System construction based on a wire-mesh sensor for flow analysis

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Abstract. Wire-mesh sensor (WMS, mesh sensor) is a device for invasive imaging of vertical and horizontal flows of liquids and gases. Visualisation of the measurement results does not require any complicated software reconstruction. The device consists of two parts: the wire-mesh acquisition module and the wire-mesh sensor. The device allows for testing of multiphase flows as well as air bubbles in air-lift reactors. The sensors are also suitable for testing various types of surface flows and the movement of loose materials along the bottom of a pipeline. This paper describes the goals and results of construction of the system for flow analysis based on a wire-mesh sensor.

1. Concept of the device

Wire-mesh sensor (WMS) is a device used for invasive imaging of vertical and horizontal flows of liquids and gases [1,2]. It does not require complicated software reconstruction. That is the cause of a very high speed of operation, depending to the greatest extent on the conversion time of the analog-to-digital converter used. The device consists of two parts: the wire-mesh acquisition module and the wire-mesh sensor [2,3]. The device enables testing of multiphase flows and the classic testing of air bubbles, which are usually performed in air-lift reactors [4]. Due to their high time resolution the sensors are also suitable for testing various types of surface flows and movement of loose materials along the bottom of a pipeline [1,5-7]. The price of a very high performance is invasiveness, but research indicates the level of measurement uncertainty of these devices oscillating around 10\% [8].

Figure 1. Block diagram of WMS
There are several types of wire-mesh sensors that differ in terms of their mode of operation or design, among which the most important are:

- impedance WMS (also known as conductance WMS) - using the voltage measurement between the transmitting and measuring lines (such as the one described in this paper),
- capacitance WMS [1,3,9] - using the measurement of capacitance between transmitting and measuring lines, it enables measurements of non-conductive media,
- thermal [6] - using thermistors connecting transmitting and receiving lines,
- triple-plane - with an additional plane of receiving lines.

There are many tomographic techniques for the analysis of technological processes [10-22] and optimization algorithms [23-28]. The method of operation of the device (regardless of its design) comes down to transmitting signals on transmitting lines and measuring these signals on receiving lines. Transmission and measurements take place in a specific sequence - for each individually activated transmission line there are measurements on all receiving lines. After completing a single cycle of all excitations and the measurements assigned to them, the control system possesses numerical data about one image frame. It can present it immediately on the display, no reconstruction is required. A specific pixel color is assigned to a specific value of the tested quantity (voltage, capacity), as each pixel is in fact a point of intersection of one sending line with one receiving line. The speed of data acquisition of the wire-mesh sensor depends on the analog-to-digital converter used, the microprocessor system controlling the entire device, dynamic characteristics of switches, decoders and LCD screen, as well as the operating mode of the device. In the project described in this paper, the screen determines the speed the most, limiting it to the refresh rate by default. This gives a maximum result of approximately 30 700 measurements per second. The actual measuring speed of the device is much higher, and oscillates around 50 000 samples per second. It is possible to obtain it for offline imaging, that is for collection of measurement data and its subsequent visualization in a higher time resolution on a computer.

2. Wire-mesh acquisition module

Wire-mesh acquisition module consists of 3 parts enclosed in a hardened plastic case: control board with LCD display, transceiver module and a power supply. The last part is an ordinary circuit based on DC/DC 12V converter powered by external source and that’s why it is omitted in this paper.

The control system used in the project is a 32-bit STMicroelectronics STM32F746NG microcontroller placed on the 32F746GDISCOVERY development board.

It was built on the basis of the high-performance ARM Cortex M7 core, it is equipped with 1 MB of built-in flash memory, but also 128-Mbit Quad-SPI flash memory and 128 Mbit SDRAM memory organized in 4 banks. The development board is connected to a 4.3-inch TFT LCD display with a resolution of 480 x 272 pixels and the ability to display 262K colors. The screen uses the LTDC controller (LCD TFT Display Controller) and the mentioned RAM, thanks to which it is possible to obtain high data transfer speeds. The capacitive touch layer of the screen communicates with the microcontroller using the SPI protocol in full-duplex mode. Quad-SPI flash memory is used, among other things, to store a large amount of raster graphics for the needs of HMI (Human-Machine Interface).

The 32F746GDISCOVERY includes a number of multimedia elements: graphic Chrom-ART accelerator, hardware audio codec, built-in stereo speakers, 2 MEMS microphones, camera connector, line in and line out via minijack connectors. The board is equipped with microUSB communication interfaces operating in Full Speed and High Speed modes, a microSD card connector as well as a 10/100M Ethernet connector and controller. The integrated ST-LINK/V2 programmer allows you to quickly program the system without additional accessories, directly via the miniUSB port. The entire system can be powered by a microUSB socket or, as in the described case, by a pin connector from a 5V source.
Figure 2. 32F746GDISCOVERY development board. Front view

Figure 3. 32F746GDISCOVERY development board. Rear view

STMicroelectronics provides free software: TouchGFX Designer with a TouchGFX framework for creating graphical interfaces, STM32CubeMX for initial hardware configuration and STM32CubeIDE for firmware development, code debugging, its compilation and communication with the programmer. TouchGFX deserves special attention, allowing designers to create modern HMIs based mainly on tactile interactions, resembling interfaces known to consumer electronics devices (smartphones, heating controllers, washing machines, refrigerators). It is possible to display animations, scaled images, colored shapes, modal windows, use a number of controls, widgets, buttons or create one’s own. The simplest interactions between HMI elements and the relationship between their screens can be efficiently programmed using the interaction menu in the TouchGFX Designer. More advanced functions, such as the interaction of the HMI with the hardware, require writing one’s own code. The TouchGFX framework, due to its capabilities, allows to create a modern HMI in line with the existing corporate identity rules.

3. Wire-mesh sensor
The wire-mesh sensor is made of 0.08 mm thick non-insulated, gold-plated molybdenum wires stretched on a dielectric frame. The 32 parallel transmission lines are located perpendicularly to the 32 parallel
receiving lines and create two planes separated by a 2.5 mm spacing. In the event of the tested medium’s absence, they are not physically or electrically connected with each other. The lines on each plane are 2.7 mm apart. The points of intersection of the transmit and receive lines correspond to the pixels of the received image. The impedance level at these points is represented on the screen of the control board using the appropriate color. Due to its physicochemical properties, molybdenum does not combine with tin. Thus a multiple braiding of each line was applied around six mounting holes, three on each side. The wire is metallic bonded, braided and trapped inside the tin. The strength tests performed show that the wires do not slip out of the holes when using this solution. Even with high stresses breaking the wire, it remains trapped at the mounting points.

Figure 4. Transmitting and receiving lines

Figure 5. Wire-mesh sensor
Figure 6. Wire-mesh sensor. Mounting points of receiving lines

4. Prototyping stage
Design works carried out in Netrix S.A. Research and Development Centre aimed to create a full-size 32 x 32 lines device, that is of size unprecedented in the literature. This posed new challenges for the designer, related mainly to the speed of acquisition and the method of visualisation of its results. Additionally, due to the large number of transmitting and receiving channels, the transceiver module was designed on a four-layer laminate. The top and bottom layers are used to guide the signals. The two middle ones are digital ground and power lines. The works carried out so far consisted of developing three versions of the wire-mesh sensor and two prototypes of the transceiver module along with programming the control board. The last one is currently in the firmware optimisation and research phase.

The first version of the wire-mesh sensor, the so-called concept one, was created to confirm the theoretical assumptions of the project and consisted of a matrix of 4 x 4 lines connected to the Arduino Mega development board. It was a circuit containing amplifiers and two analog switches on the same PCB. It did not require a separate data acquisition module to operate. The second version was a full-size 32 x 32 line prototype with 40-pin IDC connectors. The third version received DVI-I connectors, a solder mask and was adapted for installation between pipes with a diameter of 100 mm.

The first prototype of a separate data acquisition module was used to develop the embedded software of the ARM STM32 system controlling the WMS sensor. It was also intended to show preliminary estimates of the quality and speed of operation of the entire device. It has not been tested with the wire-mesh sensor. The second prototype included significant structural improvements, which include:

- replacement of analog-to-digital converters with faster ones,
- adding passive protection against interferences in the wire-mesh sensor,
- redesign of the supply lines to facilitate the analysis of assembly problems,
- redesign of the excitation signal line,
- adding a buffer on the binary control lines of decoders to increase compatibility with different levels of logic signal voltages,
- adding a second buffer on digital data transmission lines in order to improve the transmission quality and increase compatibility with various voltage levels of logic signals,
- redesign of instrumentation amplifier circuits in the receiving part,
- reduction of the number of sockets for communication with the control device,
- moving all sockets to the upper part of the board
- placing full descriptions on the PCB descriptive layer,
- any design changes to achieve the above-mentioned (addition of additional filters, voltage stabiliser, etc.).

The first, conceptual version of the wire-mesh acquisition module, like the second, was devoid of the housing and a number of related solutions. In the third one, it was decided to design additional stiffening adapters and place all the electronics in a Peli Case. As a result, the support for a larger screen was implemented, a completely new HMI was designed using the TouchGFX technology, data storage on a microSD card and USB interface support were implemented. The whole is powered by an external
stabilised power supply connected to a DC socket. The front panel of the device has been designed and made by laser engraving and cutting. It is equipped with a blue illuminated bistable switch made of stainless steel.

The wire-mesh sensor in the third version, adapted for assembly, was placed between two pipes made of transparent plexiglass. The lower tube is closed at the bottom with a terminator that has a compressed air valve attached to it. It enables the study of gas propagation in the case of full immersion of the wire-mesh sensor in the tested medium (water, oil, etc.). In the case of incomplete immersion, one can observe the level of filling or the location of point overflows (streams of fluid passing through the sensor).

![Image of the device](image.png)

**Figure 7.** The third WMS prototype in a case

5. Conclusions
The presented set of the most important components has already been tested in previous Netrix S.A. research and development projects on process tomography. It was verified as reliable, easy to implement and later use. After the work on the embedded firmware is completed the device will be able to record the measurement results at high speed for later analysis and off-line image analysis. With the use of a microcontroller based on ARM STM32F7 architecture and AD7490 analog-to-digital converter, the estimated theoretical off-line imaging speed is greater than 97 frames per second at single sampling scenario. Every such frame consists of 1024 separate measurements. In fact the numbers are significantly lower due to the need to save or transfer the results and process visualisation on the screen. The maximum speed will be possible to obtain in time-limited measurements (until the buffer is full), possibly performed cyclically. This issue is one of the subjects of future research.

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