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OBSTACLE DETECTION AND TRACKING BY MILLIMETER WAVE RADAR

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Abstract: Driving assistance is a research topic which is in full these last years. An approach to detect and track several obstacles in real time will be presented in this article. Indeed, it is necessary to understand road (and vehicle) environment in order to help the driver in his task. Our approach uses a MMW Radar which permits good obstacle detections in spite of difficult weather conditions. This system is operationnal and has been implemented on our experimental vehicle.

Keywords: Sensor, Signal processing, Real time, Obstacle detection, Tracking

1. INTRODUCTION

In the last thirty years, driver assistance systems have been subject to intensive research investigation by the scientific community in order to decrease the number of accidents on the road like their consequences and thus to improve the safety of the passengers. Several systems, such as anti lock breaking, have been introduced into commercial road vehicles lately. In recent years, new projects for the recognition of objects in the vehicle environment of vehicles have been developed (Langer, 1997). In (Laneurit *et al.*, 2003), the system is able to give vehicle and absolute road obstacles localization in order to know if vehicle's trajectory is dangerous as well as to prevent the driver from potentially dangerous obstacles, using multisensor data fusion. Indeed, French National statistical studies about the road accidents (Observatoire National, 2003) have shown on the one hand that large part of accidents is due to the collision of the vehicle with fixed obstacles (bridge, tree for example), slow vehicles or have just stopped ahead as well and on the other hand with a lack of perception or a careless mistake of the driver. These studies also showed that part of these accidents could be avoided or at least their consequences minimized if the vehicles were equipped with a process detecting the obstacles and alert the driver quickly in the dangerous situations in order to increase the time for the decision and control.

It's with this objective and on the initiative of the French Ministry of Research that the PAROTO project is born. PAROTO is a french acronym of "Projet Anti collision Radar et Optronique pour l'auTOmobile". The goal of this project is to develop a demonstrator able to help the driver to better detect obstacles ahead from the informations provided by two sensors: RADAR and Thermal Camera. The association of these sensors will allow, with the use of different frequency bands (millimeter wave for the Radar and micrometric for the Camera), to reduce the rate of false alarm compared to the results obtained with a sensor alone thanks to more information on the object to be detected.

The PAROTO project includes four partners: INRETS, TEAM, SAGEM and LASMEA. In this article, we shall describe the work completed by the LASMEA laboratory which consists to built the Radar and to develop real-time signal processing algorithm.

This paper is organized as follows. In a first part, we shall present key characteristics of our home built Radar. The implementation of the system in the experimental vehicle of the laboratory will be describe in the second part. The third part shall describe the signal processing algorithm. Next, we shall illustrate

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some results in real situations. Finally, we shall give some conclusions and perspectives on this work.

2. THE RADAR OF THE PAROTO PROJECT

The objective of the PAROTO project is to detect the obstacles ahead with a high accuracy from the informations provided by a thermal camera and a Radar. The key interests to use a Radar in this project are on the one hand the accuracy of the estimated obstacle's speed and on the other hand the quality of its informations up to $150m$ in spite of difficult weather conditions.
According to the regulation in the European Union and in the United States, the wave emission frequency for a car anti-collision project is fixed to $77GHz$ (millimeter wave). The principle of the Radar used in this framework is a pulse Doppler Radar with a Doppler priority. Indeed, the priority is given to the relative speed between the obstacles and the equipped vehicle of the system. The distance of the obstacles are sorted by range gates.
Moreover, this Radar has only one antenna for the emission and the reception. This system requires the installation of a circulator (ultra-high-frequency system) and a synchronization process in order to transfer the energy either between the transmitter and the antenna or between the antenna and the receiver (see figure 1). The reception channel being very sensitive, the system must perfectly isolate this channel with the emission channel because of the strong emitted power.

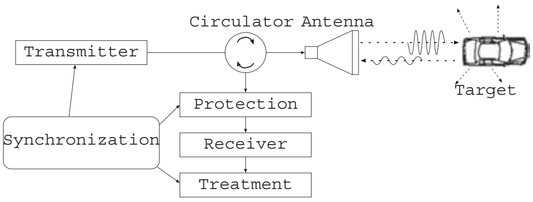

Fig. 1. Structure of the PAROTO Radar with one antenna.

2.1 Assessment of powers

The Radar technique used in this project consists to send by repetitive pulses (width $t_e = 150ns$ and period $T_r = 4\mu s$) a sinusoidal electromagnetic wave and to receive the echoes for the analysis (see figure 2). The powers assessment realized by using the mean power of the signal P_m during one period of repetition according to the power emitted P_e.

$$P_m = P_e \frac{t_e}{T_r}$$

The power of the reflected wave for a target placed at a range R with a cross section σ and with an antenna

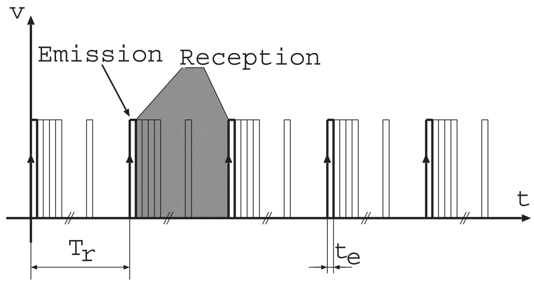

Fig. 2. Emission and reception chart.

gain G is given by the following expression(Skolnik, 1980):

$$P_r = P_e G^2 \lambda^2 \frac{\sigma}{(4\pi)^3 R^4}$$

λ is the wavelength used ($3.9mm$).
The cross section characterizes the enlightened surface by the incidental direction beam and its dimensions is a surface. It's a target characteristic (materials) which represents a measurement of its size seen by the Radar. For a power $P_e = 3mW$, an antenna gain $G = 26dB$, a range $R = 150m$ and a cross section $\sigma = 1m^2$, the mean power of the signal received by the Radar is equal to $3.10^{-13}mW$ from where the need of an effective insulation between the transmitter and the receiver.

2.2 Radar signal

The relation connecting the emission and reception signals can be expressed, in the case of only one echo (coming from an object located on the way of the wave emitted), according to the Radar-object distance R and the relative speed v in the direction of the Radar-object axis. For our impulse Radar, the emission complex signal is:

$$e(t) = A_e u(t) exp(j2\pi f_0 t)$$

where A_e is the amplitude of this signal and f_0 is the Radar frequency ($f_0 = 77GHz$ in our case). The amplitude A_e is proportional to the square root of the emission power P_e defined in the section §2.1. $u(t)$ (standardized pulse) represents the form of the pulse (duration t_e). The signal reflected $s(t)$ for only one echo can be expressed as following:

$$s(t) = A_r u(t - \tau(t)) exp(j2\pi f_0 (t - \tau(t))) \quad (1)$$

where $\tau(t) = 2\frac{R}{\lambda f_0} - 2\frac{v}{\lambda f_0} t$ represents the temporal shift between the emission and reception waves. The amplitude A_r is proportional to the square root of the reception power P_r. To take into account the antenna pattern (Maitre, 2001), we used a standardized function $G(\theta, \phi)$, θ and ϕ characterize the angles defining the position of the object compared to the axis of the antenna. In fact, the measurement represents the complex amplitude of the signal which mainly depends on:

- the position of the reflected signal compared to the origin time of the emission pulse: $2\frac{R}{\lambda f_0}$,
- Doppler frequency: $f_d = 2\frac{v}{\lambda}$,
- the object characterized by its cross section and its position compared to the axis of the antenna.

In the case of several objects, the reflected signal is the sum of the individual signals. To obtain the Doppler frequency, the variations of the amplitude of the echoes are analyzed by repeating the emission signal (period T_r).

3. IMPLEMENTATION

LASMEA Laboratory and RCS[2] society, partners in the construction of the Radar, jointly produced this integrated system in conformity with the specifications of the patent: "Anticollision method for vehicle" (Fritz, 1998). To validate the various claims of the patent, many result were obtained in real conditions with our experimental vehicle VELAC (figure 5). Our radar is a traditional Pulse Doppler type. This Radar is composed of:

- an antenna,
- a conventional radio frequency circuit (Gunn source, switch, reception mixer, etc.) characteristic of a Pulse-Doppler radar,
- two output channels I and Q (in quadrature of phase) (see figure 3),

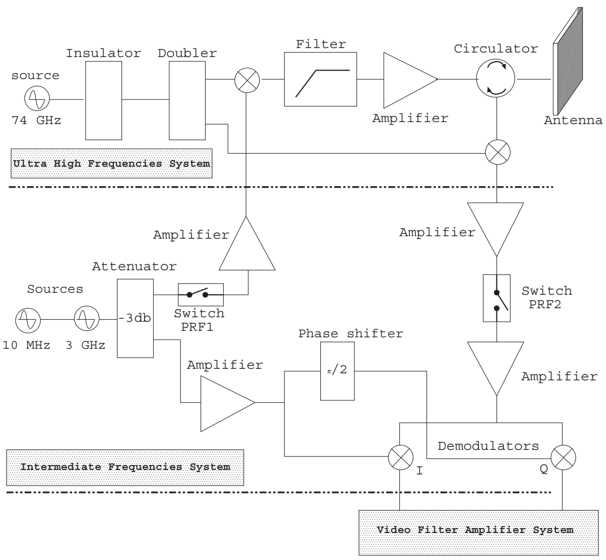

Fig. 3. Structure of PAROTO Radar.

- an acquisition and treatment unit including an analogical/digital converter,
- a digital calculator,
- a detection, recognition and false alarm rejection module,
- a decision module to indicate a dangerous situation to the driver of the equipped vehicle or the choice of a particular object in the radar beam (control speed function).

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Various systems able to obtain the same functions are known:

- The radar systems with linearly frequency wave modulated which use a traditional radar treatment. These systems determine successively or simultaneously the distance and speed of the environment's objects (Zang and al., 1994; Kumar, 1992).
- Traditional Pulse Doppler systems with high resolution distances. This sytem compute in a first time the distance and thereafter the speed by Doppler analysis (Rossettini and al., 1992).
- Two or three frequencies system. This one estimates in priority the distance by a phase measurement and then speed by Doppler measurement (Rossettini and al., 1992; May, 1990).
- Multibeam system, beam scanning system or beam width adaptation systems which compute the angular position of an object (Cornic and al., 1997).

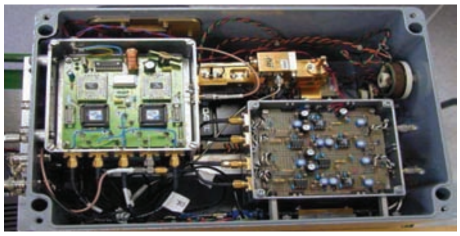


Fig. 4. Home built Radar.

Our system's advantages are:

- A simple Pulse-Doppler radar technology: only one emission frequency, a low emitted power, a switch of the emitted wave functioning at low speed, slow analogical/digital conversion, small size antenna with degraded performance and thus a low manufacturing cost, furthermore no distance-Doppler ambiguity,
- A fine use of Doppler in order to sort the objects and a distance coarse adjustment to define range gate. The use of range gates and the Doppler analysis refines the distance.

Fig. 5. Experimental vehicle: VELAC.

4. TREATMENT OF THE RADAR DATA

The objective of this step is to determine the distance and the relative speed of the objects (or obstacles) located in the enlightened space by the Radar beam. This detection is carried out from the signal $s(t)$ (equation1). Signals I and Q represent the real and imaginary parts of this signal $s(t)$. $s(t)$ is sampled in distance (index p) and time (index n) according the following equation:

$$s[p,n] = \sum_i A_r(\overrightarrow{R_i}) u_g(p\delta R - R_i) exp(j(4\pi \frac{v_i}{\lambda} n\delta t + \varphi_i))$$

Index i gives the object number returning an echo. The distance vector $\overrightarrow{R_i}$, in the signal amplitude, permits to take into account the antenna-object angle *i.e.* the target position in the radar field emission. Sampling in distance δR is proportional to the width of the emission pulse t_e by the relation: $\delta R = \frac{\lambda f_0}{2} t_e$, temporal sampling δt is proportional to the period of repetition of the pulse $\delta t = T_r$.
In our case the range data resolution is:

$$\delta R = \frac{c}{2} t_e = \frac{3 \times 10^8}{2} \times 150 \times 10^{-9} = 22.5m$$

$p = 1, ..., P$ and $n = 0, ..., N-1$ where P represents the number of range gates with a width δR and N the period number of the pulse repetition: time of analysis $T_{obs} = NT_r$.

The result of this digitalization is a complex signal (dimension $P \times N$) which the real part represents the signal $I[p,n]$ and the imaginary part the signal $Q[p,n]$ as well.

The next step is to compute the P Fourier transforms of the signals on N digitized samples according the following equations:

$$S[p,k] = FT(s[p,n])$$

where FT represents the Fourier Transform.

$$S[p,k] = \sum_i A_r(\overrightarrow{R_i}) u_g(p\delta R - R_i) FT(exp(j(4\pi \frac{v_i}{\lambda} n\delta t + \varphi_i))$$

$$S[p,k] = \sum_i A_r(\overrightarrow{R_i}) u_g(p\delta R - R_i) exp(j\varphi_i) \Delta[k\delta_v - v_i]$$

The time axis (index n) is transformed into speed axis (index k) where the function $\Delta[k\delta_v - v_i]$ is defined by:

$$\Delta[k\delta_v - v_i] = \frac{sin(\pi N \frac{k\delta_v - v_i}{v_{max}})}{sin(\pi \frac{k\delta_v - v_i}{v_{max}})} exp(-j\pi((N-1)\frac{k\delta_v - v_i}{v_{max}}))$$

with:

$$\nu_{\max} = \frac{c}{2 f_0 T_r} = \frac{3 \times 10^8}{2 \times 77 \times 10^9 \times 4 \times 10^{-6}} = 487.4m/s$$

$$k = -\frac{N}{2}, ..., \frac{N}{2} - 1 \qquad\qquad p = 1, ..., P$$

This frequential representation of the signal is due to the digitalization which limits the observation of the temporal signal to N samples.

Sampling speed is inversely proportional to the repetition period T_r. If the number of points N to compute the Fourier transforms increases, in the one hand the speed resolution also increases but, in the other hand, the time analysis too. The numerical choice of N is realized by the use of the Fast Fourier Transform algorithm (FFT) where the number of samples to be analyzed takes a value 2^N. To have $T_{obs} \simeq 8ms$ we must choose $N = 2048$. Finally, we have:

$$\delta_\nu = \frac{\nu_{\max}}{N} = \frac{487.24}{2048} = 0.238m/s$$

Before to compute FFTs, we apply a data windowing on the original signal $s[p,n]$ to reduce the side lobes in the I and Q Fourier space in order not to have several echoes for the same target in the same range gate. Thereafter, the compute of P FFT is carried out. An additional step permits to seek the echoes (obstacles) in the Fourier's space.

4.1 Seek echoes

After the compute of P FFT, a new obstacle is found if the energy in the Fourier's space (array of dimension $P \times N$) is higher than an experimental fixed constant threshold. For each obstacle, it is necessary to identify its relative speed and its distance compared to the vehicle equipped with the Radar. The index corresponding to the column of the array identifies the speed obstacle index and line index that of the distance. In our case, the number of range gates is $P = 5$ that represents a maximum analysis distance of $112.5m$.
From the Fourier transform analysis, an echos array is built. Each echo is characterized by four parameters:

- time: $n \times T_r, n \in [0, ..., N-1]$,
- amplitude: value of the power spectral density versus frequency,
- doppler: position in the column power spectral density array

$$V_{r_m} = (column - 1 - \frac{N}{2}) \times \delta_\nu$$

- range: position in the line power spectral density array

$$r_m = (line - 1) \times \delta R + \frac{\delta R}{2}$$

Finally, every $8ms$ the radar delivers a measurement of time, amplitude, range and an index speed for all echoes. The range gate is $\delta R = 22.5m$ and an index speed corresponds at a speed of $\delta_\nu = 0.238m/s$. In radar measurements, one target can generate several echoes in close range gate as well as neighbor speed samples. A pretreatment is thus necessary in order to gather the echoes emanating of the same target. In a second step, a measurement vector $Z = \begin{pmatrix} r_m \\ V_{r_m} \end{pmatrix}$ and its covariance matrix $C = \begin{pmatrix} \sigma^2_{r_m} & 0 \\ 0 & \sigma^2_{V_{rm}} \end{pmatrix}$ are associated to each resulting target.

4.2 Kalman filter based tracking

After detection of different targets, we are able to track them in consecutive frames. We assume that a target (obstacle) is a track if:

$$\begin{cases} V_r(k+T_{ini}) - V_r(k) < \alpha_{speed} \\ V_r(k+2T_{ini}) - V_r(k+T_{ini}) < \alpha_{speed} \\ RG(k+T_{ini}) - RG(k) < \alpha_{RG} \\ RG(k+2T_{ini}) - RG(k+T_{ini}) < \alpha_{RG} \end{cases}$$

where k represents the time step, V_r the obstacle speed, α_{speed} a speed threshold, RG the obstacle range gate, α_{RG} a range gate threshold, and T_{ini} an under sampling of acquisition period T to avoid the multiplication of generated tracks. α_{speed} and α_{RG} are proportionnal to T_{ini}: we use $T_{ini} = 5 * T$, $\alpha_{RG} = 1$, $\alpha_{speed} = 0.238m/s$. In this case, the Kalman initialization step is done. Kinematics model can be represented in matrix form as:

$$X_k = FX_{k-1} + GV_k, \quad V_k \sim N(0,Q) \qquad (2)$$

where $X_k = (r, V_r)^t$ is the target state vector, F the transition matrix which modelises the evolution of X_k, and $Q = \sigma^2_a$ the covariance matrix of V_k which representes the acceleration. σ^2_a was fixed according to possible maximum decelaration, obtained during a braking with an A.B.S. system: $\sigma^2_a = 7m/s^2$

$$F = \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} G = \begin{pmatrix} T^2/2 \\ T \end{pmatrix} Q = \sigma^2_a$$

The observation equation can be written as:

$$Z_k = HX_k + W_k, \quad W_k \sim N(0,C)$$

where $Z_k = (r_m, V_{r_m})^t$ is the measurement vector, H the measurement sensitivity matrix, and C the covariance matrix of W_k.

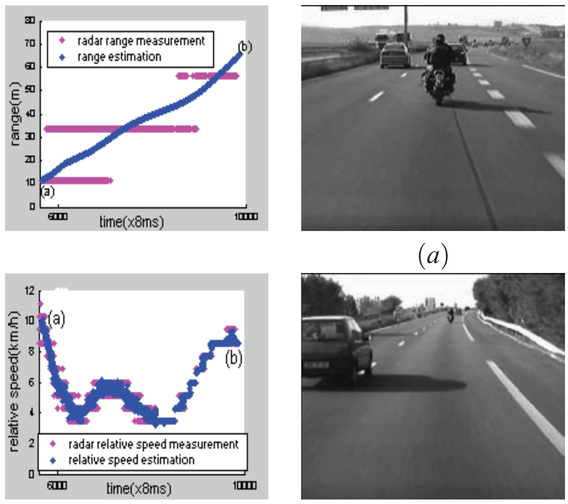
$$H = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} C = \begin{pmatrix} \sigma^2_{r_m} & 0 \\ 0 & \sigma^2_{V_{rm}} \end{pmatrix}$$

Before integrating measure into the filter, it is selected by a two steps procedure: first windowing and nearest neighbour filter. Windowing is done by using the following equation filter (Bar-Shalom and Fortmann, 1988):

$$Inn^t S^{-1} Inn \leq \gamma$$

where $Inn = Z_k - H\tilde{X}_{k/k-1}$ is the innovation , $\tilde{X}_{k/k-1} = F\hat{X}_{k-1/k-1}$ is an estimate given from equation 2, S the covariance matrix of the predicted value of the measurement vector, and γ a parameter given from table of the chisquare distribution. Finally, to associate a measurement vector Z_k to a track, a nearest neighbor standard filter is used.
Furthermore, when obstacles move out the field of view of the radar or are occulted, the algorithm use an age track approach. Obstacles parameters are updated by the predicted value of the state vector, thus it can be matched again when it reappears. The track is finished if it doesnt reappear after a fixed time interval. This tracking yields a range estimate more accurate than the gate value ($22.5m$), and also obstacle speed, as it is shown on results (see §5).

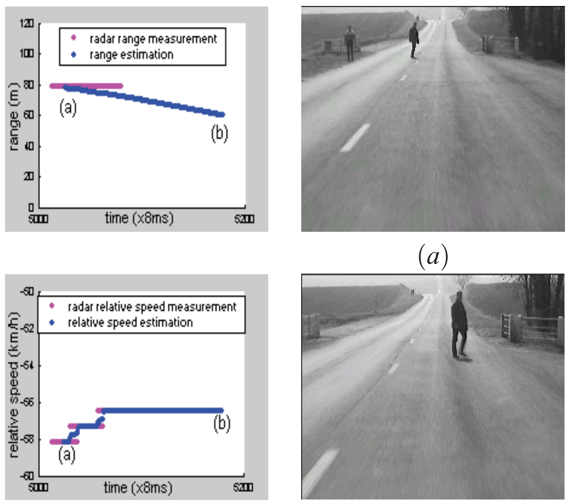
5. RESULTS



(a)

(b)

Fig. 6. motorcycle



(a)

(b)

Fig. 7. pedestrian

As it is shown on results, we can detect and track severals obstacles: motorcycle (figure 6), pedestrian (figure 7), vehicles (figure 8). Also, we are able to

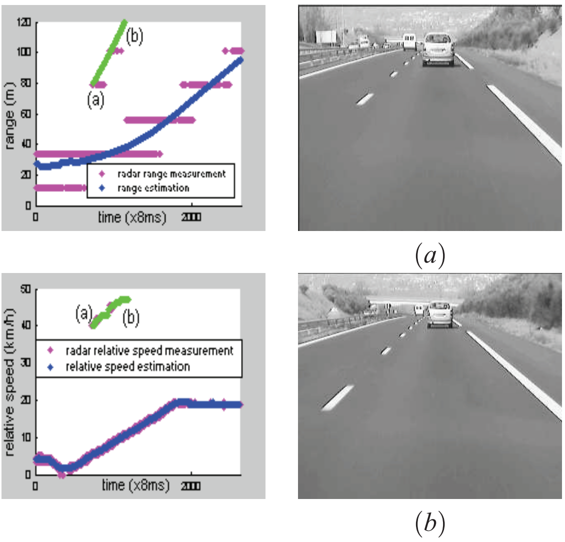


Fig. 8. two obstacles

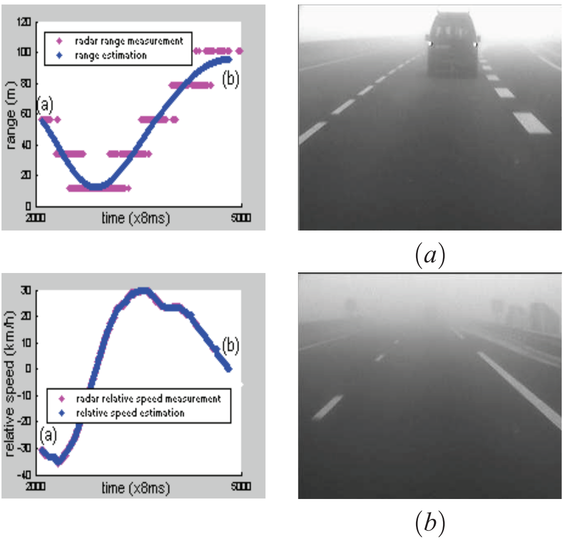


Fig. 9. obstacle in foggy conditions

track many obstacles (figure 8). On these illustrations, we show that the tracking algorithm provide a range estimate more accurately than a range gate. For the relative speed, the estimate corresponds to radar measurement. Furthermore, we can see that when obstacle's relative speed become positive the range increase (figure 9). Finally, the algorithm is able to track an obstacle even if it is not visible with a classical vision system (figure 9). In figure 7,even if Radar doesn't provide measurement (obstacles moves out the field of view of our radar), the position and the relative speed of the pedestrian are estimated. This estimation is available during a fixed period by the use of the age track approach.

6. CONCLUSION AND PERSPECTIVES

The works realized by the LASMEA laboratory in the framework of the PAROTO project were presented in this article. An experimental millimeter wave Radar 77*GHz* has been developed by the LASMEA to detect and track obstacles ahead. Our approach to estimate the distance and relative speed of the obstacles is mainly based on the FFT and Kalman filter algorithms. The future works of this project to develop a complete obstacle detection system are in the one hand to merge the results of this process with the results provided by the thermal camera process in order to identify the obstacles (distance, speed and direction) likely to be dangerous, in the other hand these informations could be merged with the informations provided by other sensors (LIDAR, classical camera, etc.). Moreover, the Radar's antenna should be changed soon in order to cover a larger field and thus to detect the obstacles in the other lanes.

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