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PELICAN: Panoramic millimeter-wave radar for perception in mobile robotics applications, Part 1: Principles of FMCW radar and of 2D image construction

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HIGHLIGHTS

- PELICAN is a MMW radar designed for perception in mobile robotics applications.
- Use of FMCW modulation for easy implementation and short-range measurements.
- Limitation to 2D imaging due to the use of a rotating fan-beam antenna.

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ABSTRACT

Robust environmental perception is a crucial parameter for the development of autonomous ground vehicle applications, especially in the field of agricultural robotics which is one of the priorities for the Horizon 2020 robotics funding (EU funding program for research and innovation). Because of uncontrolled and changing environmental conditions in outdoor and natural environments, data from optical sensors classically used in mobile robotics can be compromised and unusable. In such situations, millimeter-wave radar can provide an alternative and complementary solution for perception tasks. The aim of this paper is to present the PELICAN radar, a millimeter-wave radar specifically designed for mobile robotics applications, including obstacle detection, mapping and situational awareness in general. In this first of a two-part paper, the choice of a frequency-modulated continuous-wave radar is explained and the theoretical elements of this solution are detailed. PELICAN radar is using a rotating fan-beam antenna, and the construction of 2D representations of the surrounding environments with radar data is described through simulation results. *The second part of the paper will be devoted for a detailed description of PELICAN radar, as well as experimental results.*

1. Introduction

Robust perception is still a sensitive and challenging process in outdoor environments for Autonomous Ground Vehicles (AGV). Robots have to deal with complex and changing situations, including variations of ambient light level, day/night cycles, weather conditions (fog, rain, snow) or presence of obscurants (dust, smoke). In such situations, sometimes called Degraded Visual Environments (DVE), optical sensors (vision, laser) classically used in mobile robotics applications can be partially or completely ineffective, and the mission of the robot will not be completed.

It is no longer necessary to demonstrate the robustness and the efficiency of Millimeter-Wave (MMW) radars for perception tasks in outdoor environments. Because of a millimeter wavelength, MMW radars provide robust information even in degraded visual conditions. Such capabilities are extensively used for example in the military domain (air and maritime surveillance, missile guidance, etc.), in the field of civil aviation (approach radar, surface movement radar) or in the field of remote sensing (observation of Earth and other planets of the solar system). For the development of AGV applications, radar technology must be progressively adapted for smaller platforms, in terms of dimension, weight, energy consumption and cost.

The agricultural domain is a promising sector for AGV applications [1,2] and manufacturers are already working on the development of industrial solutions [3,4]. But the autonomy of these systems can be limited when they are faced with environmental

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conditions that cannot be controlled in outdoor and natural environments, and that are often harsh for perception sensors. Irstea Institute in Clermont-Ferrand (France) is involved in several research projects for the development of robotics solutions for the agricultural domain,[1] and it has naturally taken an interest in the development of a robust perception system based on MMW radar.[2]

Numerous research teams have used and are using MMW radars within the framework of mobile robotics domain. Obstacle detection is widely studied in automotive applications, for the detection of moving and static targets (cars, pedestrians) [5–7] or for the estimation of road geometry [8]. The imaging capabilities of radars are also used for visualization and characterization of the environment [9–12], 2D/3D mapping and simultaneous localization and mapping (SLAM) applications [13–15]. Several researches are also involved in radar-vision fusion for obstacle detection and outdoor reconstruction [16–19] relying on the complementarity of the sensors: robustness to environmental conditions and depth detection ability of the radar; high spatial resolution of the vision. One problem for the development of radar-based solutions in mobile robotics is the radar itself, because the number of radars available on the market is not so important. In the automotive domain, several specific radars are under development for vehicle and obstacle detection in degraded atmospheric conditions; but their use outside the field for which they were originally designed can be difficult due to specific design considerations. A few commercial systems can be found on the market such as a 77 GHz radar from Navtech Radar Ltd Company, but these radars have not been specifically developed for AGV applications. Our objective was to develop a specific MMW radar for perception in mobile robotics applications, with the ambition of making this radar available for the robotics community, through the availability of databases, collaboration on research programs and perhaps in the future the marketing of the radar.

The aim of this paper is to present PELICAN radar (see Fig. 1). PELICAN is a panoramic radar developed at Irstea Institute for perception in mobile robotics applications. It is a low-power K-band radar (24 GHz), and it is based on a frequency-modulated continuous-wave emission. The radar is using a fan-beam antenna, which allows to build 2D representations of the surrounding environment. Lightweight (5 kg) and small sized (diameter 40 cm, height 23 cm), PELICAN can be easily positioned on various mobile platforms.

In this first part, the theoretical elements of the developed radar are presented, as well as simulation results. *The second part of the paper will be devoted for a detailed description of PELICAN radar, and for experimental results.* The principle of frequency modulation used for the radar is presented in Section 2, with a focus on the problem of simultaneous range and velocity measurement. Section 3 develops the criteria that have to be taken into account for the choice of the carrier frequency of the radar, such as radar dimensions or regulation constraints. The adopted solution to build 2D images of the environment with radar positioned on a robot is described in Section 4, and it is illustrated with simulation results. And Section 5 concludes the paper.

2. FMCW radar principle

Radars allow the location of objects in space by transmitting electromagnetic energy, and observing the returned echo. In the radar domain, two major families can be used to estimate the position of an object: *pulse radars* and *continuous radars*.

Basically, *pulse radars* transmit a high powered short pulse, after which the receiver is switched on in order to receive the echoes [20,21]. The presence of one or several echoes indicates the presence of one or several targets. The range r_i to target i is estimated through the measurement of the delay time τ_i between pulse transmission and pulse reception, with

$$r_i = \frac{c\ \tau_i}{2}, \tag{1}$$

where c is the light velocity. Pulse radar transmits pulse of duration τ_d. During this transmission duration, the receiver is switched off for protection purposes, and the radar cannot detect any targets: the transmission duration τ_d defines a blind zone from range zero to range $\delta r = c\ \tau_d/2$. The distance δr also defines the range resolution, i.e. the ability of the radar to distinguish two close targets. For autonomous robots applications requiring accurate radar-target distance measurements over short distances, a large value of δr can lead to an unacceptable configuration. Thus, a major problem with pulse radars is to be able to operate over short time durations – in order to achieve a high range resolution – a very high peak power signal—in order to have a reliable signal reception. For that reason, frequency modulated continuous wave radars provide competitive solutions for distance measurement in short range applications.

2.1. FMCW principle

Unmodulated continuous wave (CW) radar transmits continuously a constant frequency f_0 with constant amplitude, and measures the frequency difference between the transmitted and received signals. If the echo signal is reflected on a static target (radial velocity $v_r = 0$), transmitted and received frequency are equal. If the echo signal is reflected on a moving target (radial velocity $v_r \neq 0$), transmitted and received frequencies are different because the frequency of the reflected signal is shifted by the amount of the Doppler frequency f_d.

The radial velocity v_{ri} between the radar and the target i can be estimated using the well-known Doppler shift formula [20,22]

$$v_{ri} = \frac{c\ f_d}{2\ f_0}. \tag{2}$$

As no runtime measurement is required with CW radar, no distance determination can be made and the distance between the radar and the moving target i cannot be computed. If the distance must be determined, the transmitted signal can be modulated in order to get a time reference of the received echoes: this is the objective of the frequency modulation.

The principle of *frequency modulated continuous wave (FMCW) radar* is known and used for several decades [20,23]. In FMCW radars, the oscillator generates a signal of linearly increasing frequency Δf over a period t_m. This signal is transmitted into the air via the antenna. At the receiver stage, a part of the transmitted signal is mixed with the signals received from the i targets present in the field of view of the radar. The signal which appears at the output of the mixer is filtered and amplified in order to isolate the beat signal s_b.

Let us consider i targets located at distance r_i from the radar. We assume to have a static configuration, i.e. stationary radar and no moving targets. The transmitted signal is linearly modulated over a period $t_m = 1/f_m$ with a sawtooth function, with a sweep

[1] Examples of research projects led by Irstea Institute:

- PUMAgri: Universal mobile platform for agriculture
- ActiSurTT: Active devices for vehicles security in off-road environments
- SafePlatoon: Security of convoy of autonomous vehicles.

[2] Examples of research projects led by Irstea Institute:

- PELICAN: Radar Perception Localization and Mapping for Natural Areas.
- QUAD-AV: Ambient Awareness for Autonomous Agricultural Vehicles.