS use.

For mobile robotics domain, a GPS shutdown can be catastrophic because the robot will be rapidly stopped if no redundant

localization systems are available. This problem has been one of our motivations for the development of a localization system with an approach based on microwave radar. The approach uses PELICAN radar, developed at INRAE Institute for perception applications in natural environments. The proposed solution includes two main phases:

- an initial exploration phase during which a radar map of the travelled environment is constructed. At the moment, this step is realized off-line.
- for the second phase, the panoramic images regularly provided by radar are used to compute the robot's positions and orientations within the radar map.

A general description of this process is presented in Figure 1. Computed positions and orientations can be used for navigation purposes, for example to follow a trajectory defined in the map.

The behaviors of microwave radar and GPS are complementary. Obstacle-free environments are perfectly adapted to GPS systems, avoiding GPS signals reception problems. On the contrary, the presence of obstacles is absolutely essential for the radar, because the construction of the map and the localization process are based on targets detection. Optical sensors, such as vision or laser, can be seriously affected by environmental constraints (rain, snow, alternation between day and night, etc.). Microwave radars (with their long wavelength by comparison with optical sensors) are weakly disturbed by atmospheric phenomena and allow to build robust sensors for applications in outdoor environments.

In section 2 of the presented paper, we describe the PELICAN radar imager, as well as the approach to build panoramic radar

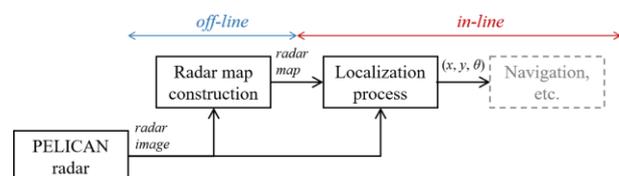


Figure 1. General description of map construction and localization.

images of the environment. The mapping algorithm used to build global maps of the environment is presented in section 3. In section 4, the principle of radar localization is described and results are presented. The last section concludes the paper.

2. PELICAN RADAR IMAGER

PELICAN radar is a microwave sensor dedicated to perception tasks in mobile robotics applications. It has been initially developed for perception in environmental monitoring applications. Theoretical and technological aspects are described in more details in (Rouveure, 2016; Rouveure, 2017). PELICAN radar is based on Frequency-Modulated Continuous Wave (FMCW) technology. FMCW radars are well suited for short range applications. With pulse radars, the duration τ_d of the transmitted pulse defines a blind zone from range zero to range $r_d = c \tau_d / 2$ (c is the light velocity). For applications requiring radar-target distance measurements over short distances, a large value of r_d can lead to unacceptable configuration. Thus, a major problem with pulse radars is to be able to concentrate over short time a very high peak power. FMCW radar provides an alternative solution, because it eliminates the blind zone introduced by the pulse duration in the case of pulse radars, and because the bandwidth of the transmitted signal can provide satisfactory distance resolutions. PELICAN radar uses a homodyne receiver (also known as zero-IF receiver): the RF signal is directly converted into the baseband, allowing the use of acquisition cards with sampling frequency reasonable values. Moreover, homodyne receivers are often considered as low-cost solutions, because they require few microwaves components.

PELICAN radar is equipped with a fan-beam antenna, which rotates in the horizontal plane. The rotation of the antenna is used to build panoramic images over 360° of the surrounding environment. The fan-beam antenna is a major characteristic of PELICAN radar:

- the large elevation beamwidth makes the radar robust to some severe variations in pitch and roll when the robot navigates in natural and non-flat environments;
- but at the same time the elevation angle of a target within the antenna beam is unknown, implying that neither the altitude nor the height of the target will be measured. The consequence is that PELICAN radar can only build 2D images of the surrounding environment.

The main characteristics of PELICAN radar are resumed in Table 1, and a general view is presented in Figure 2.

PELICAN radar is monostatic and it uses a planar array antenna. A radar spectrum is computed at each degree of antenna rotation,

Symbol	Name	Value
f_0	carrier frequency	24.125 GHz
Δf	sweep frequency	195 MHz
f_m	chirp repetition frequency	360 Hz
p_t	transmitted power	14.7 dBm
θ_{el}	antenna elevation aperture	24.5°
θ_{az}	antenna azimuth aperture	4°
G	antenna gain	21.08 dBi
ω	antenna rotation velocity	60 rpm (1 tr/s)
	range (min, max)	5 m, 100 m
	size (length-width-height)	29-24-30 cm
	weight	12 kg

Table 1. PELICAN radar characteristics.

and a panoramic image in polar coordinates is obtained each second with the merge of 360 radar spectra. Figure 3(b) is an example of a raw radar image in polar coordinates. Each column of the image corresponds to one single radar spectrum (i.e. one antenna pointing direction). Radar spectra are computed with a 1024-points FFT and a Hann weighting function. Two corrections are applied to build the image in Cartesian coordinates presented in Figure 3(c):

- *Doppler shift correction.* The form of the transmitted radar signal (sawtooth frequency modulation) does not allow measuring the radial velocities of the targets, and, as a result, we assume a static environment. In order to correct the Doppler shift introduced by the movements of PELICAN radar itself, a proprioceptive sensor measures the velocity v of the vehicle which carries the radar. Once v measured, the Doppler shift f_d can be computed and the radar spectra are shifted up or down depending on the sign of f_d , and taking into account the azimuth direction of the each spectrum.
- *geometric correction.* Antenna rotation and vehicle displacement occur simultaneously, introducing geometric distortions between the 360 spectra of the radar image. These geometric distortions lead to the detection of targets with incorrect positions and deformed shapes. We use two proprioceptive sensors (gyrometer and odometer) to estimate the trajectory of the vehicle during one antenna revolution. By combining this estimated trajectory with the azimuth values of the spectra, a consistent revolution image can be constructed.

Cartesian images are defined in the robot reference frame: the horizontal direction to the right indicates the travel direction of the robot.

Figure 3(d) is the result of the final radiometric correction. In Figure 3(c), one can see random amplitude variations over all observed surfaces. This phenomenon is an illustration of the speckle effect, which is introduced by signals interferences between targets located at roughly the same distance. Speckle noise minimization is a lively research activity, particularly in remote sensing domain (Huang, 1996). With PELICAN radar, speckle noise reduction is obtain with a multi-look filter (sliding average of N panoramic radar images). Specific signal processing can also be applied in order to improve distance and angular resolutions of radar images (Rouveure, 2014).

3. R-SLAM MAPPING ALGORITHM

Successive panoramic images are concatenated to build a global map: it is therefore necessary to determine the relative position



Figure 2. General view of PELICAN radar. The size and weight of PELICAN radar facilitate its implementation on various kinds of vehicles.

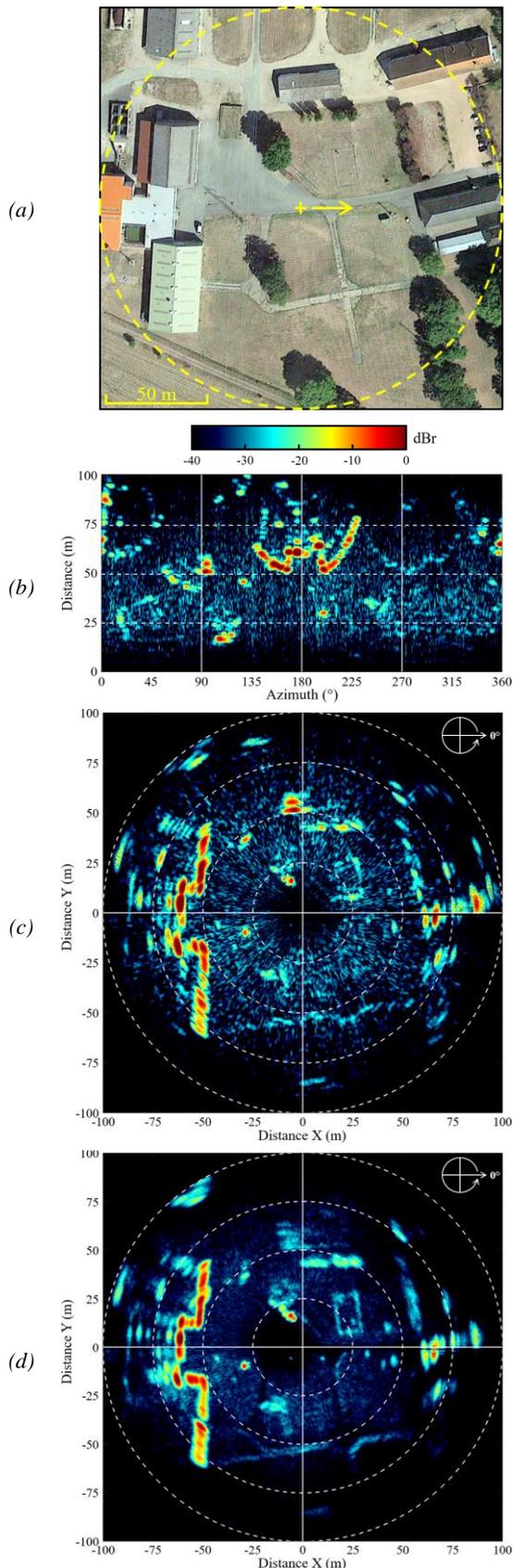


Figure 3. Radar image construction. (a) Aerial image of the test zone. Yellow cross and arrow: position and orientation of the robot. (b) Raw radar data in polar coordinates. (c), (d) Radar images in Cartesian coordinates, without and with anti-speckle filter respectively

and orientation between images. An objective is to avoid the use of GPS data, so a specific algorithm called R-SLAM has been developed (Rouveure, 2009). This algorithm is based on Simultaneous Localization And Mapping (SLAM) principles to estimate images positions. SLAM is an approach developed for several decades in mobile robotics domain (Chatila, 1985; Smith, 1987). It allows determining the positions of a robot directly through exteroceptive data (camera, laser, radar, etc.), without requirements for an absolute positioning system. Several algorithms such as EKF SLAM, FAST SLAM or Graf SLAM have proven to be effective for localization in mobile robotics (Dissanayake, 2001; Nieto, 2001; Thrun, 2005). However, these algorithms are based on landmarks detection and association, which are by themselves non-trivial operations when considering radar images processing. The situation presented in Figure 4 directed us to another solution. Figure 4(b) and Figure 4(c) are two successive radar images provided by PELICAN radar (time interval, displacement and orientation change between images: 1 s, 2.1 m and 10° respectively). One can see that both images are almost similar, and related with a proper rigid transform (rotation R + translation T). With the developed approach, rotation R and translation T are directly estimated with a dense matching between radar images. The main advantage of this solution is that each radar image is considered as a whole: landmarks detection and association are avoided. Many different approaches can be found in the literature to compute R and T . Two have been evaluated: 3D correlation and Fourier-Mellin Transform (FMT). In the current version of the algorithm, computed $[R, T]$ parameters are directly used to merge the panoramic images in the global radar map.

The radar map uses an occupancy grid representation. With this representation, space is discretized in the form of a grid of cells. The grid structure is rigid and rectangular. Each cell indicates the mean energy reflected by the corresponding area in the real world. It is often considered that grid maps are best suited for small environments, because the required memory increases with the size of the map and can lead to “out of memory” errors. In order to be able to deal with large environments, R-SLAM algorithm manages the memory through a mosaic approach. Only the part of the map in the field of view of the radar is maintained in random access memory (RAM); the rest of the map (i.e. outside the scope of the radar) is stored in bulk memory whose capacity can be extended at will. In that sense, the radar map is splitted into squares with 100 meters sides. At each time step, only a local map (made of 3×3 squares), located on the current radar position, is loaded into the RAM. As the radar moves, the 3×3 local map configuration is dynamically adapted. As long as the radar’s position remains in the central square, the 3×3 local map configuration is kept unchanged. When the radar’s position moves in one of the eight peripheral squares, this square becomes the central square and the 3×3 local map configuration is adapted: “old” squares (outside the scope of the radar) are stored in fast-access bulk memory; “new” squares are recovered from the bulk memory, or created as empty squares if they do not exist. The principle of this memory management is illustrated in Figure 5.

The interest of this memory management is threefold. First, “out of memory” errors are avoided. Second, a better management of processor live memory, avoiding dynamic allocation operations. Third, an improvement in processing time, because the amount of live memory is constant and small, resulting in smaller and constant processing times which is a crucial point with a view to real time applications.

Two examples of radar map construction are presented in Figure 6 and Figure 7. The current version of R-SLAM algorithm

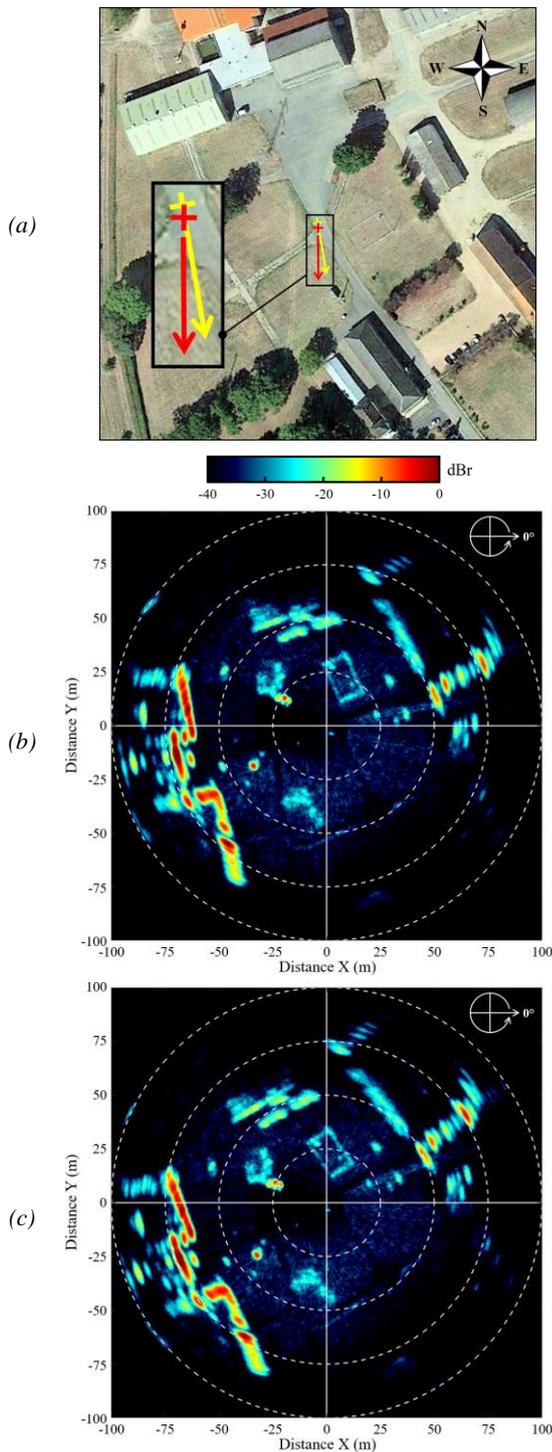


Figure 4. Example of two successive corrected radar images. (a) North-oriented aerial image of the test zone. Yellow/red crosses and arrows: successive positions and orientations of the robot. (b), (c) Successive radar images in Cartesian coordinates. Time interval, displacement and orientation change between images: 1 s, 2.1 m and 10° .

is written in Matlab[®] language and it operates off-line. In Figure 6, PELICAN radar is positioned on an experimental 4×4 vehicle, 3 m above ground. Figure 6(a) is an aerial view of the test zone. The environment highlights various configurations, with large open areas dominated by grasses, forests, isolated trees and bushes, asphalt roads and numerous buildings. The green, red and magenta dots indicate three trajectories followed by the

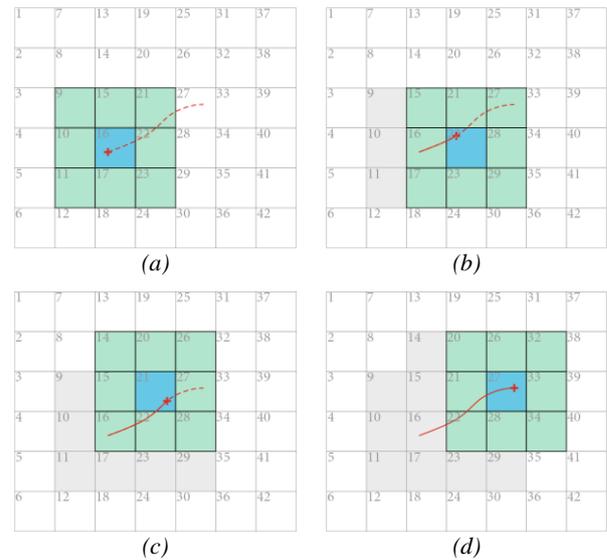


Figure 5. Principle of mosaic memory management. Images (a) to (d): successive radar positions. Red line indicates radar trajectory. Blue and green squares show the position of the 3×3 local map. When radar moves, the position of the local map is adapted. For example in (b), square labelled 22 becomes the central square of the local map: squares labelled 9-10-11 are stored in bulk memory; squares 27-28-29 are recovered from the bulk memory (if they exist) or created as empty squares, in order to obtain an operational configuration of the local map.

vehicle (GPS data for validation purposes). The total distance travelled for all trajectories is about 7.0 km, with a mean velocity of 3 m/s. About 2100 panoramic images have been used to produce the radar map in Figure 6(b), which is a merge of the three trajectories. The pixel size is 20 cm. The colored dots show the computed trajectory. The grey level variations indicate RF amplitude variations of the measured radar signal. A general view of the experimental 4×4 vehicle is also displayed in this image.

The aerial view of the second test zone is presented in Figure 7(a). In this example, PELICAN radar is positioned on AROCO robot, 2 m above ground. The environment is semi-natural, with a succession of grassy areas, woods, pavement areas and several buildings. Yellow dots indicate the followed trajectory (GPS data for validation purposes). A general view of AROCO robot is also displayed. The covered distance is about 2.2 km, with a mean velocity of 3 m/s. About 750 panoramic images have been used to produce the radar map presented in Figure 7(b). Red dots show the computed trajectory of the robot. Green dotted squares illustrate the principle of memory management with a mosaic approach. The three upper-right grey squares correspond to areas that have remained outside the scope of the radar.

4. LOCALIZATION IN AN EXISTING RADAR MAP

We assume now that the robot has at its disposal a pre-existing map; this map has been constructed during an exploratory phase. The map is frozen, i.e. it represents the whole environment in which the robot can travel. Using the real-time panoramic images provided by the radar, the objective is to determine the positions and orientations of the robot in the map. This localization task is based on all the algorithmic techniques developed for the maps construction. However, two phases have to be distinguished: (i) determination of the initial position, and (ii) tracking of the successive positions of the robot in the map.

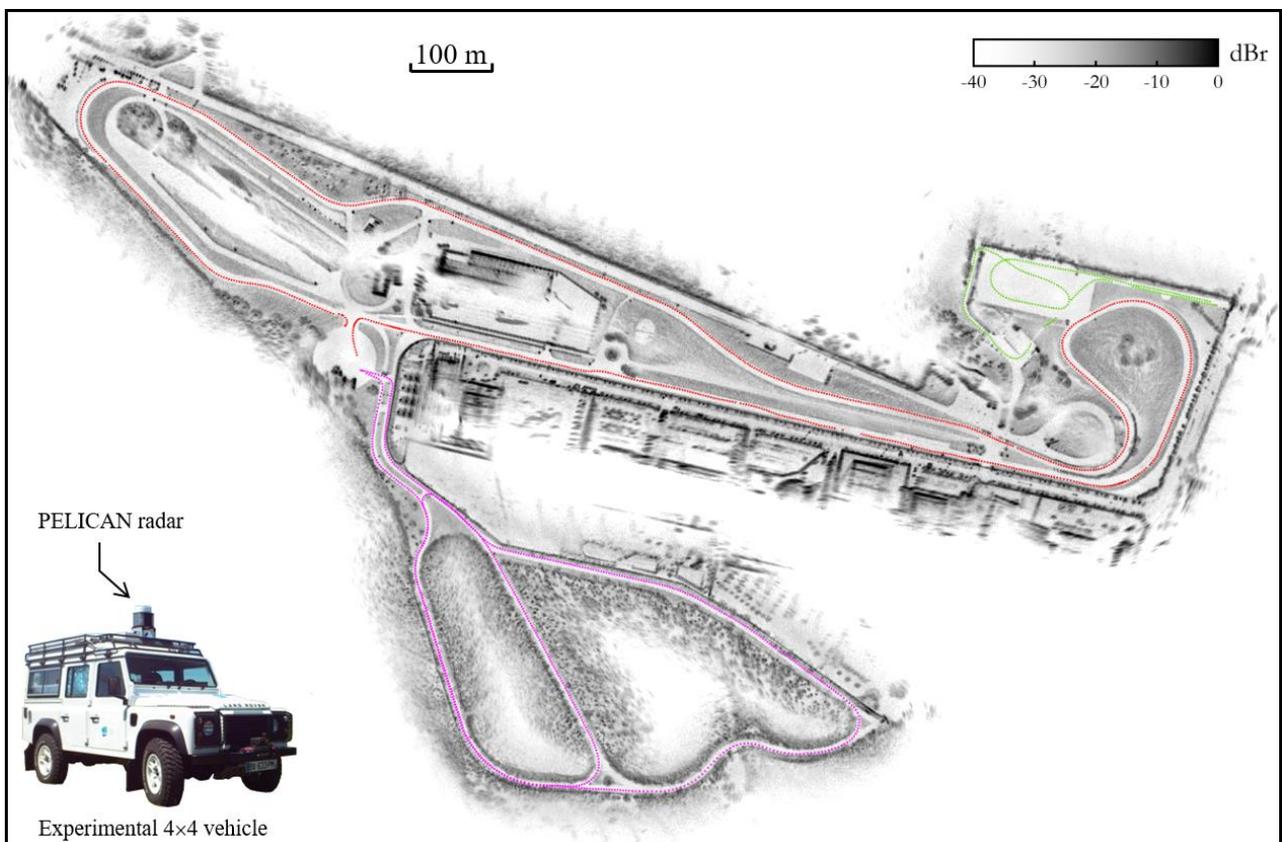
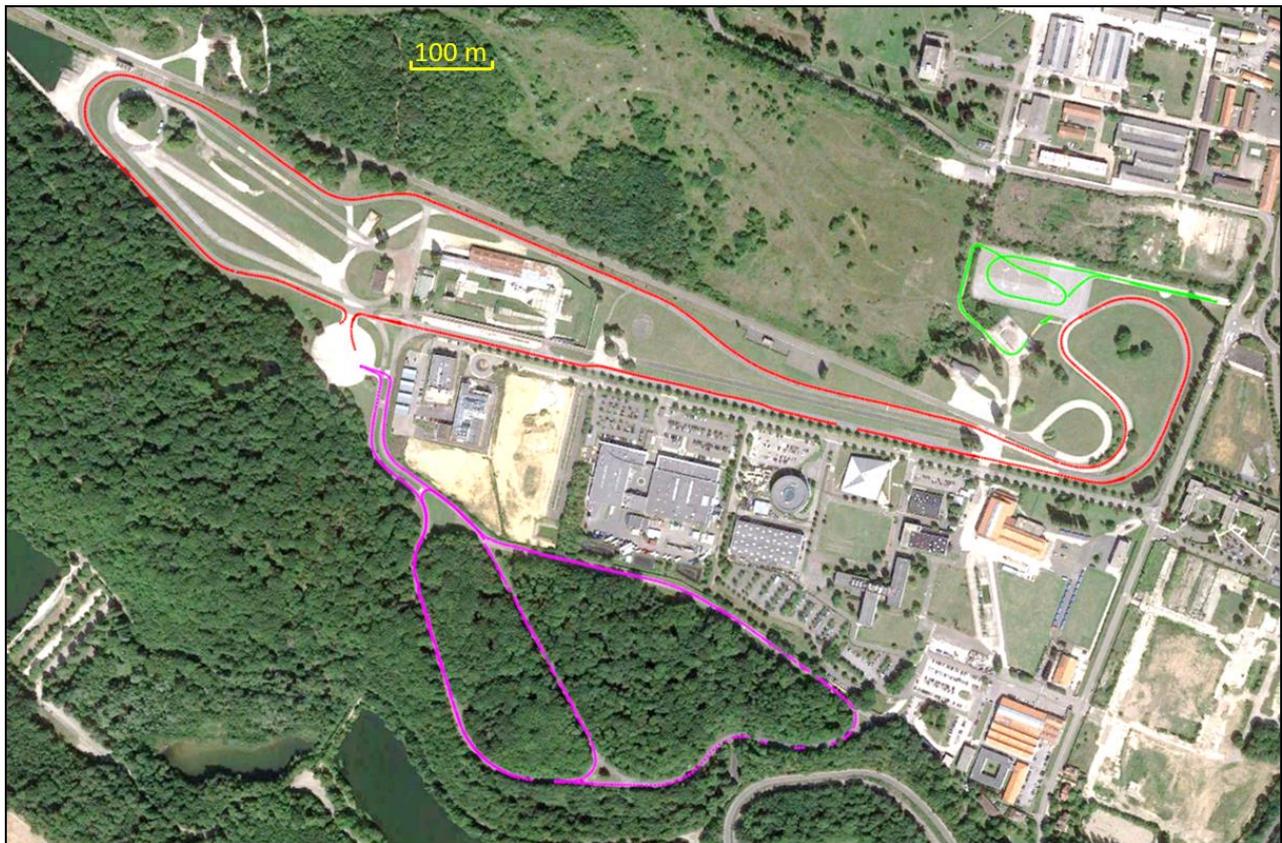


Figure 6. Example of radar map construction. (a) Aerial image of the test zone. Green, red and magenta dots indicate three trajectories (GPS data) followed by the vehicle, and which are used to build the radar map. (b) 2D radar map. The grey level variations indicate the amplitude's variations of the measured radar signal. Colored dots: computed vehicle's trajectories.

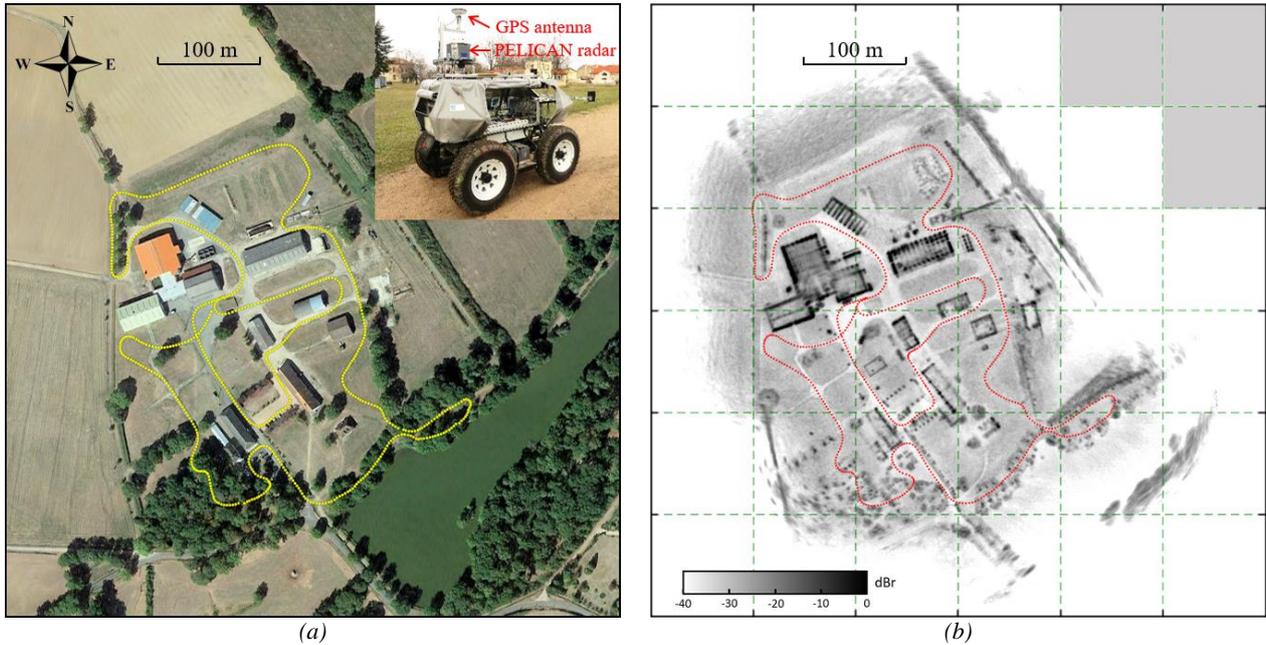


Figure 7. Example of radar map construction. (a) Aerial image of the test zone. Yellow dots indicate the trajectory (GPS data) followed by the robot. The upper-right image shows PELICAN radar positioned on AROCO robot. (b) 2D radar map. The red dots indicate the computed radar trajectory.

4.1 Initial Position

It is first necessary to determine the initial position of the robot within the radar map. In mobile robotics domain, this problem is known as the “Kidnapped Robot Problem” (KRP) (Seow, 2017). The KRP problem can be described as follows: the robot is positioned to arbitrary and unknown location, and it must determine its position without additional information. We do not work on this particular problem, which is considered as one of the worst-case scenario in mobile robotics, so two simplifications have been developed:

- a rough initial position of the robot in the map is manually provided;
- or we use a low precision GPS data reading (natural GPS). This solution implies a rough calibration of the radar map with GPS coordinates during a preliminary phase.

With this rough position of the robot, a reduced search space in the map is defined. Within this reduced search space, the initial position of the robot is automatically refined and designated by the algorithm with the matching procedures between the map and the current radar image described in the following paragraph.

4.2 Successive Position Tracking

Each second, PELICAN radar provides a new image of the environment. Knowing the initial robot’s position, the following successive positions are tracked with a 3D matching (2D shift + orientation) between the current radar image and a subpart of the radar map: to compute the p position of the robot, the subpart of the map is centered on the known $(p-1)$ position.

The matching algorithm is similar to that used for the construction of the map. Generally, we are using the well-known cross-correlation function. One major interest of this solution is that it is noise resistant: it can deal with significant modifications between the environment observed during the map’s construction, and that observed during the localization process. For example, the presence of new obstacles, or the absence of

obstacles present during the map’s construction, will not prohibit the calculation of the robot’s positions. In order to improve computing times, information from proprioceptive sensors (odometer and gyrometer) are used to reduce the search space.

An example of 3D correlation matrix is presented in Figure 8. The maximum of the matrix allows determining the robot’s shift (x, y) and orientation θ within the map. In this example, the computed shift is $x = 2.16$ m and $y = -0.26$ m, and the computed rotation is $\theta = 18.50^\circ$.

4.3 Experimental Results

The experiment is divided into two parts: PELICAN radar realizes a first displacement in order to build a map of the environment; and a second displacement through the same environment is done in order to determine the followed

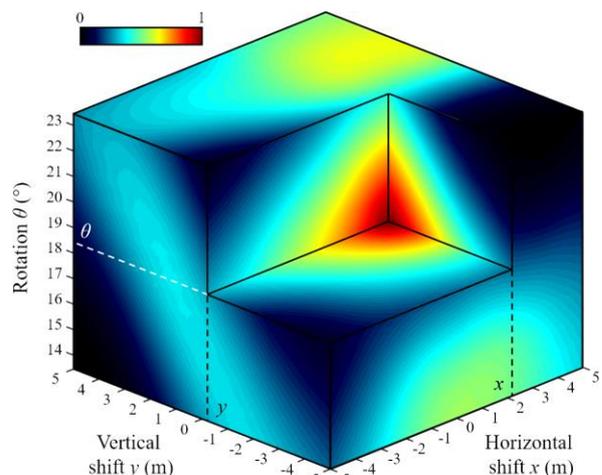


Figure 8. 3D correlation matrix example. The maximum of the matrix is used to determine the shift (x, y) and orientation θ of the robot within the map.

trajectory, with the 3D matching of the successive radar images and of the radar map.

One difficulty for the evaluation of localization performances is that the process is highly dependent on the quality of the radar map construction. Indeed, map construction process suffers from drift due to cumulative small errors: as the length of the trajectory increases, the sum of these errors can lead to substantial positioning errors. Without correction, this drift makes it difficult to compare radar's performances with an absolute localization system such as GPS. The only way to correct the drift is to use loop closures (Mukherjee, 2019). A loop closure occurs when the vehicle returns to a past location after having discovered new terrain for a while. The loop closure detection is realized if the environment is recognized, i.e. if the current radar image of the environment can be successfully matched with previous ones. The loop closure detection is then used to determine position and orientation errors: a corrected radar trajectory can be computed and used to build a more consistent radar map.

Such a loop closure detection has been used to build the radar map presented in Figure 9. PELICAN radar is positioned on the 4×4 vehicle presented in Figure 6, 3 m above ground. The vehicle is also equipped with a RTK GPS system. An aerial image of the test zone (baseball stadium) is shown in Figure 9(a). For the localization experiment, radar follows a circular trajectory around the stadium, starting from point A up to point B. The covered distance is about 685 m, with a mean velocity of 3 m/s. Yellow dots indicate the measured RTK GPS trajectory. The result of the radar-based localization process is presented in

the radar map (Figure 9(b)). To start the process, a rough initial position of the radar trajectory has been indicated manually. The error curve (Euclidean distance between GPS points and corresponding radar points) is presented in Figure 10. We obtain a mean error of 28.1 cm, and a standard deviation of 13.8 cm.

5. CONCLUSION

In this paper we present the application of PELICAN radar for (i) the construction of maps of the environment and (ii) robot's localization in outdoor and extended environments. A radar map of the travelled environment is build off-line in an initial phase, and it is used in-line for robot's localization purposes.

PELICAN is a FMCW microwave radar, whose compact dimensions and low weight facilitate its implementation on various kind of vehicles (robots, cars, tractors, etc.). The use of microwave technology is well suited for outdoor applications, because of the robustness of radar sensor which ensures a save and trouble-free operation even in adverse environmental conditions (rain, fog, dust, etc.).

Due to their respective operating constraints, microwave radar and GPS are complementary positioning systems, and one objective in future works is to merge their information in order to build a localization system able to deal with all situations encountered in outdoor robotics applications.

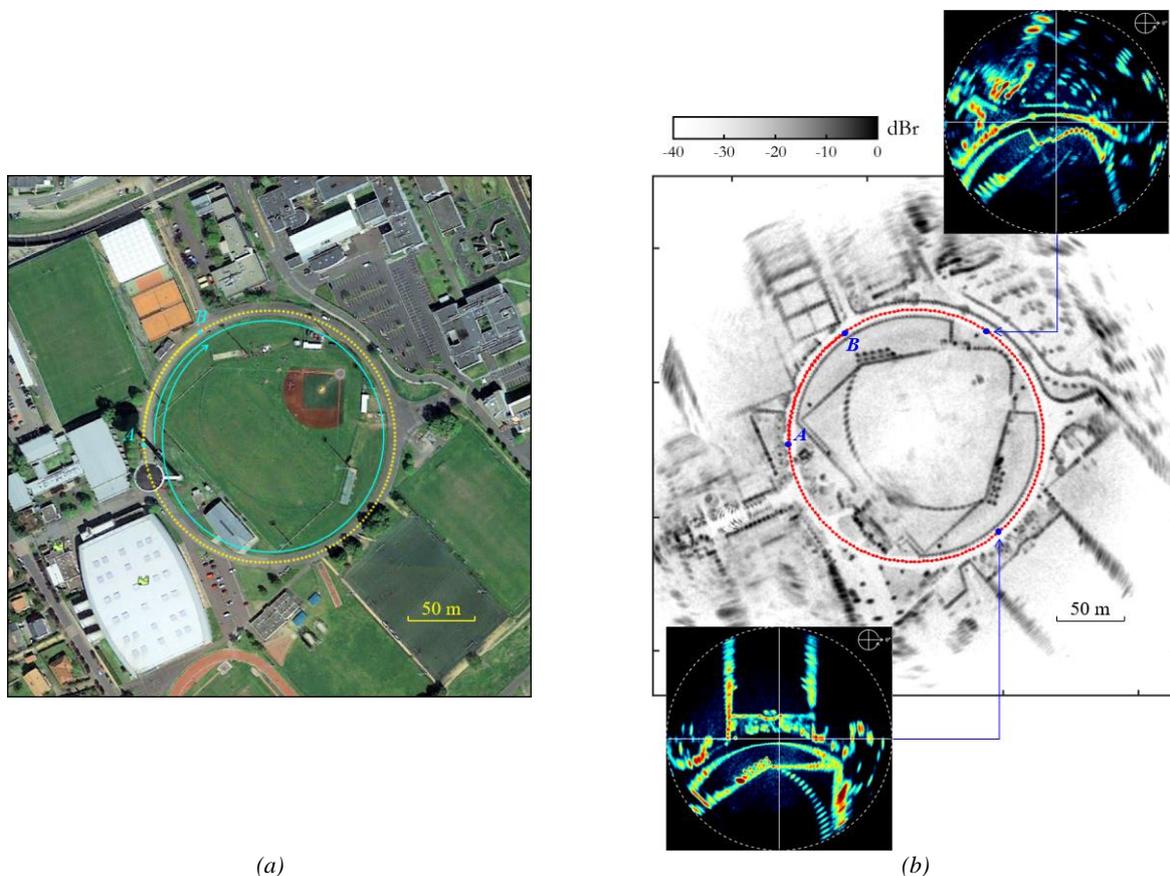


Figure 9. Experimental results. PELICAN radar is positioned on an experimental 4×4 vehicle, 3 m above ground. (a) Aerial image of the test zone. The vehicle follows a circular trajectory around a baseball stadium (covered distance: 685 m; mean velocity: 3 m/s): A and B are starting and end points respectively. Yellow dots indicate GPS trajectory (centimetric precision). (b) 2D radar map used for localization purpose. The red dots indicate the computed radar trajectory. Upper and lower images are examples of radar images used during the 3D matching process in order to determine radar's position (x, y) and orientation θ within the map.

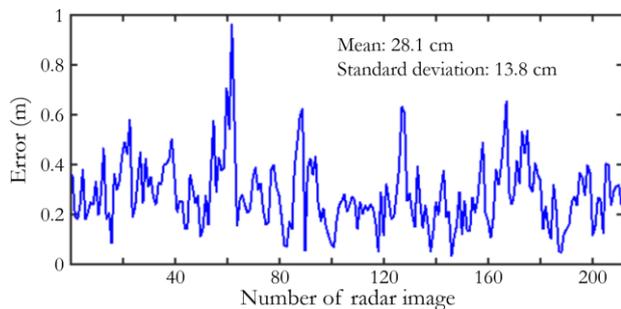


Figure 10. Positioning error. The computed error is the Euclidean distance between corresponding GPS and radar points.

ACKNOWLEDGEMENTS

This work was sponsored by a public grant overseen by the French National Research Agency as part of the “Investissements d’Avenir” through the IMobS3 Laboratory of Excellence (ANR-10-LABX-0016) and the IDEX-ISITE initiative CAP 20-25 (ANR-16-IDEX-0001).

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