Title: Radar target detection in range-doppler domain

One fundamental issue in target detection is to maintain a constant false alarm rate in various signal-to-noise ratio scenarios. The false alarm performance of a square law detector for a target in complex white gaussian interference and noise is given by

$$P_{FA} = e^{\frac{-T}{\beta^2}} \tag{11}$$

where T is the detection threshold and β^2 is the noise and interference power. In the other word, the detection threshold is proportional to the noise and interference power in the following relation:

$$T = \alpha\beta^2 \tag{12}$$

where the multiplier α is a function of desired false alarm rate. The interference power in practice is usually estimated through different techniques such as cell-averaging (CA) and ordered-statistics (OS).

In conventional radar detection, ground clutter and targets of interested may be well separated in some domains and the detection processing can take advantage of these separability. In these cases, the detection threshold T can be determined by the CFAR procedure given the statistical property of the noise and interference. However, in vehicular radar systems, the detection problem in the range-Doppler domain becomes more complicated because of the following reasons. First, vehicular radar systems face a large variety of targets that manifest different properties like shape, speed, size, and radar cross sections (RCS). Second, radar systems on vehicles may have fast-varying velocities due to the kinetic movement of vehicles, which leads to a varying range-Doppler profile of different targets. Third, clutter is omni-present to vehicular radars and many targets may be highly interfered by clutter because of their similarities in the range, RCS, and size. Furthermore, vehicular radars usually operating in short range from tens of centimeters to several hundred meters experiences heavy dependence of target echo signal strength on range. Since target signal power is highly range dependent, same threshold if adopted in different ranges would favor the detection of short-range target while leaving the detection of target in further range difficult. Those properties are further illustrated in Figure-1, and Figure-2. In Figure-1, where a radar mounted on a car is shown, we can see the various targets in the field of view (FOV) of radar such as ground clutter, strong targets of different sizes such as cars and motorcycles, weak extended targets such as curb stones, strong extended targets such as buses and long trucks, etc. Further, in Figure-2 (a), the signal power from different types of targets when the radar is moving at different velocities are shown. As can be seen the power of ground clutter at lower radar speed may be larger than that of weak target at a higher radar speed. This implies that if we set a fixed detection threshold that prevents from the detection of clutter, the detection of weak target is also impeded when the radar is moving at a higher velocity. In Figure-2 (b) the range-dependency of target signal power is shown. This figure shows that even for the same target, its power in short range is much higher than that in the farther range, which makes the detection of target in a longer range more difficult if a fixed threshold is applied. Those properties make adaptive thresholding a crucial technique in target detection in radar systems for vehicles.

The invention is based on the automatic detection in different conditions suppressing the ground clutter and improving the detection of target simultaneously. The core of this invention is that we design the detection threshold that can adapt to the radar velocity and the target range automatically. This is achieved in principle, for example, the threshold is increased for short range and decreased for longer range so that the false alarm of clutter in near range is minimized and target detection is enhanced in longer range; the threshold is increased for slow radar speed and decreased for fast radar speed so that clutter can be better suppressed and weak extended target can be better detected. Figure 3 shows the processing flow of this detection. Input data is a range-doppler domain signal, i.e., the range-Doppler map as commonly named, and output data is a list of detected range-doppler bins. In brief, the noise level is estimated in the first step. In the second step, clutter spreading is estimated which reflects the speed of radar movement along the vehicles. This is followed by compensation of the both Doppler spreading and range effect in the threshold computation in step 3 and step 4. Finally, step 5 computes the threshold. In the sequel, we will describe each processing step in detail.

Detailed description of each component of the invention and how the invention works to achieve the advantages over the existing technology are as below

1. Noise level estimation
   Figure 5 shows a typical range-doppler domain with N_r range bins and N_d doppler bins as an input of detection process. In this invention, the signal level in each cell is proportional to actual signal power.
   Noise level across different doppler with the same range does not varies but it tends to get slightly lower as the range gets further in practical automotive radar systems due to reasons such as leakage and clutter. Thus, this invention proves that the estimation of noise level should be done for each range bin and the estimation of noise level of a range bin should use Doppler cells which are associated with that range bin only. This is in fact a one-time noise level estimation in one-dimensional Doppler domain. Besides mitigating the range-dependence of noise level, this estimation benefits the implementation since the computation load of this one-time one-dimensional based estimation is much lower as compared to the estimation on every cell and or estimation with two-dimensional window.
   Using similar approach as OS-CFAR, the noise level at a range bin can be estimated by taking the k-th cell of N_d sorted cells associated with that range bin. The value of k can be empirically designed to suit the particular radar system and application. After this step, the noise level of each range r is estimated and denoted by $\beta^2(r)$.
2. Ground clutter spreading estimation

   1) Ground clutter modeling

   The signal level of ground clutter gets lower as its range gets further. It also gets lower as it spreads more across doppler when the radar moves faster with the ego vehicle. The spreading can be observed very clearly when the radar operates in a side-looking mode. Unfortunately, the same things happen with extended targets. This effect is described in more detail in the following according to radar equation and target model. The description is based on the reflection geometry of ground clutter and extended target that is illustrated in Figure-3.

First, for extended target and clutter located at a direction θ when the radar is moving at velocity of v, the received power due to one range-Doppler resolution cell can be written in the following form according to the radar equation:

$$P_r(\theta) = \frac{P_t G_t(\theta) G_r(\theta) \lambda^2 \sigma(\theta,v)}{(4\pi)^3 R^4 F_n K T_o B L_s} \quad (1)$$

where P_t is the transmit power, $G_t(\theta)$ is the transmit antenna gain at the direction of θ, $G_r(\theta)$ is the receive antenna gain at the direction of θ, R is the range of the target, F_n is the noise figure, K is the Boltzmann's constant, T_o is the temperature in degrees Kelvin, B is the system bandwidth, and L_s is the loss factor, and the target RCS σ is further expressed in the following form for moving radar at speed of v:

$$\sigma = \alpha R \delta(\theta, v) \delta_R = \frac{\alpha R \delta_R \delta_v}{v cos(\theta)} \quad (2)$$

where α is the target reflectivity, δ_R is the range resolution size, δ_v is the velocity resolution, $\delta(\theta, v)$ is the angle of view at the target direction associated with the current velocity and velocity resolution, which is given by .

$$\delta(\theta, v) = \frac{\delta_v}{v cos(\theta)} \quad (3)$$

This equation is from the computation of Doppler velocity based on the geometry:

$$V_d(\theta) = v sin(\theta) \quad (4)$$

By differentiating both side with respect to θ, we have

$$\frac{dV_d(\theta)}{d\theta} = v cos(\theta) \quad (5)$$

Replacing $dV_d(\theta)$ by δ_v and $d\theta$ by $\delta(\theta, v)$ in (5) we can get (3).

Then, inserting (2) into (1) we have:

$$SNR = \frac{P_r(\theta)}{F_n K T_o B} = \frac{P_t G_t(\theta) G_r(\theta) \lambda^2 \alpha \delta_R \delta_v}{(4\pi)^3 R^3 v cos(\theta) L_s} \quad (6)$$

From (6) we can see that the SNR at one range-Doppler cell due to the clutter or extended target is proportional to the range resolution, doppler resolution and inversely proportional to range and radar platform velocity when radar is in movement. Furthermore, if we assume the antenna pattern follows a cosine function, the SNR equation can be further simplified, which can reveal the dependence of SNR on target angle. As for moving target, it still follows (6) by replacing the velocity by the relative velocity. This is meaning that as the range goes farther and velocity goes higher, the SNR decrease.

When the radar is static, the radar equation for a resolution cell become:

$$SNR = \frac{P_r(\theta)}{F_n K T_o B} = \frac{P_t G_t(\theta) G_r(\theta) \lambda^2 \alpha \delta_R \delta(\theta)}{(4\pi)^3 R^3 F_n K T_o B L_s} \quad (7)$$

Where $\delta(\theta)$, i.e., angle of view, is equivalent to the angular resolution. Thus, when radar is static, the SNR of ground clutter and static extended target within certain resolution cell will follow (7) which is proportional to the angular resolution size.

If the ground clutter and extended target is significantly larger than the resolution cell, multiple resolution cells will be occupied and the SNR for each resolution cell will be described by (6) and (7).

The difference between ground clutter and the extended static target is that they have different the target reflectivity α. This is the foundation of our adaptive thresholding scheme.

Based on the SNR modeling in (6) and (7), a threshold that is based on the SNR of clutter can be predicted in theory for every range-Doppler cell given that the velocity and precise geometry is know in advance. Thus, the detection of target as well as the reduction of false alarm due to clutter can be achieved. However, this may not be realistic in practical applications since target geometry and ground clutter distribution is largely unknown, or at least, not accurately known. Thus, automatic determination of the threshold is devised based on automatically estimating the ground clutter SNR in this patent.

2) Ground clutter Spreading estimation

Most detection algorithms, including ours, are based on signal level thresholding. The threshold must be high enough to reject ground clutter and noise but lower than the signal level of targets. In the patent, the threshold is dynamic in order to maximize the detection probability of targets in different range while keeping the probability of false alarms from noise and ground clutter low. Thus, the threshold is designed to take accounts of range, ground clutter spreading in doppler due to the radar movement, and noise level.

Figure 6 shows the signal level from cells associated with range bin r_{ref}. r_{ref} is a range bin that is used to estimate the width of ground clutter spreading. It is normally chosen where the signal level of ground clutter is high. This can be done empirically or determined by considering the antenna beampattern and the radar position and attitude in the vehicle. The width of ground clutter spreading s is estimated by measuring the width between two edges where the signal crosses the threshold $\chi_{s_ref}\beta^2(r_{ref})$. χ_{s_ref} is an adjustable SNR parameter for estimating the width of ground clutter spreading and $\beta^2(r_{ref})$ is the noise level estimation at range bin r_{ref}. In general, when the radar is static, the clutter spreading is at its minimum and clutter spreading increases along with increasing radar velocity. Although ~~we~~ the patent provides this automatic estimation method, other method based on accurately modelling the radar EM wave propagation and the radar platform movement can also be used to provide better values for this parameter.

3. Threshold computation: ground clutter spreading compensation

The detection threshold must be able to compensate the radar velocity effect as reflected by the clutter spreading in the Doppler domain. In order to maximize the detection of targets when the width of the ground clutter spreading changes with a varying velocity of the ego vehicle, the SNR for thresholding the signal at range bin r_{ref} is computed according the clutter spreading using following equation:

$$\chi(r_{ref}) = \frac{s_{min}}{s}\chi_{static_ref} \quad (8)$$

where, s_{min} is the width of ground clutter spreading at range bin r_{ref} when the radar is static and χ_{static_ref} is an adjustable SNR parameter which the value must be higher than the SNR of ground clutter at range bin r_{ref} when the radar is static

in order to reduce false alarms. This equation comes from an assumption that the total power of ground clutter in a range bin is roughly constant and the power spreading is roughly even across doppler.

4. Threshold computation: range compensation
   The SNR for thresholding the signal at range bin r can be computed using following equation:
   $$\chi(r) = \frac{\mathrm{f}(r)}{\mathrm{f}(r_{ref})}\chi(r_{ref}) \quad (9)$$
   where f(·) is a polynomial function of range which can be obtained either using empirical curve fitting on experiment data or theoretically based on Eq. (6) and (7). In practical implementation, in order to prevent the SNR from going to be too low, we can also set a threshold χ_{min} in a way as described in the following. If the value of $\chi(r)$ is less than χ_{min}, then the value of $\chi(r)$ is adjusted to χ_{min}. The threshold can be set empirically based on the radar measurement and performance requirement. Equation above is used to automatically adjust the SNR threshold in order to follow the signal level of ground clutter. Also, χ_{min} is used to maintain false alarm rate by preventing the value of $\chi(r)$ from being too low.
5. Thresholding
   Finally, the threshold for cells associated with range bin r can be computed using , for example, the following equation:
   $$T(r) = \chi(r)\beta^2(r) \quad (10)$$
   Base the threshold, a detection can be performed by comparing the range bin under test against the threshold.

   From the automatic thresholding development, we can see:
   1) For a fixed range, the threshold varies as the clutter spreading changes along with varying radar velocity. Since the scaling factor in (10) is changing, it is not a CFAR detector. Instead, it is a detector that favours the target detection.
   2) However, since a further thresholding x_min is employed, there is maximum acceptable false alarm rate.
   3) For target detection at different range, the scaling effect is mainly due to the range dependence of target. Thus, adjacent range bins in the same Doppler index should have similar detection performance given that the associated RCSs and the noise levels are the same.
   4) The detection method in the patent in summary is to optimize the detection of target while reducing the false alarms from extended clutter and noise. The reduction of false alarms associated with clutter is especially useful in automotive radar.

The essential characteristic required by any components of the invention is the ground clutter spreading is distributed evenly across doppler.

And about whether it is possible to change or replace any of the components by equivalent components without changing the invention are as below

1) ground clutter spreading estimation can be changed with other computation method such deep learning or advanced system level simulation.

2) the implementation of noise level detection can be designed according to the requirement of application and performance by employing methods other than ordered statistics and by incorporating adjacent range bins at different range segments.

3) more advanced thresholding techniques may be applicable by making use of the information available based on the patent, such as the clutter spreading, clutter power, noise level, and signal SNR.

Claims

While some embodiments of the invention have been described by the illustrations with diagrams, as a person skilled in the art will recognize that the invention can be carried out with many modifications, variations, and adaptions without departing from the scope of this invention defined in the following claims.

1. A method for adaptively detection of radar target, comprising:
    a. Noise level estimation from the range-Doppler data of size *Nr* x *Nd*
    b. Ground clutter spreading estimation
    c. Threshold computation with ground clutter spreading compensation
    d. Threshold computation with range compensation
    e. thresholding

2. The method of claim 1, wherein the noise level estimation is performed for each range bin and the estimation of noise level of a range bin uses Doppler cells which are associated with that range bin only.
3. The method of claim 2, wherein:
   the noise level estimation approach can be such as OS-CFAR, where the noise level at a range bin can be estimated by taking the *k*-th cell of *Nd* sorted cells associated with that range bin; the value of *k* can be empirically designed to suit the particular radar system and application;
   the noise level of each range *r* is estimated and denoted by β^2(*r*).
4. The method of claim 1, wherein:
   in order to maximize the detection probability of targets in different range while keeping the probability of false alarms from noise and ground clutter low an adaptive threshold is built based on the clutter level that taking into account of range, ground clutter spreading in doppler due to the radar movement, and noise level.
5. The method of claim 4, wherein:
   the signal level from cells associated with reference range bin r_ref is used to estimate the width of ground clutter spreading;
   the width of ground clutter spreading *s* is estimated by measuring the width between two edges where the signal crosses the threshold χ_(s_ref) β^2 (r_ref);
   χ_(s_ref) is an adjustable SNR parameter for estimating the width of ground clutter spreading and β^2 (r_ref) is the noise level estimation at range bin r_ref;
   although we the patent provides this automatic estimation method, other method based on accurately modelling the radar EM wave propagation and the radar platform movement can also be used to provide better values for this parameter.
6. The method of claim 1, wherein:
   the detection threshold is designed to compensate the radar velocity effect as reflected by the clutter spreading in the Doppler domain;
   in order to maximize the detection of targets when the width of the ground clutter spreading changes with a varying ego velocity of the ego vehicle, the SNR for thresholding the signal at range bin r_ref is computed according the clutter spreading using following equation:

$$\chi(r_ref) = s_min / s\ \chi_(static_ref) \qquad (13)$$

   where, s_min is the width of ground clutter spreading at range bin r_ref when the radar is static and χ_(static_ref) is an adjustable SNR value higher than the SNR of ground clutter at range bin r_ref when the radar is static in order to reduce false alarms.

7. The method of claim 1, wherein:
the thresholding is further designed by considering range effect:

$$\chi(r)=f(r)/f(r_ref)\ \chi(r_ref) \quad (14)$$

where f (·) is a polynomial function of range which can be obtained either using empirical curve fitting on experiment data or theoretically based on Eq. (6) and (7);
8. The method of claim 7, wherein:
in practical implementation, in order to prevent the SNR from going to be too low, we also set a threshold χ_min in a way as to maintain false alarm rate by preventing the value of χ (r) from being too low;
if the value of χ (r) is less than χ_min, then the value of χ (r) is adjusted to χ_min.
The threshold χ_min can be set empirically based on the radar measurement and performance requirement.
9. The method of claim 1, where the threshold is finally given at each range as:

$$T(r) = \chi(r)\beta^2(r) \quad (15)$$

Base the threshold, a detection can be performed by comparing the range bin under test against the threshold.