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An FPGA-based controller for a 77 GHz MEMS tri-mode automotive radar

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ABSTRACT

This paper presents a Xilinx Virtex 5 FPGA platform based signal processing algorithm that was designed, implemented and experimentally verified for use in a MEMS based tri-mode 77 GHz FMCW automotive radar to determine range and velocity of targets in the vicinity of a host vehicle. It provides short (SRR), medium (MRR), and long-range radar (LRR) coverage using a single FPGA. The MEMS radar comprises of MEMS SP3T RF switches, microfabricated Rotman lens and a microstrip antenna embedded with MEMS SPST switches, in addition to other microelectronic components. A CA-CFAR module has been used to eliminate false targets in a multi-target clutter affected scenario. The developed algorithm enables the MEMS radar to detect 6 targets in a time span of 6.1 ms between a distance of 20–170 m with range resolutions of 0.07, 0.11 and 0.19 m respectively for SRR, MRR and LRR. A maximum relative velocity of 300 km/h can be determined with a velocity resolution of 6.84 km/h. The refresh rate is 2.048 ms for each mode of radar which is nearly 40 times lower than the commercially available BOSCH LRR3 radar. The developed FPGA based radar signal processing algorithm can be implemented in an ASIC which can be batch fabricated to lower the production cost for high chip volumes. This will enable automotive radars to become a standard item for all the vehicles on the road.

1. Introduction

The global auto industries are extensively pursuing radar based proximity detection systems for applications including adaptive cruise control, collision avoidance, and pre-crash warning to avoid or mitigate collision damage. In [1], it has been reported that a forward collision warning/mitigation system comprised of radar sensors has the greatest potential to prevent or mitigate up to 1.2 million crashes (20% of a total of 5.8 million police-reported crashes each year), up to 66,000 nonfatal serious and moderate injury crashes, and 879 fatal crashes per year. These estimates were obtained by analyzing actual crash records from the 2004–08 files of the National Automotive Sampling System General Estimates System (NASS GES) and the Fatality Analysis Reporting System (FARS). Ironically, the IIHS study found that the forward collision warning crash avoidance features that could prevent or mitigate fatal and nonfatal injury related crashes were available only on just a handful of luxury vehicle models due to the high cost of the currently available forward collision warning technology. Thus a low cost radar technology for forward collision warning system that can be made available to all the on-road vehicles would be able to prevent/mitigate up to 1.2 million crashes per year. The strategic Automotive Radar frequency Allocation (SARA) consortium specified that a combined SRR and LRR platform in the 77–79 GHz range will enable to reduce size and improve performance of automotive radars [3,4]. In [3] it has been identified that in the long term, 77 GHz will become the only reasonable technology platform to serve both short and long range radars.

In [3,5] it has been determined that frequency modulated continuous wave (FMCW) radar with an analog or digital beamforming capability with a low cost SiGe based radar front end is the technology of choice for forward collision warning applications. Though GaAs or SiGe based MMICs are being pursued vigorously to minimize the cost and size while improving the performance of automotive radars [3,6], the auto industry is seriously considering the small cost, batch fabrication capability of the MEMS technology to realize more sophisticated radar systems [2]. The project goal of a European consortium SARFA has been set to utilize RF MEMS as an enabling technology for performance improvement and cost reduction of automotive radar front ends operating at 76–81 GHz [7]. In [8], a MEMS based long range radar comprised of a microfabricated Rotman lens and MEMS SP3T switches and a microstrip antenna array has been presented.

The DistronicPlus™ system uses one long range and two short range radars in the front, two other short range radars in the front for park assist, and two short range radars in the rear to provide an effective collision avoidance system. Due to the individual short and long range units, the price tag of the DistronicPlus™ system is relatively high.

Almost all the commercially available automotive radars use microelectronic based ASICs. However, FPGAs are becoming increasingly popular in the development phase for rapid prototyping as opposed to

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DSP based solutions. Relative advantages of an FPGA based system over the DSP based ones for automotive radars are discussed in [9–11] where it has been determined that FPGAs can offer superior performance in terms of footprint area, high throughput, more time-and-resource efficient implementations, high speed parallel processing, digital data interfacing, ADC and DAC handling, and clock management in a relatively low-cost platform.

Previous research [8] has shown that instead of a passive antenna system, a MEMS based reconfigurable microstrip antenna in conjunction with MEMS/GaAs SP3T switches and a microfabricated silicon based Rotman lens can be used to realize a compact tri-mode radar that can provide all the short, mid and long range functionalities in a small form-factor single unit. An FPGA based control unit will control the operation of an array of MEMS/GaAs SPST RF switches embedded in the reconfigurable antenna array to dynamically alter the antenna beamwidth to switch the radar from short to mid to long range using a predetermined time constant. This will reduce the price tag significantly by multiplexing the functionality of three different range radars in the same hardware. Additionally, the passive microfabricated Rotman lens will eliminate microelectronics based analog or digital beamforming components as used in commercially available automotive radars. Consequently, the overall system will become less complex, faster, lower cost, and more reliable. Due to the faster signal processing and digital data interfacing capability, an FPGA like Xilinx Virtex 5 can offer a very robust control of VCO linearity and a faster refresh rate for range and velocity data. In addition to the conventional signal processing tasks, control algorithms for the MEMS GaAs SP3T and SPST RF switches can also be embedded in the same FPGA.

In this context, this paper presents the design, implementation, and experimental validation of Xilinx Virtex 5 FPGA based signal processing algorithm that can be used in an integrated MEMS tri-mode radar system. The developed algorithm is able to determine the target range and velocity with a very high degree of precision in a cycle time that is several orders of magnitude shorter than the state-of-the art 3rd generation long range radar (LRR3) from Bosch [12]. A preliminary version of this paper was published in [15] that presented RTL level Verilog simulation results. In this paper the results obtained from FPGA implementation of the tri-mode radar are presented. Furthermore a CA-CFAR (Cell Averaging-Constant False Alarm Rate) module has also been implemented and used to eliminate false targets in a multi-target clutter affected scenario. Only an abstract of this paper was published in [16]. This paper makes two main contributions: handling of three radar modes in one design and FPGA implementation and testing that demonstrate the proof of concept.

This paper is organized as follows: Section 2 presents an overview of the MEMS tri-mode radar. The tri-mode radar signal processing algorithm is described in Section 3. The motivation for the choice of FPGA platform for algorithm implementation is also discussed in this section. Hardware implementation is presented in Section 4 and experimental validation results are presented in Section 5 followed by conclusion in Section 6.

2. MEMS tri-mode radar operating principle

The operating principle of the MEMS 77 GHz FMCW radar, illustrated in Fig. 1, is as follows: (1) A voltage controlled oscillator (VCO) is attuned by an FPGA implemented control circuit which generates a triangular signal (V_{tune}). The VCO then generates a linear frequency modulated continuous wave (LFMCW) signal with a bandwidth of 800 MHz, 1400 MHz and 2000 MHz respectively for long range radar (LRR), medium range radar (MRR) and short range radar (SRR) with a center frequency of 77 GHz. (2) The signal generated is then fed into a MEMS SP3T switch. (3) The SP3T switch, regulated by an FPGA implemented control circuit, sequentially switches the FMCW signals between the three beamports of the Rotman lens. (4) The FMCW signals after travelling through the Rotman lens cavity arrive at the array ports of the Rotman lens. The time-delayed in-phase signals are then fed into a microstrip antenna array which radiates the signal in a specific direction. (5) The microstrip antenna has SPST switches embedded into it. The scan area of the antenna array depends on the antenna beamwidth, which in turn depends on the number of patches in the microstrip. Increasing the number of patches makes the beam narrower. The higher the number of patches, the narrower will be the beam. It has been determined that for a short range radar, a beamwidth of 80° is necessary to scan an area up to 30 m in front of the vehicle as shown in Fig. 2. For mid-range, a beam width of 20° is necessary to cover an area between 30–80 m ahead of the vehicle and in the LRR mode, a beam width of 9° is necessary to scan an area 80–200 m ahead of the vehicle. (6) The beam from the Rotman lens can be steered across the target area in steps determined by a predefined angle as shown in Fig. 3. This steering can be done by the sequential switching of the input signal among the beamports of the Rotman lens. (7) An FPGA based control circuit controls the operation of the SPST switch so that the signal output at a specific beamport of the receiver Rotman lens can be mixed with the corresponding transmit signal. (8) The received signals obtained from the SP3T switch are then fed into a mixer where it is mixed with the transmitted signal to generate Intermediate Frequency (IF). (9) The IF generated are then passed into an Analog to Digital (ADC) converter, where they are sampled and converted into digital signals. (10) Lastly an FPGA implemented algorithm processes the digital signals from the ADC to determine the range and velocity of the detected target. In this way a wider near-field area and a narrow far field area can be progressively scanned with minimal hardware.

This paper deals with the signal processing aspect of the MEMS tri-mode automotive radar. Research efforts are currently underway to develop and integrate the switch control and transmit control sub-systems with the signal processing sub-system.

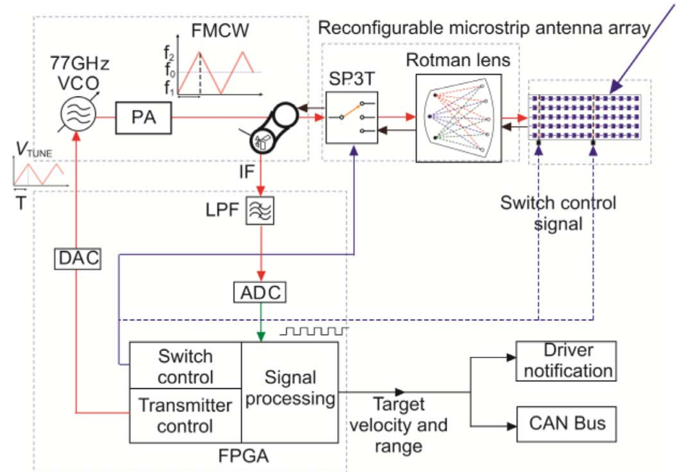

Fig. 1. MEMS tri-mode radar block diagram.

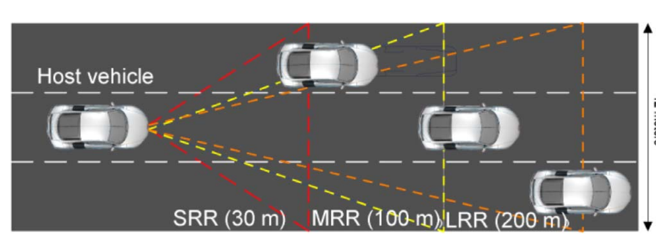

Fig. 2. Antenna beamwidth: short range (left), mid-range (center), long range (right).