Indian Institute of Space Science and Technology

Thiruvananthapuram

AV312 Computer Architecture and Organisation

Track-4: R&D with Indian Processors

A

System Design Document on

Ikshana : A FMCW Radar Module

Submitted by

B Tech Electronics and Communication Engineering 2018 batch

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Department of Avionics

Section I : Hardware Resource Section

1) **Name of Hardware Resources** * **- SHAKTI Vajra (C64-A100) on Artix7-100T FPGA**

If selected Hardware Resources with ARTIX7-100T FPGA, then provide justification for not making use of the Hardware Resources with Artix7-35T FPGA, which may result in an optimal utilization of the Hardware Resources for the innovative solution proposed. (if not applicable put N/a)

We are planning to use Shakti C class processor, which is a 6 stage in-pipeline architecture, thus requiring relatively more number of LUT's. Apart from this we are planning to add soft-core extensions like FFT block and CSI2 Blocks which requires additional LUT's. In addition, the application we chose is a processor intensive, requiring to compute the FFT operation multiple times in a short span of time ($\sim$ 512-point FFT, thrice in 40 ms), which is another reason for choosing Vajra SoC

If selected Hardware Resources as other (FPGA Board other than Artix7-35T and Artix7-100T), then please mention the details of FPGA Board of your choice (like Name of Vendor, Series etc.). (If not applicable put N/a)

N/A

If selected Hardware Resources as Other (FPGA Board other than Artix7-35T and Artix7-100T) then select processor eco system of your choice among SHAKTI – E32, SHAKTI- C64, VEGA ET1031 or VEGA AS1061. (if not applicable put N/a)

N/A

Section II: Technical Aspects of Innovative Solution

Ikshana : A FMCW Radar Module

Proposal Summary

Advancement in millimeter-wave (mm-wave) semiconductor technology and development of signal processing techniques have led to significant improvements in the automobile industry. Recently, path-breaking research activities were done in order for enhancing the performance of Autonomous Vehicles, giving rise to a colossal boost to Advanced Driving Assistance Systems (ADAS). In this context, automotive radar has emerged as a low-cost system that provides robust performance in inclement environmental conditions such as heavy precipitation, pollution, or bad illumination.

Frequency Modulated Continuous Wave (FMCW) radars are becoming increasingly popular in a variety of industries and applications, especially in Self-Driving Cars (SDCs) mainly for speed control, steering control, object detection, hazard warning etc. The reasons for their popularity are attributed to the following characteristic features:

- Accurate short-range measurements
- Low sensitivity to clutter
- Low cost
- Robustness
- Easy integration with the rest of the vehicle

We propose to develop Ikshana, an FMCW Radar Module, in this abstract. Ikshana is planned to be developed using the Vajra (C64-A100, Shakti C-class) SoC developed by IIT Madras. Ikshana is a low cost solution, which can be utilized for developing many useful indigenous products, including autonomous vehicles, night-vision goggles for soldiers, speed detection radars for law enforcement agencies, and specialized radar applications for drones. The main parameters based on which applications choose a radar module include: (i) range, (ii) relative velocity, and (iii) azimuthal angle.

The proposed Ikshana prototype module will be implemented on Xilinx Arty A7-100T FPGA using BSV. We plan to add some soft-core extensions to the Swadeshi processor, such as the FFT Block, CSI2 Block and DMA Block because the performance and speed are crucial for our module. Also, we plan to employ advanced signal processing techniques for improving the estimation of range, velocity and direction of arrival.

Further, in order to complete the proposed system design, the output results of the system are planned to be displayed in an informative way, on a monitor via VGA interface.

Theoretical Background and Technical Outline

FMCW Radar is the center aspect in the technology being used for this proposal design. It stands for Frequency Modulated Continuous Wave (FMCW) Radio Detection And Ranging (RADAR). It essentially transmits a continuous carrier modulated signal with its frequency linearly increasing with time known as *Up-chirp* and similarly, a signal with linearly decreasing frequency known as *Down-chirp*.[20]

Frequency is modulated over carrier frequency f_c with bandwidth as B as shown in the figure 1. The signal is transmitted over chirp time T_s from the transmitting antenna and the same will be reflected from the object and received at receiver after a delay of time $t_d = \frac{2R}{c}$ [20] as shown in Figure 1. From this, relative distance between source and object (RADAR) can be found out as shown here.

In the case of stationary target, difference between transmitted and received signal contains single frequency component named as beat frequency f_b which is almost constant for certain amount of time but in the case of moving targets, there will also be a Doppler Frequency shift*, f_d that should be considered along with Beat frequency f_b [20]. This will lead to two different frequency for both Up-chirp and down chirp known as f_{bu} and f_{bd} respectively, but that can't be distinguished properly in the magnitude plot of FFT because of smaller difference[19].

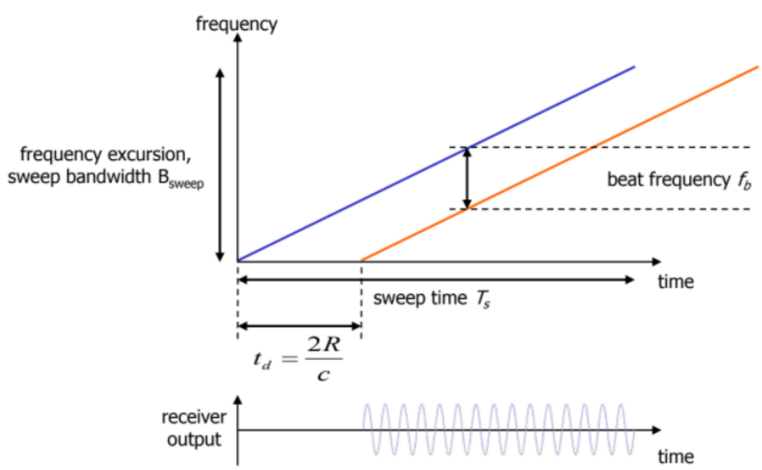

Figure 1: Frequency chirp diagram of FMCW radar

By equating slope in the figure 1,

$$\frac{B}{T_s} = \frac{f_b}{(\frac{2R}{c})}$$

$$\implies \boxed{R = \frac{f_b T_s}{2B} c}$$

where,
B is sweep bandwidth
T_s is chirp time
R is Relative distance between Radar & Object
f_b is beat frequnecy measured from FFT plot
c is speed of light

Owing to the difficulty in distinguishing the Up-chirp frequency f_{bu} and Down chirp f_{bd} as discussed earlier, another method of using the phase of received signals for measuring velocity is considered. In that, we need to detect any change in the phase value of multiple chirps because phase is sensitive enough to detect minor changes in the range as shown in the Figure 2 [19]. Finally, this position change in a small time can be used to determine relative velocity as shown below.

*Doppler shift can cause frequency shift of amount f_d depends on relative motion of Radar and object.

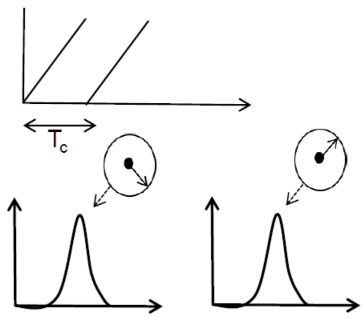

Figure 2: Frequency chirp diagram of FMCW radar for velocity measurement

Here,

$$\Delta\phi = \frac{4\pi}{\lambda}(V_r T_c)$$

$$\implies \boxed{V_r = \frac{\lambda\Delta\phi}{4\pi T_c}}$$

where,
T_c is chirp time
V_r is relative velocity of Radar and object **(Relative Velocity)**
$\Delta\phi$ is the difference in the phase value on multiple chirp measured form FFT plot
λ is wavelength corresponds to carrier frequency

Similarly Angle can be measured by phase difference between *multiple receiver data* as shown in the Figure 3.[19]

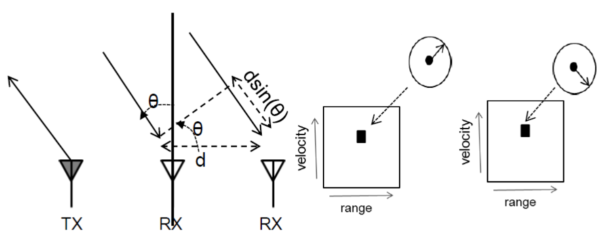

Figure 3: Receiver antenna part of FMCW radar for angle measurement

Here,

$$\Delta\phi = \frac{2\pi d sin(\theta)}{\lambda}$$

$$\implies \boxed{\theta = sin^{-1}(\frac{\lambda\Delta\phi}{2\pi d})}$$

where,
$\Delta\phi$ is the difference in the phase value on multiple receiver data measured form FFT plot
θ is **Angle of Arrival** of signal coming from object as shown in figure 3
d is distance between two consecutive receiver antenna
λ is wavelength corresponds to carrier frequency

Proposed Approach

In this section, various details of the proposed approach are provided along with a block diagram and the scope of the proposed module in various fields.

A Brief Review of Existing Techniques

Rapid advances in technology has given rise to the development of several Automated and autonomous vehicles technologies. One of the most crucial part of the automation is acquiring the knowledge of its surrounding i.e. perception of other vehicles. This is done using ultrasonic sensors, RADARS, LiDAR and cameras or even combination of these. From table 1, we can see that RADAR has high range, quiet good Resolution and accuracy, low maintenance and affordable price. And also, with the current research in RADAR technology such as 3D Antenna, Sub-Terahertz & 4D Imaging[14], RADAR alone can be used for perception purpose giving an edge over other technologies[16].

	Ultrasonic	**RADAR**	**LiDAR**	**Cameras**
FOV	Low	Medium	Medium or High	Medium or High
Max Range	Low	High	High	Medium or High
Accuracy	Low	Medium	High	Medium
Resolution	Low	Medium	Medium	High
Size	Small	Small	Medium	Small
Weather Affection	Low	Low	Medium	High
Maintenance	Medium	Low	Medium	Medium
Price	Low	Medium	High	Medium or High

Table 1: Main features of sensors used in perception systems in Automated and autonomous vehicles technologies[18][13]

From figure 4 we can see maximum range and FOV of current RADAR technology for different types of RADAR. As we already know that range resolution of radar is inversely proportional to the chirp BW, and most of the automotive RADAR uses 4GHz BW which has a resolution of 3.75cm[19], which is quiet a good value. Angle resolution is inversely proportional to number of receivers (which is limited in most of the cases), so virtual antenna concept can used here for increasing the resolution. This can be done using the following Multiplexing techniques:

- Time division multiplexing[21] – Velocity resolution decreases.
- Frequency Multiplexing[21] – Requires a larger spectrum (which is not available).
- Binary Phase Modulation[21] – Requires much higher computing power.

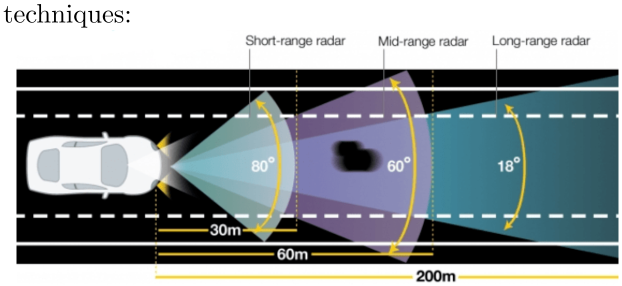

Figure 4: Current RADAR Technology[14]

Methodology

Ikshana (proposed FMCW radar system) consists of two major modules, namely:

- Transceiver module
- SoC module (based on the Shakti C-Class Processor)

The FMCW radar system transmits a linearly increasing frequency signal during Up-chirp and decreasing frequency signal during Down-chirp. The generated frame of chirps is transmitted using the transmitter antennae present in the transceiver module, after amplifying it.

The received signal consists of information like range, direction of arrival and velocity encoded in it (in terms time shift, spatial variation and doppler shift in frequency domain), about the objects present in its immediate surroundings. This received data is filtered, amplified and is given as an input to a mixer, whose output is an IF (Intermediate/Beat Frequency) signal after being filtered again. The signal is then digitized in the ADC of the transceiver module before it is sent to the SoC through the CSI2 interface. Note that the SPI interface is used for interrupt signals and control signals, from SoC to Transceiver module and vice versa. The received data is sent to the CSI2 block in the SoC module, where it is preprocessed (data depacketization and segregation) and sent to the FFT block for computing the Range FFT.

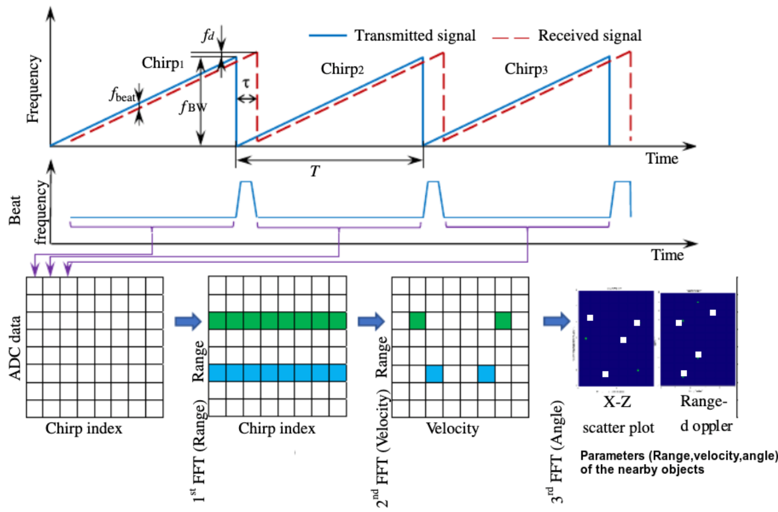

Figure 5: An example describing the various steps involved in the process of the methodology, being discussed in this section[15]

A peak detection of this sequence of Range FFT data (for each chirp) is performed. Then, the Range-Velocity FFT (Doppler FFT or 2D FFT) is performed on the sequence of phasors corresponding to these peaks, whose peaks give us a list of possible Range-Velocity pairs (peaks in the 2D RV plot). Further to estimate the azimuthal angle of the objects in vicinity, a similar process, involving computation of another level of FFT called Range-Velocity-Angle (3D FFT), is performed on the corresponding phase data of peaks†. This process at the end results in a list of (R, V, θ) tuples, corresponding to the range, velocity and azimuthal angle of possible targets. These parameters are then sent to the Display unit which is planned to be displayed dynamically (using scatter plots and tables) on the monitor by using a VGA interface.[22] The flow diagram of this overall process and the significant blocks have been emphasized in Figure 7.

The transceiver module is interfaced with the microprocessor using the CSI2 interface. We know that by default Artix Arty A7-100T does not support MIPI CSI-2 protocol we need to implement D-Phy Receiver on both hardware and software level. The output data pins of transceiver can directly be connected to Arduino R3 Headers using jumper cables and FFC adapter. For software level implementation either IP provided by *Xilinx* or any other open source IP can be used by modifying it to according to our requirements. This receiver can then be integrated with microprocessor using AXI-4 bus so that data from transceiver can be processed further using DSP techniques.

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The MIPI CSI-2 RX Controller core receives 8-bit data per lane, with support for up to 4 lanes, from the MIPI D-PHY core through the PPI. As shown in Figure 6, the byte data received on the PPI is then processed by the low level protocol module to extract the real image information. The final extracted image is made available to the user/processor interface using the AXI4-Stream protocol. The lane management block always operates on 32-bit data received from PPI irrespective number of lanes.[7]

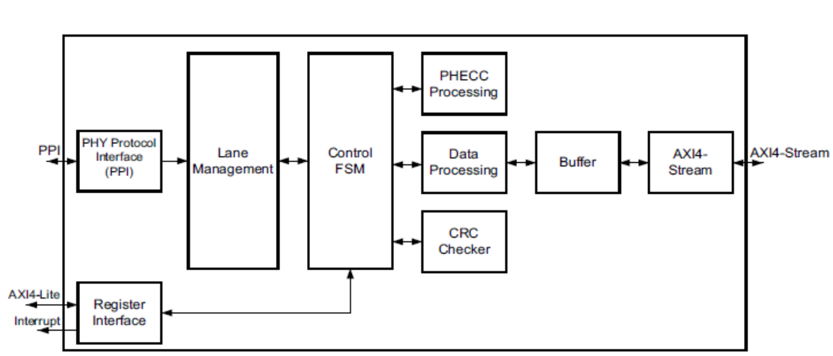


Figure 6: CSI-2 Receiver Subsystem[7]

Because response time and updation rate are critical aspects for this processor-intensive application, it has been planned to add an FFT Block extension (softcore) in the core of Processor Shakti-Vajra SoC to perform this FFT operation. First, it

†Peak Detection on 2D FFT data from multiple spatially distributed receivers

is planned to code the FFT algorithm in C language which can then be converted into Bluespec Verilog (BSV). Conveniently, RTL can also be generated using the Xilinx Vivado HLS tool [3][4][5]. Similarly, the results are planned to be displayed in the form of updating (R,V,θ) tuples and a dynamic scatter plot, which therefore requires a verilog implementation for the VGA interface [6]. Finally, all the BSV Codes and RTL's of FFT Block, Display Block, CSI2 Interface and Direct memory Access (DMA) can be combined with Shakti-Vajra SoC as extension on the FPGA Arty-A7 100T board. Later, they can further be integrated to the Shakti SDK, for being able to use their functionality efficiently.

Scope of Work

The scope of the proposed Ikshana FMCW Radar module extends to many fields and has innumerable potential applications. The initial idea for developing such a module was motivated by its plausible use in Self-Driving Cars (SDCs) and Advanced Driving Assistance Systems (ADAS) (details provided later) but it is very much possible to customise the basic *Ikshana* module to meet the standards set by various other applications. Some of the potential applications where the module can be deployed (after customization) are briefly listed below:

→ **Autonomous Vehicles** : Ikshana can prove to be an integral component of Self-Driving cars by *continuously* providing valuable inputs that assist the ML/DL models at the core, in order to make well informed and efficient decisions along with inputs from other sensors. The typical decisions might include speed control, steering control, object detection, hazard warning etc.[13][9]

→ **Radar Altimeters** : Ikshana can be customized to be used in aerial and space applications. For example, it can be used to measure altitude above the terrain for aircrafts, spacecrafts and auto-piloted landers, topographical mapping and Remote Sensing Applications like estimation of windspeed using satellites.[2]

→ **Liquid Level Measurement** : FMCW sensors can be used in oil, LNG tankers and fuel storage tanks to measure product volumes specially for space application.[10]

→ **Assisting the Visually Impaired** : Multitarget warning through millimeter wave radar and RGB-depth sensors.[15]

→ **Night Vision Systems and Goggles** : This can be used in defense and army-based applications where terrains are harsh.

→ **Drone-based radar systems** : These can be outfitted on drones in order to detect obstacles as well as identify friend-enemy drones.[15]

→ **Biomedical Applications** : Can be useful in Breast Tumor diagnostics, remote monitoring of cardio-respiratory activity, the monitoring of artery walls and vocal cord movements etc.[17]

→ Non-contact measurement of distance Applications using security sensors against intrusion, and human vital-sign detection and measurement.[10]

Requirement of Equipment/ Accessories/ Components/ Resources other than the Hardware Resources provided under the Challenge‡

Required Component	Quantity	Estimated Value (for 1 unit)	Total Estimated Value(including delivery charges)
AWR1243FBIGABLQ1 – AWR1243 Radar transceiver Module[1]	5	₹2,612.67	₹15,669.45
Digilent I/O Expansion Module 410-219[8]	3	₹1,477.89	₹5633.67
Molex0526101771Connector FFC-FPC	8	₹50.14	₹501.2
Jumper Wires and connectors	-	-	₹600
Power Management Unit	-	-	-

‡Standard LCD Monitor (for Display purpose) prices are not included.

Block diagram

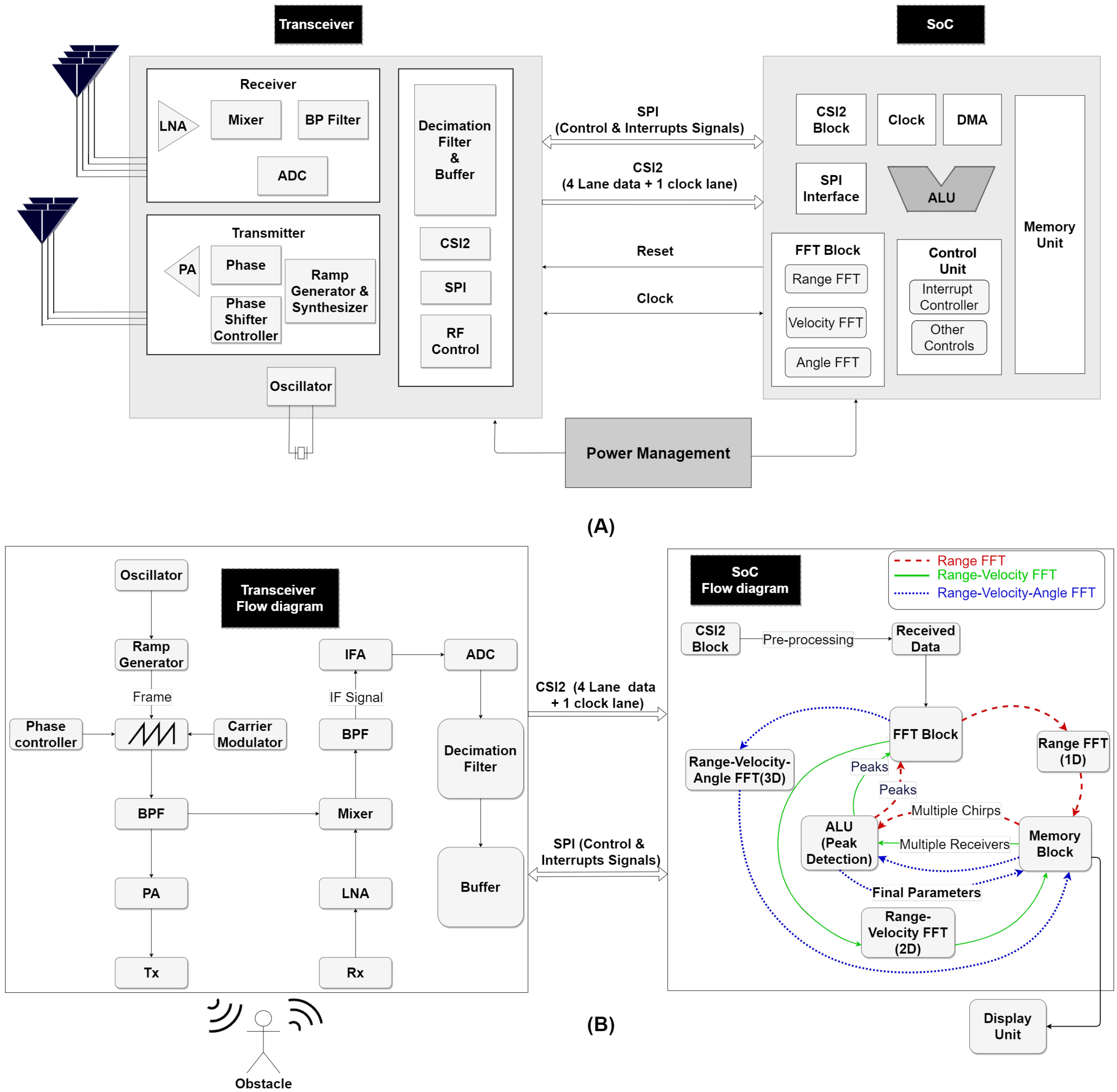


Figure 7: (A) High Level Block diagram representation of the Transceiver and SoC Modules in *Ikshana* (B) Flow Diagram representation of various steps involved in the working of Transceiver and SoC Modules of *Ikshana*

The important blocks of the transceiver module and SoC that would be required during the typical operation of *Ikshana* have been highlighted in the block diagram shown in the (A) part of the figure shown above. The various operations that are to be performed during the regular operation are illustrated briefly in the (B) part.

Preliminary work

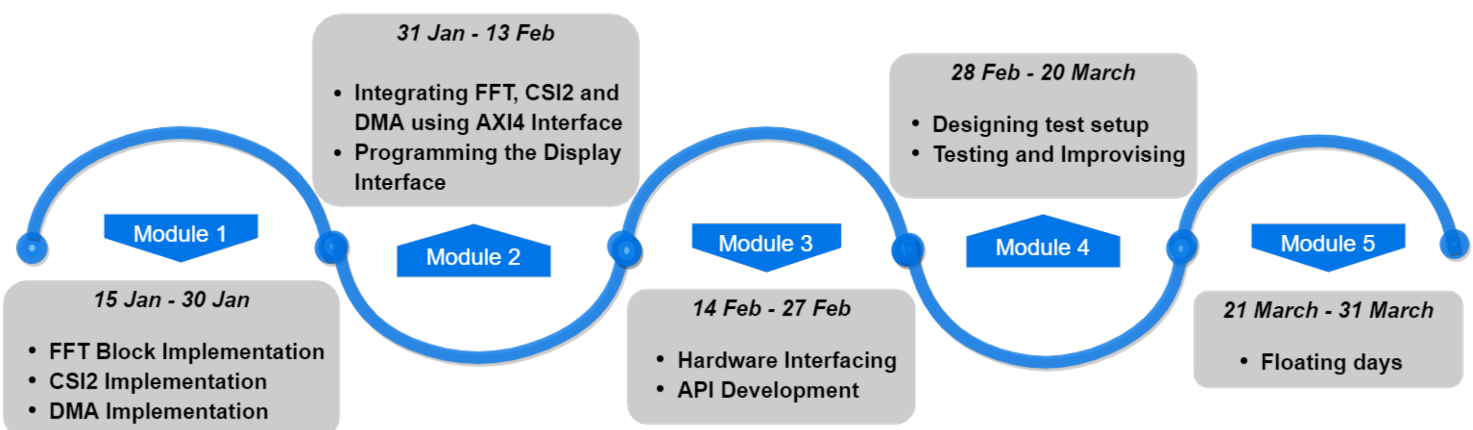
1. **Understanding RADAR (August,2020)**
   The most basic and initial study was done on understanding the Radars and the concept behind Frequency Modulated Continuous Wave Radar. The study helped us find the importance of Radars in various applications. This analysis helped us get into the idea of developing a signal processing system over an Indian processor which could be used in various Radar based applications.[19]

2. **Selection of Transceiver IC (September,2020)**
   The Team spent a significant amount of time in the selection of an appropriate Transceiver IC taking into consideration the costs, data rate, clock speed, number of transceivers, ADC sampling rate and how efficiently this IC could be interfaced with an appropriate *Swadeshi* processor. Based on the above considerations, AWR1243 was chosen as the most appropriate IC for our application.

3. **Selection of Suitable Processor (September,2020)**
   Simultaneously with the selection of Transceiver IC, a constant effort was also made in selecting an appropriate processor from the lot. The study was done on the basis of clock speed, availability of FPU, DMA, capability of booting Linux, Cache, performance in DMIPS/MHz, ease of adding hardware blocks, etc. We concluded with the selection of Shakti C-Class processor.

4. **Extensions to the processor (October,2020)**
   A further effort was put in exploring the possibility of adding suitable hardware extensions within the Bluespec Verilog (BSV) Code in order to process the data from the Radar IC efficiently. Significant effort was made in designing an appropriate FFT extension block in the processor along with CSI2 interfacing and DMA.

Quarterly Timeline (Tentative) vis-a-vis activities



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Section III: Business Aspects of Innovative Solution

Innovativeness of proposed idea

The proposed Ikshana FMCW radar system is expected to be the first of its kind implementation of a radar module in the automotive sector using Indian processor (SHAKTI C-Class). At present, with the limited operating frequency of processor and non-availability Artificial Intelligence (AI) IP core, only data processing and possibly display unit are possible. However, when fabricated in a chip our design can be developed into a complete system which can be used for automation of vehicles. Note that a basic idea of automation in vehicles is shown in Figure 1.

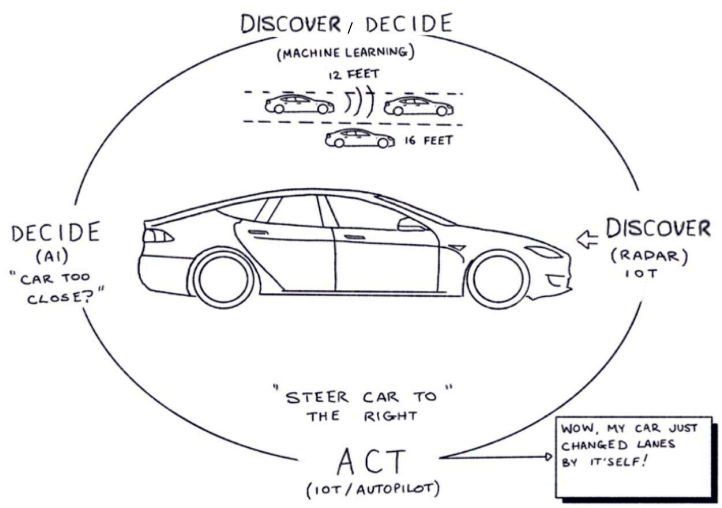

Figure 1: Basic Idea of Automation[2]

Combining different modulation technique such as OFDM and multiplexing techniques, we can get far better results than current Radar technologies provide in the automotive sector Among the sensors used in perception systems in automated and autonomous vehicles technologies radar have high range, good resolution, high accuracy, low maintenance cost, and affordable price. Along with the current research in Radar technology such as 3D antennae, Sub-Terahertz, and 4D Imaging, Radar technology alone can be used for perception purposes in the future giving an edge over other sensors and technologies.

For processing the data acquired from the transceiver module FFT is required and is planned to be implemented as a custom IP core using the DSP Slices present on the FPGA board. This FFT block (DSP block) will also be useful for other computational purposes such as SONAR, RADAR, signal acquisition block for GPS, spectrum analyzer, and image Processing. The FFT block will be implemented as a soft core resulting in higher speed, greater computational capability and more flexibility. It can also be provided as an open source IP core for upcoming microprocessor challenges in the future as it will be useful for future participants and also it will increase the capacity and implementation range of the SoC (such as use in night vision glasses, providing assistance for visually impaired people, mid-range trackers etc.)

For interfacing the transceiver module to the microprocessor, Camera Serial Interface-2 (CSI-2) protocol would be required which can be implemented using an external D-PHY receiver or using gate level logic circuit as D-PHY receiver for implementing the protocol. This protocol could also be used for interfacing other devices such as display modules, image processing modules (Radars, Lidars, Cameras etc.) CSI-2 provides high data transfer rate and less data loss can be useful for processing high resolution images. Many industries use CSI-2 due to the overall increased performance of the microprocessor.

Opportunity & Market feasibility

The proposed FMCW Radar System (Ikshana) can prove to be a valuable addition in a variety of applications in various industries in India. The implementation of FMCW radar over an Indian processor could enhance the prestige and technical capability of our nation. Due to consideration of factors like low cost investment, Swadeshi design, as well as the potential to be used by many indigenous products, it can be considered as an excellent example of the Atmanirbhar Bharat initiative started by the government.

In Indian automobile industry, the proposed Ikshana system can be used as an integral component of Self-Driving Cars and Advanced Driving Assistance Systems(ADAS). Note that various levels of automation in automobiles have been described in Figure 2. The inputs provided by the proposed module (in a continuous manner), can assist ML/DL models at the core, in order to make well informed and efficient decisions along with inputs from other sensors. The typical decisions might include speed control, steering control, object detection, hazard warning etc.

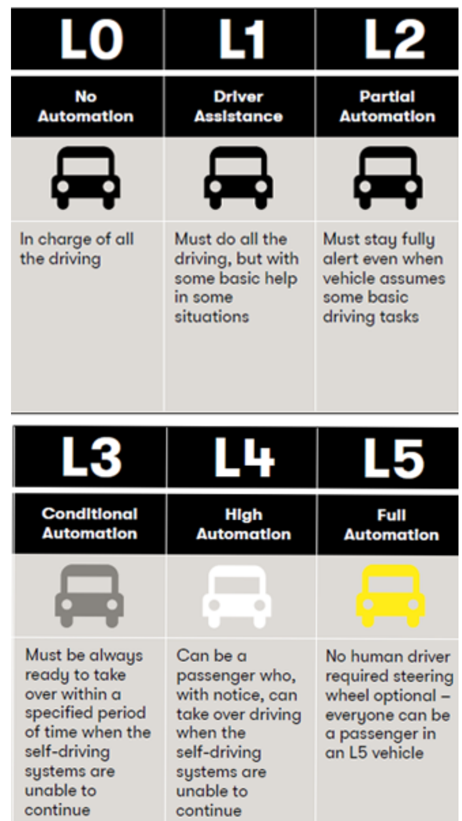

Figure 2: Various Levels of Automation[3]

The US-based car company, Tesla has been a pioneer in this field of automobile automation with the total miles logged by their cars has grown exponentially from 0.1 billion in May 2016 to an estimated 1.88 billion as of October 2019.[1] With India emerging as one of the largest passenger vehicle markets, the proposed Ikshana system can help in developing a home-grown indigenous automation and perception systems, which has a huge potential in near future.

In Aerospace and Aeronautical Industry, FMCW radar is being used as a major part in radar altimeters. It is the device that measures altitude above the terrain that is useful in aircrafts, spacecrafts, satellites, and auto-piloted landers. It is also used in satellites for topographic mapping and Remote sensing application such as estimate wind speed over sea surface from satellites.

Along with these applications, the Ikshana module can be beneficial for various other small scale and medium scale Indian companies and startups, which are looking forward to using such a system. The following are a wide range of other applications, where Ikshana can be potentially used:

- Fluid Level Measurement
- Assisting the Visually Impaired [5]

- Night Vision Systems and Goggles
- Unmanned Aerial Vehicles (UAV's) and other drone-based radar systems
- Biomedical Applications
- Non-contact measurement of distance Applications using security sensors against intrusion, and human vital-sign detection and measurement.[4]

Commercialization Roadmap

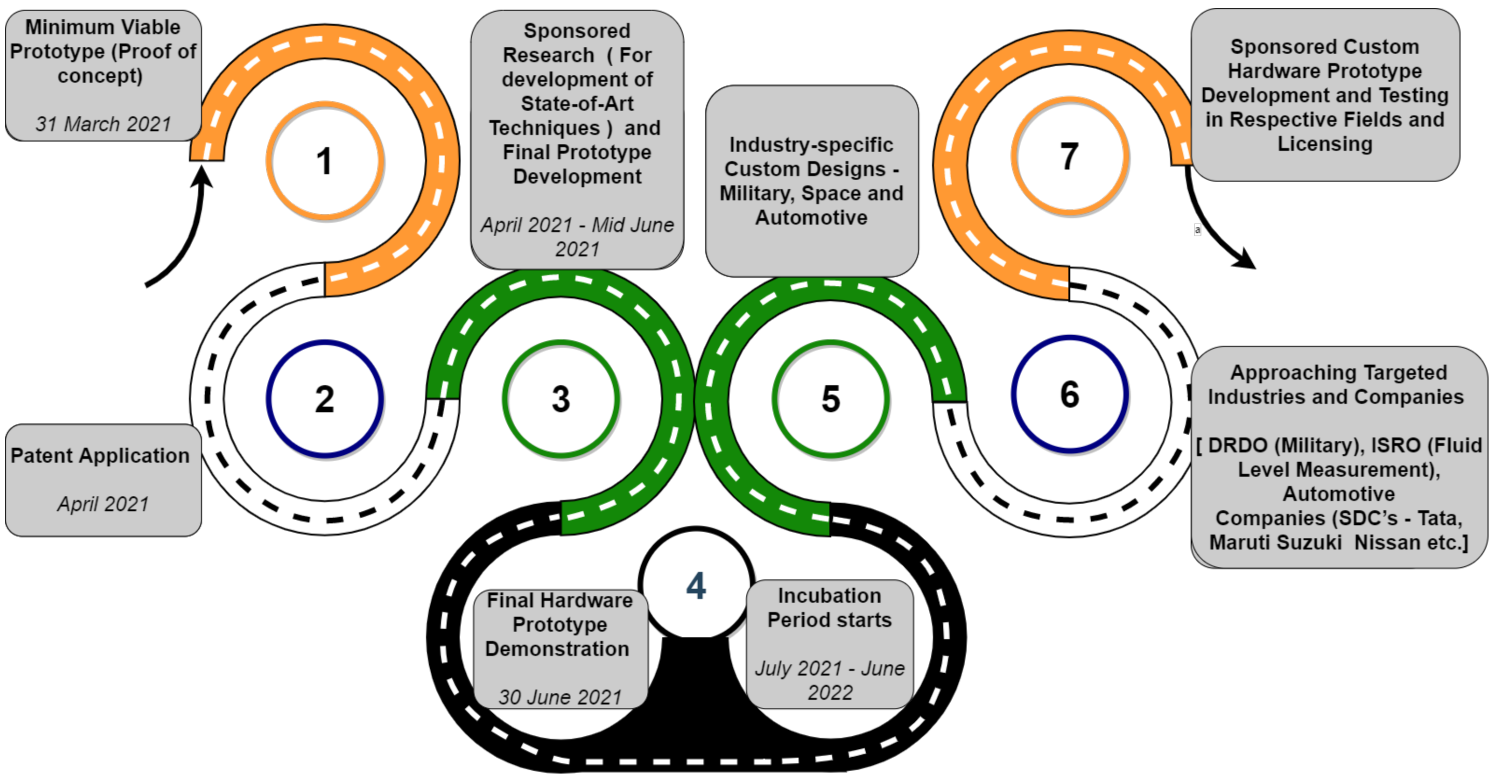

Figure 3 : Commercialization Roadmap with Market entry strategy and scalability.

Potential Challenges Involved

Developing *Ikshana* can be a challenging task, that we are willing to take up because of its immense potential in multiple domains. The potential challenges that we have to overcome in order to realize this project are :

1. **Design of Custom Modules**:

   Different industries have different requirements and in order to make our product stand out we need to optimize our design according to their specifications. For Example, in the automotive sector, the measurement of range, velocity and azimuthal angle is required but the response time and update rate of the values needs to high, thereby enabling the automobile (or the driver) to make critical decisions appropriately in a timely manner. In space-related applications like Liquid Level Measurement, the measurement of velocity is not that important but high precision range (liquid level) measurement becomes a critical aspect. For Military Applications, the response time and precision both are parameters that need to be optimized, as the consequences will catastrophic otherwise.

2. **Heavy Competition in International Market**

   To make our product a success in the existing market, we need to overcome the barrier of competition. For example, in the automotive sector, there are many leading international companies in the world that are trying to make advance in the field of SDC's and Driver Assistance Systems. For Indian Companies to compete with others (thus keeping the spirit of *Atmanirbhar Bharat* vibrant), it is important to employ modules that offer state-of-the-art performance. Cheap Labour for Large scale manufacturing provided by some countries is also a risk factor for our product. But the silver lining in this challenge is that the Indian market is relatively unexplored in this aspect and therefore, this provides us with many opportunities to make our product a success.

Establishment of Linkup/Collaboration

We will first be approaching IIST's own startup incubation cell Space Technology Innovation and Incubation Cell (STIIC). It has been initiated with a mission to foster the spirit of innovation and bring up successful entrepreneurs. With the support and guidance of STIIC we are also planning to prepare our search for possible external collaborators and end users who might be in need of this solution.

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