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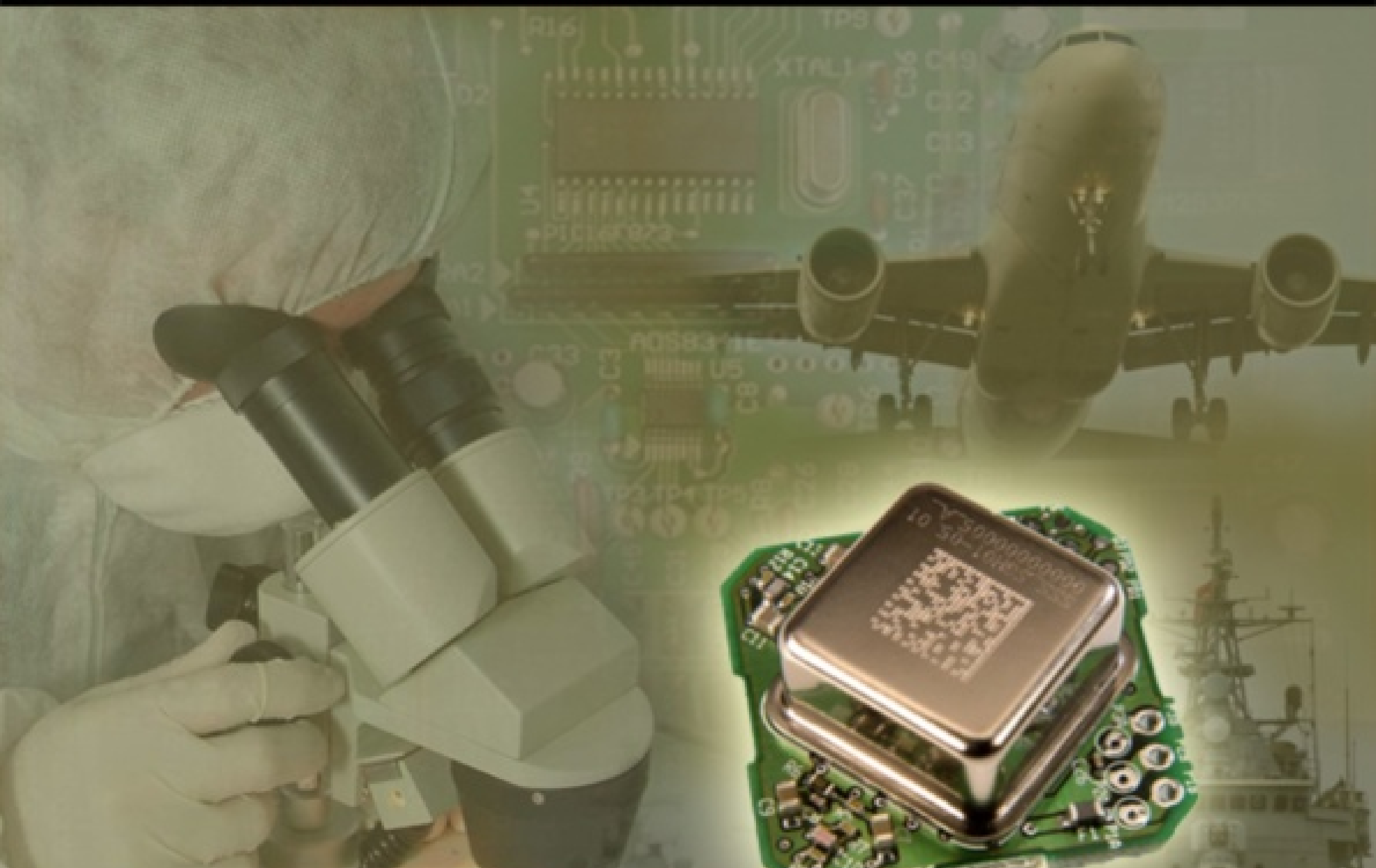

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A Versatile Prototyping System for Capacitive Sensing

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Abstract: This paper presents a multi-purpose and easy to handle rapid prototyping platform that has been designed for capacitive measurement systems. The core of the prototype platform is a Digital Signal Processor board that allows for the entire data acquisition, data (pre-) processing and storage, and communication with any host computer. The platform is running on uCLinux operating system and features the possibility of a fast design and evaluation of capacitive sensor developments. To show the practical benefit of the prototyping platform, three exemplary applications are presented. For all applications, the platform is just plugged to the electrode structure of the sensor front-end without the need for analogue signal pre-conditioning. *Copyright © 2008 IFSA.*

Keywords: Blackfin, uCLinux, Capacitance liquid fill level, Spatial filtering, Flow measurement

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1. Introduction

Capacitive sensing has gained increasing importance in the last decades and is successfully employed in various applications in industrial and automotive technologies [1]. Capacitive sensors can be utilized to solve many different types of sensing and measurement problems. They can be integrated into a printed circuitry board or a microchip and offer non-contacting sensing and high resolution. Capacitive sensors are for instance applied for measuring tasks in rotary and linear position encoding, liquid level sensing, touch sensing or for proximity detection [2]. Aside from the non-contacting principle, capacitive technology also allows for a low-cost implementation of sensors, especially since reliable low-price devices are available for higher frequencies (e.g. due to achievements for mobile telephone systems). The development of modern electronic systems is typically characterized by an increasing complexity and by competitive pressure, which demands new procedures and technologies for the development progress to increase quality on one hand and keep time and costs low [3]. A variety of devices exist, which can be used to measure the capacitance of a sensor front-end. Probably the simplest way for the user to measure a capacitance is to use an impedance analyzer or a capacitance measuring bridge. If a multi-electrode setup shall be surveyed or online measurements shall be conducted, these solutions might be inappropriate. Commercial available measuring systems offer the functionality of measuring capacitances with high speed (up to 50 kHz) and/or high resolution, but in most cases the output signal is an analogue voltage and requires additional hardware to digitize and evaluate the measurement signals [4]. A multi-purpose prototyping system featuring fast data acquisition and suitable data pre-processing for capacitive measurement problems is hence required for industrial development as well as for research applications. In this paper we describe a rapid prototyping platform that allows using one universal hardware for many different capacitance sensor applications. The time to develop, test and validate new algorithms and new measurement principles can therefore be minimized. The interface between the rapid prototyping platform and the host computer shall be simple and reliable. The end user should not spend time for implementing data exchange algorithms. This paper presents the development platform as well as applications – a fill level measurement setup, a flow meter for granular material and a sensor aimed to detect out of bounds of tennis balls are realized.

2. System Description

The prototyping system is utilized to interconnect the sensor front-end with a host computer in an efficient and convenient way as shown in Fig. 1. To develop and test a certain capacitive sensor front-end (i.e. an electrode assembly), the multi-purpose rapid prototyping platform can be efficiently utilized. The advantage of using a powerful computation unit on the platform is the ability to decrease the amount of data to be transferred between the host computer and the measurement setup by means of suitable data pre-processing. The capacitive sensor prototyping platform basically consists of a capacitance to digital Application Specific Integrated Circuit (ASIC) and a Blackfin Digital Signal Processor (DSP) board with onboard memory and uCLinux operating system. Fig. 2 shows a block diagram representation of the basic components of the system.

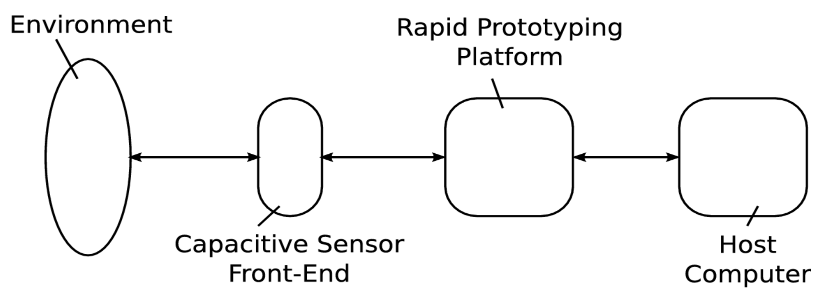

Fig. 1. Use of the rapid prototyping platform to interconnect the capacitive sensor front-end with a host computer.

2.1. Hardware

The capacitive sensor front-end setup may consist of a maximum number of 16 electrodes with our capacitance to digital converter ASIC. This ASIC is able to measure the inter-electrode capacitance between the activated transmitter electrode(s) and one receiver electrode featuring in-/quadrature phase (I/Q) demodulation. When selecting a switching pattern, the ASIC takes care about activating the transmitter electrodes. The 16 transmitter electrodes can be switched on and off flexibly by means of user-defined sequences. The configuration of the ASIC is done via Serial Peripheral Interface (SPI), while the high speed data transfer of the measurement results is done via parallel bus. A Blackfin uCLinux stamp board is used as interface, data processing, and communication platform. This board is equipped with an Analog Devices Blackfin DSP, 64 MB of SDRAM and 4 MB of Flash memory to store the bootloader and the uCLinux kernel image. The Blackfin DSP is well suited for a rapid prototyping platform due to its exceptional wide range of peripheral interfaces. The Blackfin BF537 DSP offers synchronous and asynchronous serial ports, high speed parallel interfaces, GPIOs and even 10/100 MBit Ethernet. The maximum core clock frequency reaches 600 MHz with a system bus frequency of up to 100 MHz. As one of the fastest representatives of the Blackfin series, the BF537 reaches a computation power of up to 1200 Million Multiply Accumulate (MMAC) operations per second. A photo of the rapid prototyping platform is shown in Fig. 3.

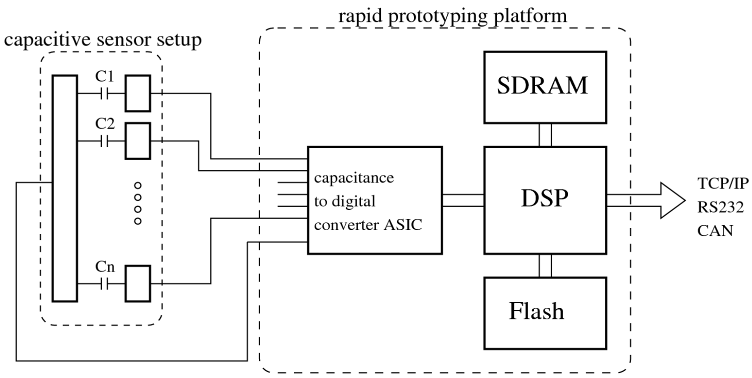

Fig. 2. Block diagram of the basic components of the rapid prototyping platform and the capacitive sensor setup (front-end).

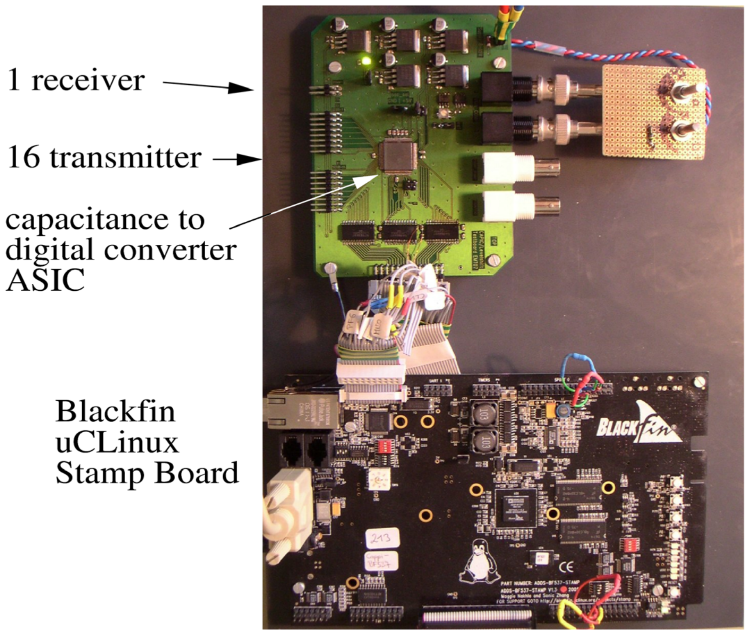

Fig. 3. Photo of the rapid prototyping platform comprising Blackfin Stamp board and ASIC board.

2.2. Software

One aim of the prototyping platform is that the user should not spend much time for implementing data exchange interfaces. An uCLinux operating system is hence used, which allows for a convenient, fast and reliable data transfer. In contrast to a conventional Linux operating system uCLinux has the ability to run on processors without a Memory Management Unit (MMU–less systems). Access to peripherals is gained by kernel modules. In the current version of the prototyping platform, one kernel module for the DSP parallel port is used and another one for the SPI port. Data transfer from parallel interface into the DSP memory is done by Direct Memory Access (DMA). This allows for the CPU to compute output data, e.g. correlation or frequency estimation routines, while receiving new measurement values. Another advantage of grabbing parallel data via DMA is the real-time capability of the overall system due to the external clock driven DMA transfer, although the uCLinux system itself cannot guarantee real-time behavior.

2.3. Host Communication

One of the most comfortable solutions for transferring data is an interface via uCLinux built-in web server. The programmed measurement routine on the DSP may write data into a specific folder, which is accessible by any web browser. This allows complete stand-alone sensor solutions. If higher data transfer rates are required, a socket communication is implemented, where a measurement daemon listens on a predefined "socket" for incoming commands. In case of a measurement command, the daemon starts the measurement and appropriate signal processing routines and sends the desired information back to the host system through the socket. On the host side both communication approaches can be easily implemented in MATLAB, LabView, C or any other programming language. Furthermore, data interpretation algorithms developed in C on the host side may be cross-compiled for Blackfin uCLinux without any changes and can be executed directly on the DSP to eliminate data transmission latency and provide a stand-alone sensor solution.

2.4. System Performance

The capacitance to digital converter ASIC is capable of handling electrode layouts with an offset capacity of up to 20 pF, while the measurable capacitance variations are in the range of some fF. A large number of capacitive sensor applications with a wide variety of different demands can hence be served. Commercially available circuitries [4], [5] typically offer high resolutions at low measurement rates. Our capacitance measurement system provides a lower resolution of 10 bit but can be operated at high measurement rates. The current setup allows for measurement rates of up to approximately 100 kHz for a single electrode and approximately 6 kHz for complete measurement cycles of 16 electrodes respectively. The number of active transmitter electrodes, as well as their measurement frequency can be easily set by software. Furthermore, analog gain and offset can be tuned by software to adopt the rapid prototyping platform to electrode structures of various dimensions.

3. Applications for the Prototyping Platform

To show the practical benefit of the rapid prototyping platform, three exemplary applications are implemented and have been tested. In all cases, the platform is just plugged to the electrode structure of the sensor front-end. The first example is a capacitive fill level sensor, which is designed for non-invasive fill level monitoring of fuel or water vessels. In a second example we show a possible setup for capacitive velocimetry of moving particles in a pipe, which is a frequent measurement task in pneumatic conveying of bulk solids. A third setup shows the applicability of the rapid prototyping platform for the detection of hits of a tennis ball aimed to be used in sports to support referees in their in/out bound decision.

3.1. Fill Level Measurements

Fill level determination by means of capacitive sensing is a frequently arising measurement problem in process instrumentation [6], [7], [8]. For the measurement setup in our application, a non-conducting cylindrical vessel was equipped with a pump and an outlet valve to control the water fill level in the vessel. A calliper is used to provide reference data of the fill level height. One receiver electrode and 16 transmitter electrodes are mounted in parallel along the vertical axis on the vessels outside (see Fig. 4). The liquid inside the vessel causes a change in dielectric permittivity for the region around the transmitter electrodes (i.e. in the sensitive region of the individual electrode) below the fill level. The capacitance between each active transmitter segment and the receiver is increased in case of presence of water ($\varepsilon_r = 80$) in the vicinity of the segment. This sensor principle can be applied to a wide variety of fill level measurement problems. A sensor element comprising 16 transmitter and one receiver electrode can be mounted inside a tank, if the tank is made of conductive material and the liquid is non-aggressive. Or, if a non-conductive material is used, like for automotive tanks, the sensor can be mounted on the outer surface of the tank. The sensor resolution can be increased by an arbitrary application specific design of the electrode geometry. Transmitter electrodes are operated in time division multiple access (i.e. all transmitters are activated one after the other and there is always just one transmitter active at a time). Our approach to determine the fill level is to accumulate all single capacitance values and to normalize them as shown in Fig. 5. The measurement results show that the curve is not straightly linear. This effect is most likely caused by the imperfect printed electrode layout, in particular due to transmitter and receiver wire routing. The nonlinearity could be handled either by a carefully designed electrode layout or by a calibration of the sensor setup. Note that the entire fill level computation can be done onboard on the rapid prototyping platform and that the actual fill level can be directly provided either in digital form for example by means of Controller Area Network (CAN) or as an analogous signal like a 4-20 mA current output.

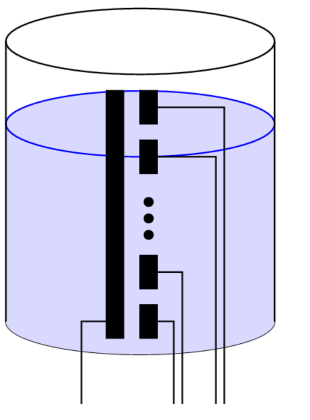

Fig. 4. Schematic electrode layout for measuring liquid fill level with 16 transmitter and one receiver electrode.

3.2. Velocity Determination by Means of Spatial Filtering

The basis of spatial filtering methods [9], [10] is the evaluation of signal amplitudes caused by moving particles through grating-like structures. Bypassing particles have an impact on the readout of the measurement signal, which is dependent on the particle velocity and on the geometrical dimensions of the sensing volume. For a given sequence of sensitive volumes with a certain extend in flow direction, a slow particle will cause lower frequency contributions than a fast moving particle will. The basic principle of velocity determination by means of spatial filtering is shown in Fig. 6. In our setup, eight pairs of electrodes are mounted on the outer surface of a non conducting pipe with a diameter of

75 mm. The transmitter electrodes act as eight independent transmitters that can be activated independently, while the receiver electrodes are all connected to constitute one single receiver electrode. Fig. 7 illustrates the setup with opposed transmitter and receiver electrodes and a particle moving through the assembly.

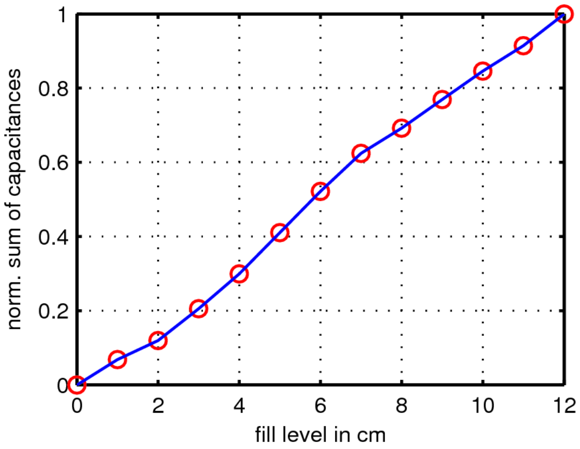

Fig. 5. Normalized sum of capacitances depending on the fill level. The nonlinearity is most likely caused by a non ideal electrode layout.

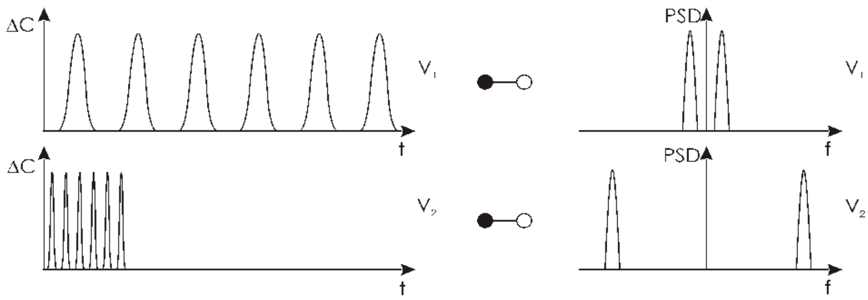

Fig. 6. Basic principle of velocity determination by means of spatial filtering. The quasi-periodic time signal (left) is transformed into the frequency domain (right) and evaluated.

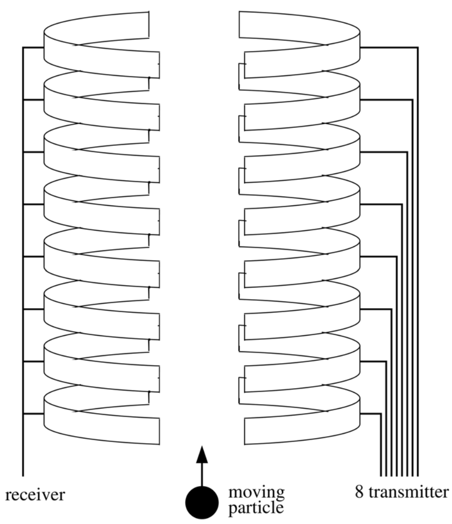

Fig. 7. Schematic electrode layout for measuring particle velocity.

An electrode structure like the one presented in Fig. 7 does not feature constant sensitivity over the whole pipe cross-section. There are areas of higher sensitivity (close to the gap between transmitter and receiver electrodes) and lower sensitivity (e.g. at the pipe center or close to the electrode centers). To test the setup and to allow for reproducible measurement results, a motor-driven setup is used to move a wooden sphere with a diameter of 23 mm on a thin nylon line through the electrode array. The velocity of the moving sphere can be varied by changing the motor rotation speed.

Measurement results acquired with the rapid prototyping system are shown in Fig. 8. In this experiment, the sphere was moved through the sensitive volume with lower velocity first and then with approximately double speed. To evaluate the functionality of the capacitive flow sensor principle for granular material flow, the sensor was tested at a laboratory conveying rig. In this setup monodisperse plastic pellets are conveyed using airflow in a closed pipe produced by a fan. A throttle flap allows for the adjustment of the conveyed air mass and hence of the number of conveyed particles. The transmitter and receiver electrodes are mounted on the outer surface of a pipe with a diameter of 75 mm. Fig. 9 shows, that the sensor setup is able to track even single particles with a size of 4 mm and a permittivity ε_r of about 3. The sequence of 0.2 s is recorded with a sample rate of 16 kHz. At time steps 0.12 s and at 0.22 s two passing particles cause four periods in the output signal of the spatial filter.

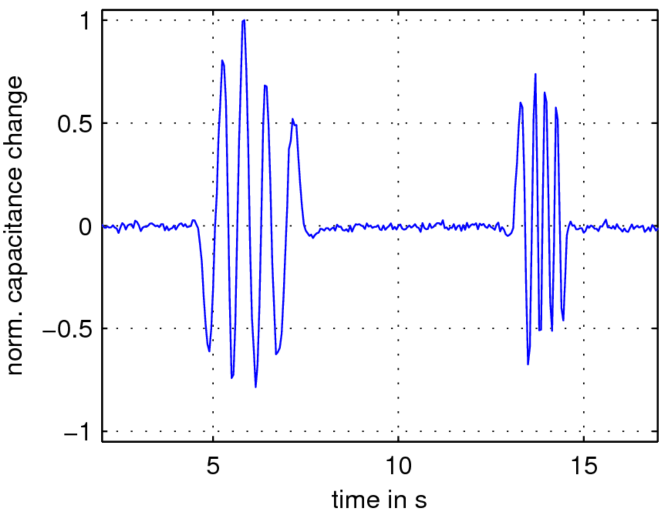

Fig. 8. Measured capacitance variation over time. The particle velocity in the first burst is approximately two times lower than in the second burst.

To estimate the particle velocity frequency estimation, based on a Fourier Frequency Analysis, is applied. Fig. 10 shows the estimated frequency for three different throttle flap positions. The lower spectral power for slow particles results from a lower number of conveyed particles within the measurement time window and therefore an inferior measurement signal energy. For the measured results in Fig. 9 and 10 a differential excitation of electrodes has been used, i.e. transmitter electrodes are subsequently excited with alternating polarity [11].

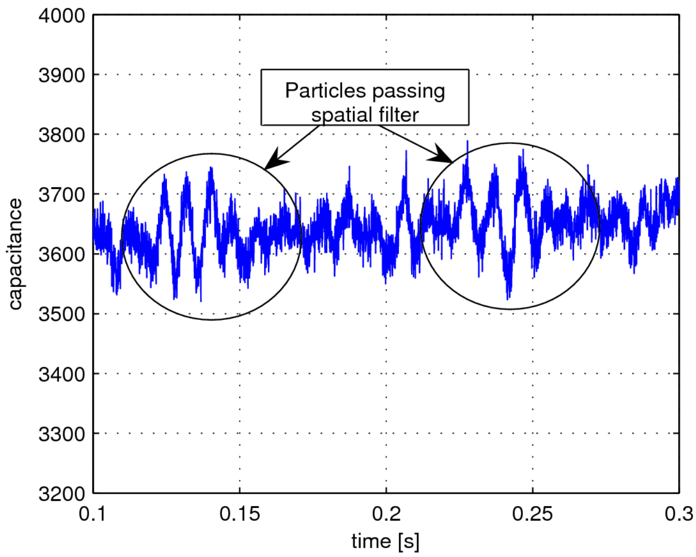

Fig. 9. Measured capacitance as a function of time for differential electrode excitation. Two particles passed the electrode setup at 0.12 s and at 0.22 s.

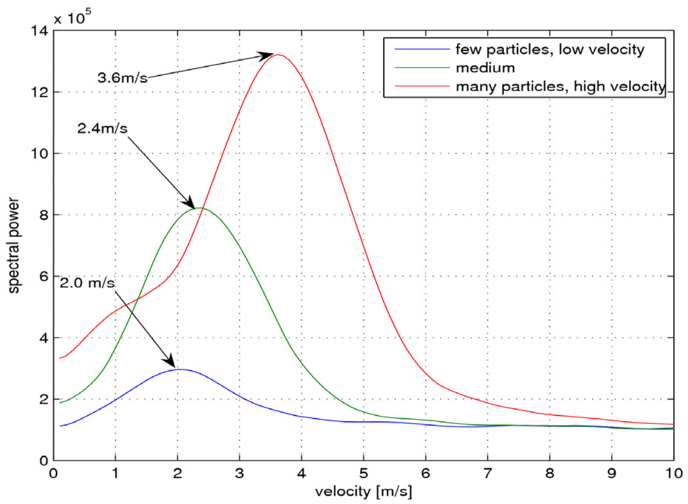

Fig. 10. Frequency estimation for three different throttle flap positions showing a peak frequency shift. The lower spectral power for slow particles results from a lower number of conveyed particles within the measurement time window.

3.3 Detection of Line Hits for In/Out of Bound Detection

As defined in the tennis rules a ball is “in bound”, if it hits the line. Similar rules can also be found for badminton or volleyball and referees decisions are sometimes subject of discussion. The task of the proposed sensor application is to detect, in case of doubt, whether a tennis ball has hit the line or not. Vision-based measurement methods are difficult to install, expensive and can hardly provide the required resolution in case of disagreements. For that purpose, the multi-layer capacitive sensor is aimed to be placed on top of the field border line. The capacitive sensor setup basically consists of a thin layer of flexible foam material covered by two measurement electrodes. In Fig. 11 the electrode arrangement can be seen. The measurement principle is based on a deformation or a force measurement respectively. If a ball hits the electrode assembly the flexible foam layer is compressed and therefore the distance between the two measurement electrodes decreases [12]. The reduced distance causes an increase of the capacitance, which can be evaluated by means of the rapid prototyping platform. Without any shielding the measurement electrodes would be directly exposed to the surrounding environment and therefore be sensitive to electrical fields and varying permittivity distributions in the vicinity. To avoid these unintended cross–sensitivities and disturbances and to focus on force measurement, a shielding layer on top and on bottom of the sensor is provided.

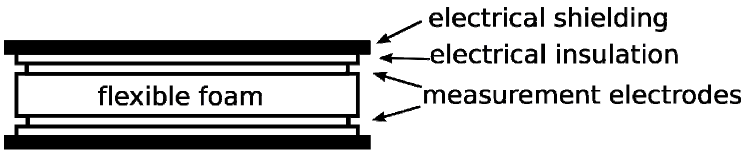

Fig. 11. Schematic view of the sensor geometry. A layer of flexible foam is covered by the measurement electrodes. Disturbances are avoided through a surrounding electrical shield.

For practical experiments the sensor front-end was mounted on a board of wood and the impact of a tennis ball hitting the sensor surface under various angles was investigated. Fig. 12 shows a sample sequence of a tennis ball bouncing at the sensor surface. The ball was released in a high of 30 cm above the horizontal sensor surface, which results in an impact velocity v_i of approx. 2.6 m/s. The plot shows that the ball hits the sensor at 0.1 s and bounces four times. The amplitudes of the ball impact and the time intervals between two impacts both decrease since the bouncing of the ball is dampened by gravity. After the balls comes to idleness the mean value of the signal is higher than before the impact since the sensor then measures the weight of the ball. This experiment shows that the sensitivity of the setup is sufficient to even detect bouncing ball movements with low kinetic energy. To evaluate the behavior of the sensor under more realistic conditions the sensor surface was inclined relative to the trajectory of the tennis ball so that the ball hits the sensor under certain well defined angles. Fig. 13 shows two results of impacts with same ball speed, but with different impact angles. For both cases the I and Q channel of the complex signal are shown.

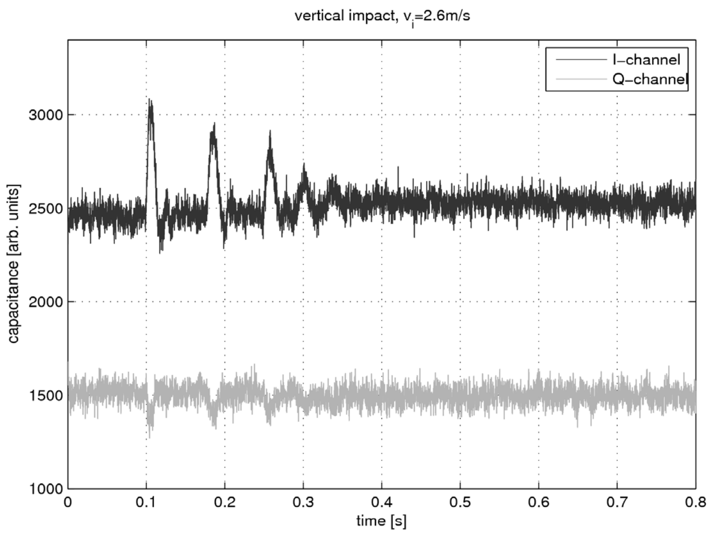

Fig. 12. Sample result of a bouncing ball on the sensor surface. The ball hits the sensor normally to the surface with a velocity of approx. 2.6 m/s and bounces until idleness.

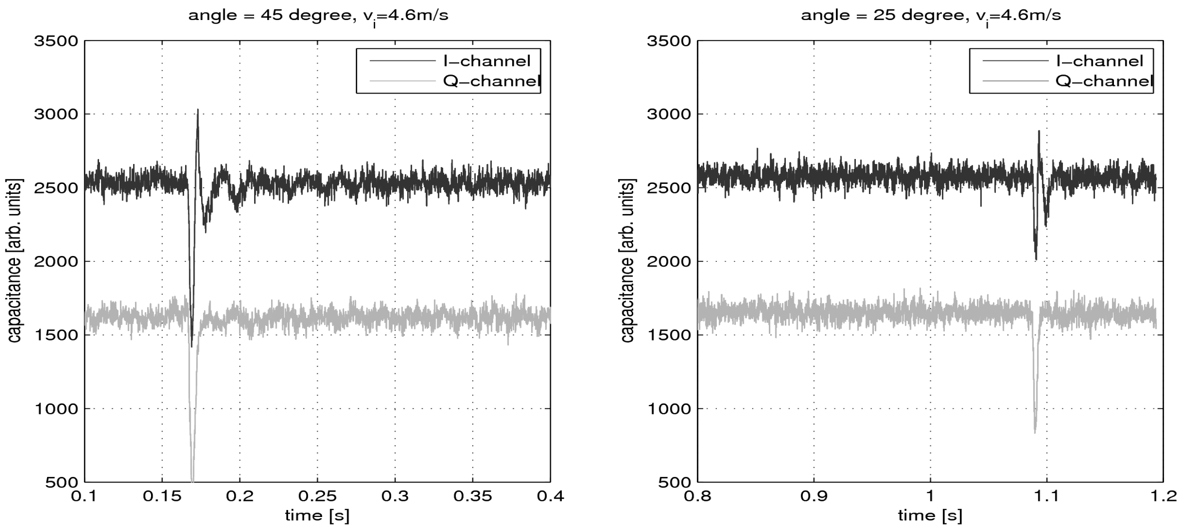

Fig. 13. Sample results of a ball hitting the surface under an angle of 45 degrees (left, time step 0.17 s) and 25 degrees (right, time step 1.08 s). The impact velocity is 4.6 m/s in both cases.

4 Conclusions

In this paper we present a versatile rapid prototyping platform for a wide range of capacitive applications to be found in modern sensing. The platform allows developers to reduce the design- and evaluation time for new capacitive measurement principles and new electrode topologies. It provides high data acquisition rates and a high computational power allowing for the implementation of sophisticated signal processing algorithms in stand-alone applications. The hardware is based on an Analog Devices Blackfin DSP in conjunction with a capacitance to digital converter ASIC. The DSP runs on an uCLinux operating system and therefore offers easy access to measurement data by 10/100 Mbit TCP/IP network interface, CAN bus or analogous outputs. Functionality and applicability for various capacitive sensor architectures is shown in three different sensor realizations, namely a liquid fill level-, a flow sensor, and tennis in/out of border detection. The experiments show, that although the number and dimensions of the electrodes differ in the three applications, the multi-purpose platform can be utilized without requiring any hardware adjustments.

Acknowledgments

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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