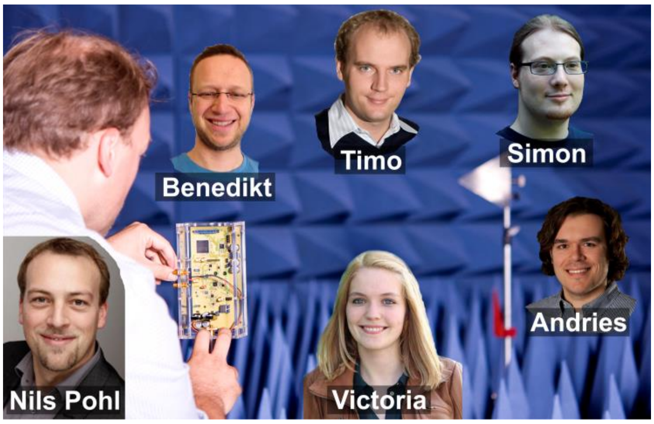
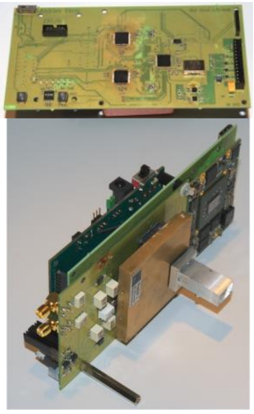
Texas Instruments Innovation Challenge: Europe Analog Design Contest 2014
Project Report

Advanced High Resolution Radar Systems for Future Industrial and Medical Applications

Team Leader:	Timo Jaeschke	[timo.jaeschke@trapid.de]
Team Members:	Victoria Kloubert	[victoria.kloubert@trapid.de]
	Simon Küppers	[simon.kueppers@trapid.de]
	Andries Küter	[andries.kueter@trapid.de]
	Benedikt Janßen	[benedikt.janssen@trapid.de]
Advising Professor:	Nils Pohl	[nils.pohl@fhr.fraunhofer.de]
University:	Ruhr-University Bochum, Germany	
Date:	31.07.14	

Qty.	**TI Part Number & URL**	**Qty.**	**TI Part Number & URL**
2	ADS42JB69 (ADC)	1	TPS2553 (Power Switch)
1	LMK04828 + CDCV304 (Clock)	1	TLV320AIC3111 (Audio CODEC)
1	MSP430G2553 (Power Control)	1	LM3671 (Step-Down DC-DC)
4	TPS7A4700 (LDO)	2	LM2735XMF (DC-DC Regulator)
1	INA220 (I2C Sensor)	X	Optionally many more TI OpAmps





Project abstract: Applications involving radar systems have come a long way over the years, yet the medical field still seems to be nearly unconquered by this kind of technology. On the other hand radar sensors are a standard technique for tank level probing in industrial applications.

In this project we present a novel highly accurate and low cost radar sensor, which is suitable for a wide variety of new applications. These include for instance medical ones, while it also advances established industrial application scenarios.

Within this project we show how the developed sensors can be used to enhance the human's visual sense by scanning the spatial region in front of the user. The acquired data is used to model an auditive space for the user to be able to imagine the scanned visual space in terms of target angles and distances. As a second example on the versatility of the sensor, we show the same sensor with an advanced ADC-backend for use in several industrial scenarios for example flow metering or high measurement rate applications like machine health monitoring and online calibration of positioning systems. In those applications radar sensors can monitor runtime parameters, be included in closed loop controls, help to prevent faults, and therefore reduce costs and improve safety.

Introduction

Ongoing advances in Silicon-Germanium technologies in conjunction with the today available signal processing capabilities allow for highly integrated low-cost radar sensor designs in the millimeter-wave region for a wide variety of emerging applications. The benefit on an increase in frequency not only manifests in the ability to use more compact high gain antennas or even on-chip integrated antennas, but additionally results in higher accuracy for distance measurements with micrometer accuracy and nanometer repeatability. For many industrial applications accuracies better than 1µm are sufficient, therefore radar could in future become feasible as a replacement for expensive laser-interferometer based calibration devices. By the use of frequency modulated continuous wave (FMCW) millimeter-wave radar systems with center frequencies of 80 GHz or 144 GHz, and sweep bandwidths of more than 30%, we have recently shown that measuring distances in the micro- and even nanometer range is possible. By the use of this technology, we want to extend the standard realm of radar applications into areas that have not been touched before by systems of this kind. Therefore, we want to use the opportunity of participating in the Texas Instruments Innovation Challenge and advance into two distinct and innovative applications for our radar technology.

The first field of application we have chosen is to use our highly integrated radar sensors for augmenting the reality of the user, for example to assist visually impaired individuals navigating through their daily lives. Such kind of system could also be used to help emergency services to navigate in smoky or foggy terrain, for example in a fire accident. Radar sensors provide very unique advantages in these applications. Due to the larger wave-length compared to optical systems, it is possible to see through fog and dust, even in areas with heat sources where infrared based sensor systems are not working. Figure 1 shows the simplified setup for this application. A radar sensor is used to scan the environment. The target's angle and distance information are collected, evaluated and mapped to the audio space by using virtual 3D audio rendering techniques. Then an audio signal is synthesized which represents the simplified information of the surrounding area. For future applications this technique can even be improved by electronically scanning phased array radar sensors or low-cost accelerometers for tracking the actual head position and radar beam angles.

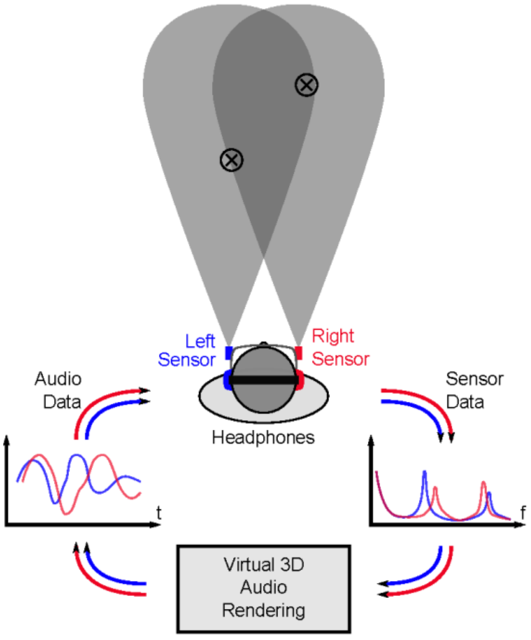


Fig. 1 Schematic view of the proposed radar vision sensor.

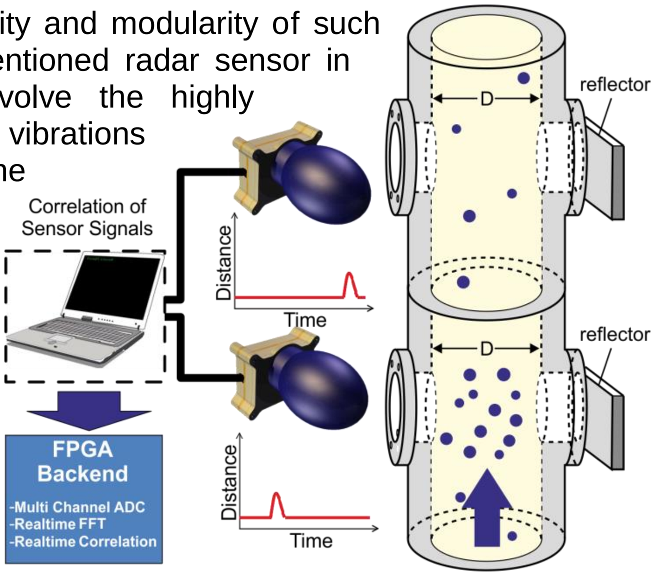


Fig. 2 Schematic view of the flow metering application.

Secondly, we want to show the versatility and modularity of such radar systems, by using the before mentioned radar sensor in industrial applications. This could involve the highly accurate measurement of distances and vibrations in multi target environments like in machine health monitoring or precise distance measurement systems for micro machining positioning systems. Compared to CW sensors, the FMCW principle has the tremendous advantage that the sensors are multi-target capable even in vibration measurement scenarios. Another interesting industrial application is the use of radar sensors for bulk solid or gas flow metering in pipes and pneumatic conveying systems by correlating the measured distance fluctuations of two sensors measuring the distance to a static reflector target through the media inside the pipe. Here the permittivity fluctuations of vortexes are correlated, and due to the known distance between the two sensors the flow velocity could be determined. In Fig. 2 the schematic view of this application is given. One can easily imagine that such a measurement principle demands for high measurement rates of more than 1 kHz, which come along with high requirements regarding the ADC and DSP parts for real-time signal processing of the radar sensor systems.

With the described medical and industrial field of applications, we want to show, that modern SiGe based millimeter-wave radar sensors are ready for covering many emerging applications. The small millimeter-wave radar sensor developed by our group is capable of operating power efficient as well as employing a record distance measurement performance at reasonable cost.

The system consists of a custom MMIC, but to achieve the best system performance also the surrounding parts are very important. Several TI components have been used to achieve the best possible solution for both applications.

Motivation for Project

Today’s processing systems are becoming more and more ubiquitous and thus the potential for new applications is growing. This trend is strengthen by the increasing performance and energy efficiency of such computing systems, allowing small and mobile systems that assists people in their daily lives. This circumstance induces a growing need for small, energy efficient and versatile sensors, which enable these pervasive systems to sense their environment. Powerful systems equipped with potential sensing capabilities can be more than just another fancy gadget, but can help people who have partly lost their sensing capabilities. Moreover these systems herald the next industrial revolution by being the basis for cyber physical systems and therefore enabling a highly computerized and automated industry. Due to the increasing number of embedded systems in industrial application their energy efficiency is becoming more and more important.

The Institute for Integrated Systems wants to take part in these developments and to contribute with their knowledge about highly accurate and efficient radar sensors in the field of medical and industrial sensors. Besides the great capabilities of the radar technology, the military background of it is a strong motivation to put this technology to serve in civil applications, such as industry or healthcare. Furthermore we are inspired by the challenge opened by the multifarious aspects of the mentioned applications. In order to create an auditive sensing experience it is necessary to take psychoacoustics into account, a field of research that is normally not strongly represented in electrical engineering. This gave us the opportunity to use the knowhow of the Institute for Integrated Systems, combining it with new findings and successfully develop a system to cope with the described challenges.

Theoretical Background

The radar system used in this application uses frequency modulated continuous waves that are transmitted into free air by the use of antennas. Since every kind of material that is within the beam of the antenna reflects these electromagnetic waves to some extent, these reflections are directed back to the system and are being received through the same antenna, that they have been sent out. In order to process the range profile that has been acquired by the sensor, the momentarily transmitted signal gets multiplied (frequency mixed) with the momentarily received signal. Figure 3 shows a block diagram of a simple FMCW radar.

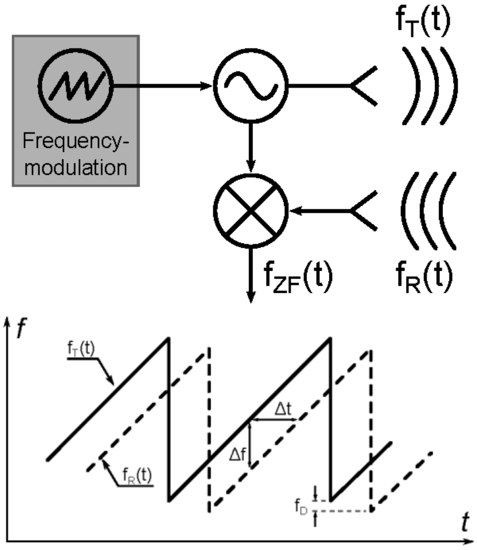


Fig. 3 FMCW radar principle.

When using linearly frequency modulated signals as shown in the bottom of Fig. 3 this operation results into an immediate frequency signal f_{ZF}, that contains frequencies that are directly proportional to the distance of the target. This relationship can easily be demonstrated by assuming that a single target exists in front of the sensor. In this case, the reflected signal equals a time-delayed version of the transmitted signal. When employing the multiplication on these signals, the resulting frequency difference is constant. In succession to this down-converting operation, the standard processing that is being done on the IF signal is a FFT, which reveals the range profile of the reflections in the antenna beam.

The frequency domain shows peaks at distinct frequencies that directly correspond to the distance *R* of a single target in front of the sensor. The following equations show the mathematical relationship between the target distance and the frequency content in the IF signal, which depends on the ramp slope of the transmitted signal, as well as the bandwidth that is used during the frequency sweep:

$$R = \frac{c_0 \cdot \Delta t}{2} = \frac{c_0 \cdot f_{ZF}}{2 \cdot \Delta_{ramp}}$$

The range resolution δ_r of a radar system describes the minimal distance between two objects, which is needed to identify them as separate objects. It depends on the ramp slope Δ_{ramp} of the radar system, the speed of light c_0 and a factor of the used window function B_W in signal processing. The relation of these factors and the resulting range resolution is represented by the following equation:

$$\delta_r = \frac{c_0 \cdot B_w}{2 \cdot \Delta f}$$

The IF frequency for a given distance can be calculated by:

$$f_{ZF} = \frac{2 \cdot R_{max} \cdot \Delta_{ramp}}{c_0}$$

By taking into account the Nyquist criterion the minimum sample rate to digitize the IF signal is:

$$f_{sample,min} = \frac{4 \cdot R_{max} \cdot \Delta_{ramp}}{c_0}$$

For short maximum detectable distances in combination with relatively long ramp durations around e.g. 4 ms 1 MSPS 16 Bit A/D converters are sufficient. For systems covering a wide bandwidth together with high measurement rates around around 1 kHz, resulting in 1 ms ramp duration. In combination with large measurement distances the maximum IF frequency could easily increase to 50 MHz or more. Even with 8th order anti aliasing filters some oversampling is needed to prevent degradation of the IF signal due to aliasing, which demands for high ADC sampling frequencies.

Implementation

In order to achieve a versatile implementation of the system, a modular approach has been chosen. This is not only useful, in respect to the interchangeability of system parts, but also necessary to lower the overall costs of the system, since all high frequency components have to be designed using appropriate but costly circuit board substrates. The realized high frequency module contains the custom radar MMIC which was developed at the RUB. It contains several key building blocks for radar systems and is shown in Fig. 4. In order to achieve a stable and accurate system performance, an offset PLL concept involving two separate phase locked loops has been chosen. The phase locked loops stabilize the main oscillator, which is used to emit the electromagnetic waves by means of a microstrip-to-waveguide transition and a standard gain horn antenna.

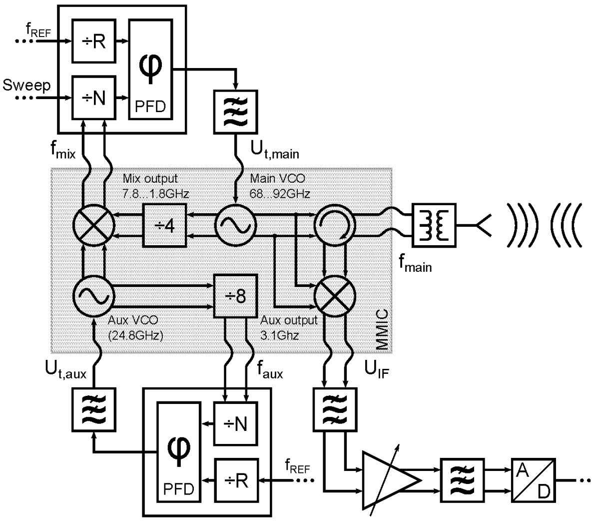


Fig. 4 Block diagram of the radar MMIC.

In this submission, the developed high frequency radar frontend module is being used in conjunction with different backend systems, tailored to the exact needs of the application. Because of this, two different backend modules have been realized for the vision sensor and the high performance system.

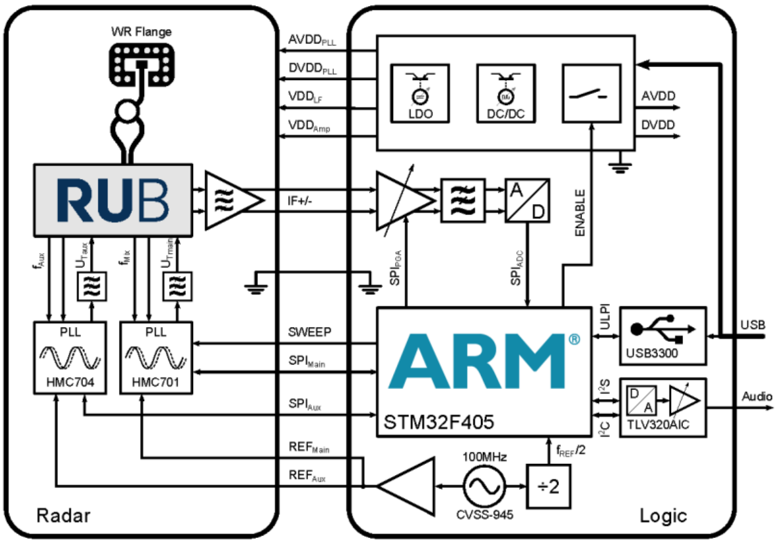


Fig. 5 Block diagram of the vision sensor system.

Beginning with the vision sensor backend for the vision aid sensor, the block diagram of the system is shown in Fig. 4. A complex power supply has been implemented to allow for extremely low noise power rails using a single 5V USB input voltage. For this, TI's LM2735 and LM3671 dc/dc converters have been used to generate the required voltages to operate the radar system. The high switching frequencies of 1.6 MHz and 2.0 MHz respectively have been chosen to allow for extremely small board space and minimal noise injection into the IF signal chain, that uses a bandwidth of 1 MHz. Also the low quiescent current of the step-down dc/dc converter has been utilized to lower the power consumption, especially in the case, where the microcontroller's sleep mode is being used. In addition to this, a TPS2553 high-side power switch has been used, to be able to cut power to the radar subsystem and thus conserve as much power as possible, when the system is in idle state. In order to provide a headphone output, a TLV320 audio codec has been used. The extremely small form factor combined with the integrated headphones amplifier and the miniDSP processing made this integrated circuit the first choice for the vision sensor backend.

For the high performance backend we opted for an FPGA-based approach which made it possible to utilize the emerging JESD204B standard. While most ADCs operating at 10 MSPS+ employ parallel LVDS lanes to cope with the data rate of high speed, high precision sampling (often approaching or even exceeding 1 Gbps per channel), JESD204B uses highly serialized data streams and dedicated CML-transceivers with integrated signal conditioning to transfer multiple gigabits of data per second on a single differential pair of traces. This eliminates a lot of the problems circuit designers face when implementing parallel connections, like crosstalk and channel skew, but comes with its own set of challenges concerning signal integrity.

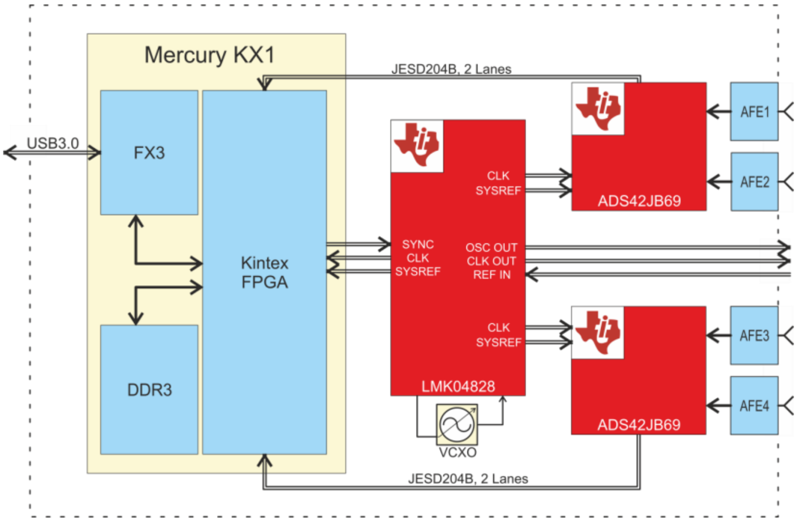


Fig. 6 Block diagram of the high performance backend with fast 4 channel AD conversion and FPGA interfacing for real-time processing.

In our system for the industrial high performance radar sensors, we use two TI ADS42JB69 ADCs to sample the IF signals of up to four radar frontends. This part is ideally suited for this job for a number of reasons: It can interface directly with our analog frontend and it provides the high sample rate that is needed for vibration measurements. Additionally, because of its advanced transceivers and the relatively low line rate of 2.5 Gbit/s, we were able to integrate it onto our main PCB without the need for advanced SI simulation tools by just respecting the basic high speed digital layout rules. Our FPGA platform of choice is the Enclustra Mercury KX1 which provides us with a Kintex-7 FPGA, generous amounts of DDR3-RAM and a FX3 USB3.0 controller to interface to the PC. A photograph of the 6-layer impedance controlled PCB with the ADCs and the clock manager is shown in Figure 7.

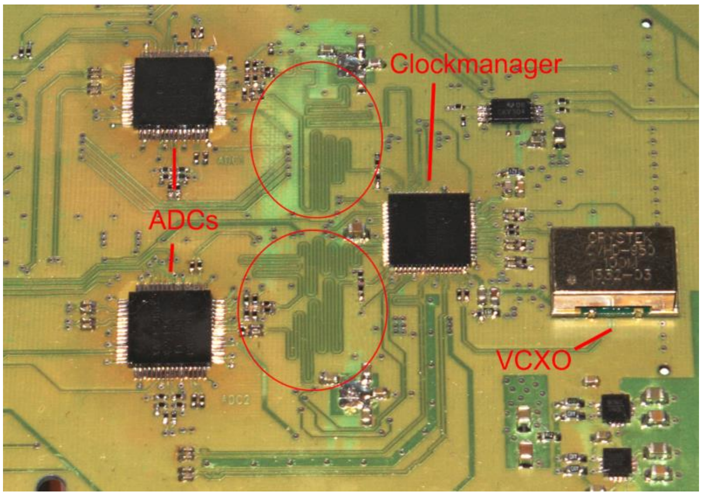


Fig. 7 Photograph of the ADC and clock distribution part of the high performance backend.

One major source of problems when dealing with source-synchronous LVDS is the need for the data streams to be phase aligned with the clock signal. This is not the case for JESD204B. Here, the clock of each stream is recovered using the data coding and a low speed reference clock. To eliminate a system wide clock drift that almost certainly occurs when using multiple clock sources for each component, a clock manager has to be used. Since this device has to provide multiple ultra-low jitter clocks for ADCs, the FPGA, and the analog radar frontend (AFE), we chose the LMK04828, which is specifically designed to provide all features needed for a JESD204B-based system. Its dual-loop PLL architecture additionally allows for reference locking (e.g., 10MHz, GPS/PPS) to synchronize multiple systems.

For a high performance analog system, a clean supply is very important. In our system this is achieved by using switch mode converters with a high switching frequency of 1 to 2 MHz which is well above the expected frequency of the input signal when observing a near target. Furthermore, our sample rate of 150 MSPS is high enough to prevent aliasing of the switching frequency and associated harmonics back into the relevant frequency range. To reduce SMPS noise even further, each power rail is filtered with ferrite beads and an additional LDO with good PSRR characteristics, namely the TPS7A4700. Although because of its strappable output voltage this LDO would typically be used when a variable output voltage is required, it performs equally well in fixed output situations because it alleviates the need for odd-valued feedback resistors which leads to a tidier BOM. Power staging is performed by a MSP430G2553 microcontroller because of its small footprint and easy integration as well as its very cheap development and debug tool, the MSP430 Launchpad.

Experimental Results & Realization

We realized demonstrator systems for both proposed applications. A versatilely usable radar frontend was build with an optimized design for high volume mass production suitability. The millimeter-wave PCB was designed to allow manufacturing by standard PCB supplier processes. The waveguide antenna port was depth milled into the 1 mm backside copper cladding of the module. A photograph of the system is shown in Fig. 9. This module, which can be used for both applications, comprises the millimeter-wave MMIC, the phase locked loop synthesizers with integrated linear ramp generation together with the highly optimized active loopfilters, and an IF pre-amplification stage. Additionally the millimeter-wave transition to feed the signal to an antenna is integrated.

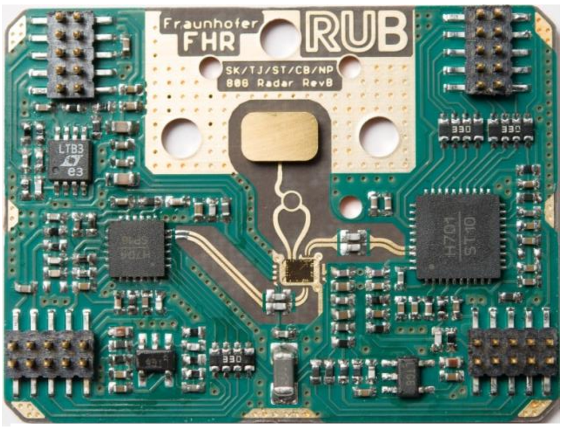


Fig. 9 Millimeter-wave radar frontend.

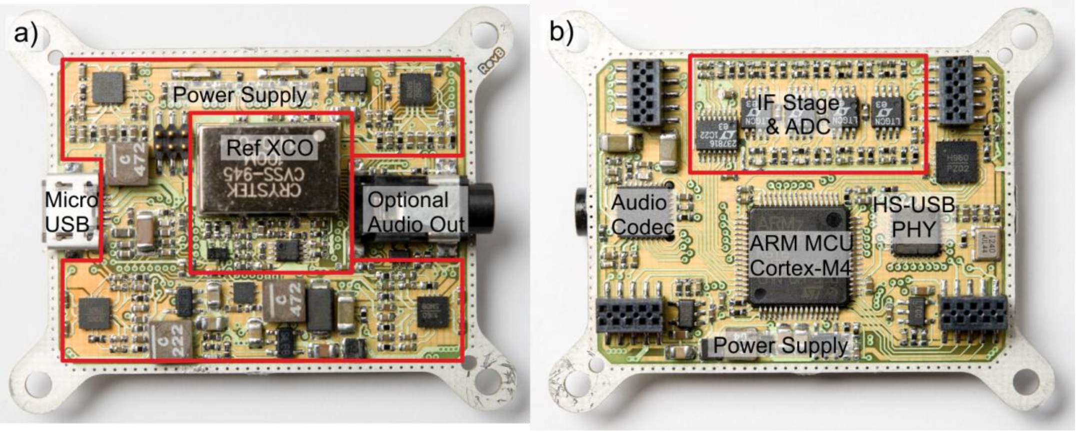


Fig. 8 Top and bottom side of the vision sensor radar backend PCB.

Figure 8 shows the manufactured 4-layer PCB with the vision sensor backend. The backend can be powered from an USB port. The Micro-USB connector can be seen on the left of the module. On the bottom of the module an ARM Cortex M4 based microcontroller can be seen. We did not use a TI part, because to allow onboard processing, a high operating frequency of 168 MHz in combination with a large RAM is necessary and the used microcontroller additionally provide a high-speed USB2.0 interface. The radar system is fully operable, but the sound synthesis is still implemented as a proof of concept. After digitizing the IF signal the ARM Cortex core applies a FFT on the data and searches for peaks. Right now only the strongest target is recognized. The distance of the target is mapped to a hearable frequency and a sound is synthesized by a digitally oscillator and given to the TI DAC. Due to the warning character of high frequencies the distances are mapped upside down, this results in close targets being represented as high frequency sounds. Additionally the volume of the signal is adjusted with respect to the hearing threshold level of the human ear to provide the same volume over all distances. The proof of concept works very well and in future the 3D audio synthesis using head related transfer functions will be implemented as well as multi target audio synthesis capability.

To show the performance of the radar sensor for industrial distance measurement applications the distance between the sensor and a target on a linear actuator with a glass scale (100 nm accuracy) was measured, while moving the target over 10 mm in a distance of 65 cm. The glass scale position was used as reference and compared to the measured distance acquired with the radar sensor.

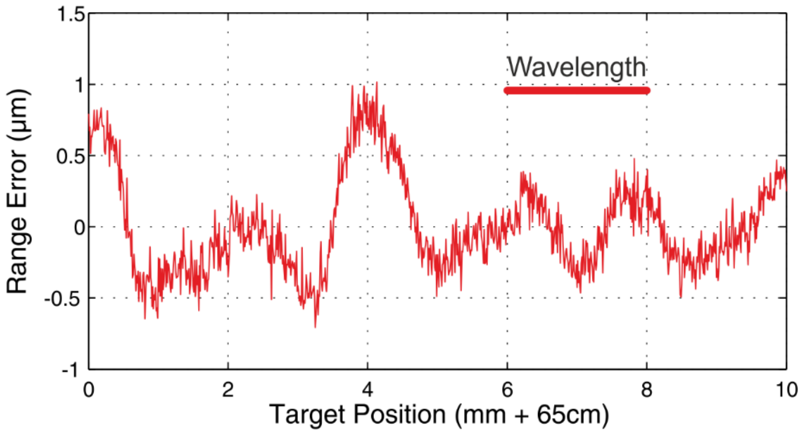


Fig. 10 Measured distance error of the radar compared to a 100 nm glass scale assisted linear positioning unit with a corner reflector target.

Figure 10 shows the excellent result of this measurement. The measured distance error is below 1 µm which is a very good result for a contactless measurement system and was previously only achieved by optical systems like laser interferometers. The larger wavelength which is used for the radar systems is additionally much more robust against dust and fog than laser based systems, which is very important for distance measurements in harsh environments like the steel industry.

Conclusion & Summary

The presented demonstrator systems show excellent results in the proposed novel healthcare and industrial applications. There is still a lot of work to do, but in general we can say that state-of-the-art FMCW radar sensors, like the two presented systems, are interesting for many emerging applications.

The proposed vision sensor system can enable impaired people to be more self-determined in their daily life. In our opinion it is an extremely promising project and deserves to be continued. The implemented demonstrator system is based on a single sensor without any angle estimation and angle representation in the acoustic signal. Implementing the complete idea will take some more time, but we are looking forward to hopefully see this idea realized with 3D audio mapped target representation and maybe also with an electronically scanned phased array antenna in combination with a highly integrated sensor one day.

Present and future industrial applications provide promising use cases for low cost radar sensors. Due to the advances in semiconductor technology low cost SiGe radar sensor MMICs are covering higher and higher frequency regions with excellent performances. Above 200 GHz, which will be possible with production SiGe technologies in the next years, also integration of antennas on the MMICs will be feasible and this will further reduce cost of FMCW radar systems. First measurements with the realized industrial demonstrator system showed excellent distance measurement results with accuracies better 1 µm and a repeatability around 80 nm with very high measurement rates up to 1 kHz. These are outstanding results for low cost sensors like the proposed one. First tests in the proposed flow metering application also showed very promising results. The new high performance backend is still in development. The ADC and clock part is already implemented and tested. The ADC data is right now transferred into the FPGA boards RAM and the USB3 Interface for FPGA RAM readout with a PC is working, too. But there is still a lot of work to be done by implementing the radar algorithms on the FPGA for real-time multi channel processing and interfacing the radar boards.

Future plans

With respect to a market ready application of the vision sensor, a 3D audio mapping algorithm, that allows an intuitive spatial auditory representation of the user's environment, has to be evaluated. For this purpose, the amplitude mono-pulse technique can be used to determine the azimuth angle of incident the electromagnetic reflections emitted from the targets. In order to use this technique, either two radar sensors or a single sensor employing beam steering using phased array antennas has to be used. For a cost-effective and miniaturized application, the beam steering network could be integrated onto the MMIC.

The sensor for industrial applications is in a design state which is not far away from first field tests. The algorithms could still be improved for achieving an even better accuracy. In this field the main research focus will be further miniaturization of the systems by higher integration levels of the sensor with on-chip antennas, together with MIMO systems and multi sensor solutions, which are interesting for industrial radar imaging applications like production quality assurance systems and NDT.

Bill of materials

High Performance ADC Backend:

QTY	Manufacturer	Part Number
1	C&K	CK_1101M2S3A
1	C&K	TDA04H0_B1_
1	Crystek	CVSS-945
1	Diotec	1N4004
1	enclustra	ME-KX1-160-1C-D10
1	enclustra	KX1_CON_A
1	enclustra	KX1_CON_B
1	FOX Electronics	FXO-HC736R-10
1	Hirose	FX10A-168P-SV
2	Hittite	HMC1023
2	Hittite	HMC1060
1	LT	LT1761
2	LT	LTM8032
1	Lumberg	NEB 21 R
1	MOLEX	87831-1420
2	Murata	NFM31PC276B0J3L
6	NXP	9335 895 40215
2	Panasonic	ELK-E333FA
1	Samtec	UUSB3_AB_S_X_SM
2	TI	ADS42JB69IRGCT
1	TI	CDCV304PW
1	TI	LMK04828BISQ
1	TI	MSP430G2553IN20
1	TI	INA220AIDGST
4	TI	TPS7A4700RGWT

RF Frontend + Vision Sensor Backend

QTY	Manufacturer	Part Number
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1	AMPHENOL	T812120A100CEU
1	AVAGO	HSMG-C110
1	AVAGO	HSMS-C110
3	BOURNS	CAT16-330J4LF
1	COILCRAFT	XAL4020-222MEC
1	COILCRAFT	XFL3012-104MEB
1	COILCRAFT	XFL2006-473MEB
1	COILCRAFT	XPL2010-102MLC
2	COILCRAFT	0402HPH-R22XJLU
2	COILCRAFT	XAL4030-472MEC
1	Crystek	CVSS-945-50.000
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1	Hittite	HMC960LP4E
4	Hittite	HMC1060LP3E
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1	KEMET	C0402C182J3GACTU
1	KEMET	C0402C391J5GACTU
1	KEMET	C0402C470J5GACTU
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3	KEMET	C0402C182J3GACTU
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4	KEMET	C0402C181J5GACTU
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1	MULTICOMP	MC00625W0402182K
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1	SAMTEC	FTSH-103-01-L-DV
4	SAMTEC	FTS-105-02-F-DV
4	SAMTEC	FLE-105-01-G-DV
1	STM	STM32F405RGT6
1	TDK	C2012X5R1A226K125AB
1	TDK	C3216X5R1A107M160AC
2	TDK	C1608X5R1C475K080AC
4	TDK	C1005X5R0J475M050BC
4	TDK	C1005X5R0J475K050BC
6	TDK	C1005X5R1C105K050BC
16	TDK	C1005X5R1C105K050BC
34	TDK	C1005X5R0J475M050BC
1	TE	CPF0402B47RE1
2	TE	CPF0402B33RE1
1	TI	TLV320AIC3111
1	TI	LM3671MF-3.3/NOPB
1	TI	TPS2553DRVT-1
2	TI	LM2735XMF/NOPB
1	TXC	7M-24.000MAAJ-T
1	WELWYN	PCF0402PR-120RBT1
2	WELWYN	PCF0402PR-1K0BT1
2	WELWYN	PCF0402PR-680RBT1
3	WELWYN	PCF0402PR-200RBT1
10	WELWYN	PCF0402PR-1K0BT1
14	WELWYN	PCF0402PR-2K0BT1
18	WELWYN	LRCS0402-0R1FT5
2	WURTH	742792731
1	WÜRTH	742792602
2	WÜRTH	742792731

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