A methodological review of Velostat-based tactile sensor arrays

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***Abstract*—Velostat, originally developed as a packaging material, has gained widespread use in the creation of tactile sensor arrays due to its piezoresistive properties. This methodological review aims to thoroughly examine a tactile sensor array system, analyzing each component and identifying potential areas for improvement or future research. Additionally, this review seeks to propose hardware requirements for a versatile and high-performing data acquisition framework.**

I. Introduction

Tactile sensors measure physical interaction through touch, applied pressure or temperature changes. These sensors often take the form of arrays, which provide a three-dimensional map of the interaction being measured. This map can be used in numerous applications, such as the following examples:

- sleep monitoring (e.g., [1]);
- posture monitoring (e.g., [2], [3]);
- floor-based foot pressure measuring (e.g., [4]);
- shoe insole pressure measuring (e.g., [5], [6]);
- interactive sensing floors (e.g., [7]);
- MIDI-controllers (e.g., [8]).

While such arrays are usually expensive, patented, or vendor-dependent, there has been a significant amount of research dedicated to finding alternatives. One such alternative is Velostat, a composite polymer consisting of carbon-impregnated polyethylene that exhibits stimuli-dependent electrical conductivity. Other solutions have also been discussed, for instance, a matrix of strain gauges (often used for shoe insoles) or fabric treated with a conductive polymer [9]. However, both of these solutions are complex and result in a low-resolution measurement.

Master's thesis to obtain the diploma Master of Science in: Electronics and ICT Engineering Technology. Academic year 2022-2023.

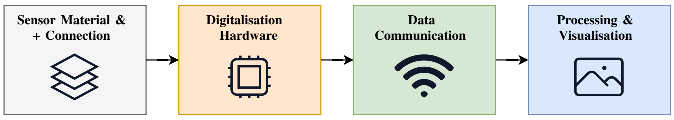


Fig. 1. Schematic overview of a tactile sensor array system

This methodological review focuses on the ways Velostat can be used as a tactile sensor array. In other words, this review will compare different methods for retrieving tactile information from the material, processing the data and visualising the tactile points accordingly.

The long-term goal of our research is to develop a tactile sensor array test bench for Velostat. In this methodological review, we present the first step towards this goal. Furthermore, we aim to answer the following research questions:

1) What are the possibilities to improve the tactile resolution while keeping the number of probes low?
2) What are some feasible requirements for a versatile and performant data acquisition framework?

II. Methodology

We reviewed a large number of potential papers in order to gather a comprehensive understanding of the tactile sensory array field. While our research is primarily focused on Velostat, we also included papers that did not use this material due to their distinct research outcomes or unique approaches. Considering a diverse range of research approaches allowed us to gather a more holistic view of the field and helped us to develop a more nuanced understanding of the various approaches and techniques for tactile sensor array systems.

III. Findings and discussion

In this section, we will do a methodological review of each system's module to present our findings and discuss them. We will state potential improvements and endeavour to answer our research questions. The tactile sensor array system and its modules are shown in Figure 1.

A. *Sensor Material and Connection*

The Velostat (sometimes referred to as Linqstat) material consists of a polymeric foil (polyolefins) impregnated with carbon black. In other words, this makes the material electrically conductive and can consequently be used as a packaging material to protect electronics from electrostatic discharge. According to the original trademark filing by the manufacturer, Custom Materials, this material has no known applications beyond this use [10]. In addition to its conductive characteristics, Velostat belongs to the group of piezoresistive materials, meaning that its resistance changes in response to pressure and latent heat. As a result, Velostat is frequently used to create sensors.

Since creating a sensor from Velostat was not intended by the manufacturer, the available information in the provided datasheet is scarce. As a result, extensive research has been done by Dzedzickis et al. [11] characterising Velostat and improving our understanding of this material. During their research, the following characteristics were evaluated; sensitivity, hysteresis, mechanical compression, response time and transverse resolution. In brief, their research has been valuable for the understanding of Velostat.

In order to measure the resistance, and thus the pressure, probes need to be connected to the material. This can be done in various ways, but the most common way is to create a matrix that divides the Velostat into multiple sensors. As a result, the size of a single sensor will define the tactile resolution. The microcontroller will scan every single sensor one by one and can be compared, due to the Velostat's piezoresistive characteristics, to the reading of a variable resistor. During the scanning sequence, the current will be converted to an appropriate voltage, this is usually done in 2 ways: a voltage divider or an operational amplifier circuit.

The voltage divider is often used because of its simplicity, Ramirez et al. stated they specifically opted for the voltage divider to keep the circuitry simple [12]. The greatest disadvantage of this method is the non-linearity. On the other hand, an operational amplifier is more complex but has the benefit of being linear.

A different method, by Yang Zhang et al. [13], works by inserting a small AC current between a pair of adjacent electrodes and creating an electric field. This process repeats for all combinations of current-projecting and voltage-measuring pairs, resulting in a mesh of cross-sectional measurements. This method only works for a grounded object, such as a user's finger, thus shunting some current to ground.[1] Despite being able to locate a grounded object, measuring the pressure has not been tested yet. The largest advantage of using the *adjacent electrodes* method, is the fact that the resolution is not bound to the number of electrodes per area. Therefore, the tactile resolution could be improved in other ways compared to the matrix-based method.

A variation on the prior method by Yang Zhang, researched by Youzhi Zhang et al. [14], works by alternately constructing two uniform electric fields with orthogonal directions in the piezoresistive film. By measuring the change in boundary potential between the two uniform electric fields, it is possible to accurately determine the location of the contact region in the piezoresistive film. The results of the experiment demonstrate that the sensor can effectively detect the position of contact in real time and has some ability to classify the magnitude of the contact force.[1]

A complete overview of the most common ways to connect electrodes to the Velostat is shown in Table I.

B. Digitalisation hardware

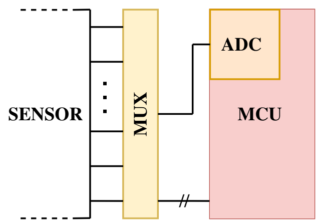


Fig. 2. Schematic overview of the digitalisation hardware

In this section, we will be looking at the digitalisation system. A schematic overview can be found in Figure 2. The Analog to Digital converter is the most important part of this system, it converts our analogue sensor signal into a digital representation. There are two main types of ADCs: internal and external.

Internal ADCs are often integrated into a microcontroller unit (MCU) and are typically lower cost and consume less power, but may not have as high a resolution or accuracy as external ADCs. As a result, the choice of MCU will ultimately dictate the characteristics of the ADC.

External ADCs, on the other hand, are standalone devices that are connected through a communication interface, such as I2C or SPI. These ADCs are generally more accurate and have a higher resolution than internal ADCs, but are typically more expensive and require extensive knowledge to make use of their full potential. [18]

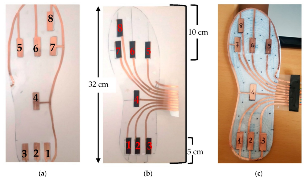
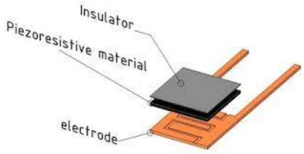
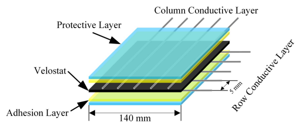
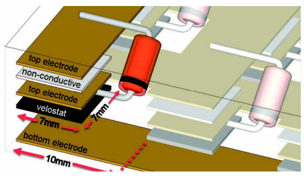
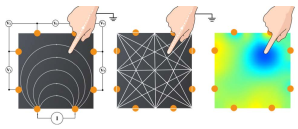
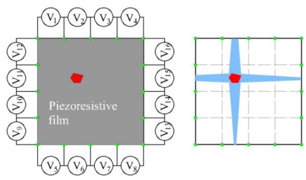
In general, researchers use the internal ADC of the MCU, since it is sufficient and easy to implement. Niconiconi [19] has made a list of microcontrollers with fast ADCs, shown in Table II.

Some researchers have utilized Atmel ATmega328-based evaluation boards, such as the Arduino and Lilypad, for their experiments. It has been observed that the ADC in these boards is faster than what is stated in the datasheet, as reported by Open Music Labs [20]. Despite this advantage, the connectivity of these boards can be a limiting factor. As an alternative, Espressif's ESP32 line of microcontroller units has gained popularity due to their low price. Upon further investigation, it has been found that many users have expressed concerns about the accuracy of these ADCs [21], and to date, these issues have not been adequately addressed.

The choice of MCU, and subsequently the ADC it employs, ultimately depends on the preferences and expertise of the researcher. A review of the options presented in Table II reveals that most of the available choices are sufficient and offer a comprehensive set of features.

[1]Explanation originates from their work

TABLE I
MOST COMMON WAYS TO CONNECT ELECTRODES TO THE VELOSTAT

Style	Description	Ref.	Figure
Velostat sandwich	The Velostat sandwich is composed of two copper layers with Velostat material sandwiched in between. When multiple of these sandwiches are created, they form an array of sensors. The figure illustrates an example of this, where eight Velostat sandwich structures are placed between two layers of PVC.	[5]	
Interdigital transducer	The Interdigital transducer consists of a bottom layer containing two isolated copper electrodes that measure the current passing through the Velostat material. An insulation layer is included in the sensor design to protect the Velostat from any unwanted conductivity. When multiple of these transducers are underneath a single sheet of Velostat, they form an array of sensors.	[15]	
Linear Matrix	The Linear Matrix sensor is composed of a layer of conductive rows and a layer of conductive columns, with Velostat material positioned in between. Each individual sensor formed by the intersecting rows and columns is addressable, allowing for the creation of an array of sensors through programmatic control.	[16]	
Cross-talk avoidance Linear Matrix	This Cross-talk avoidance method is an adaptation of the Linear Matrix design, incorporating a measure to mitigate cross-talk. This is achieved by inserting a diode between the intersection point of a row and column and the connection point of the Velostat material. The figure depicts an example of this design, where a double-layer PCB is used to connect the diode.	[17]	
Adjacent Electrodes	The Adjacent Electrodes method involves the use of electrodes placed on the sides of the Velostat material. This method operates by applying a small AC current between a pair of adjacent electrodes, which creates an electric field within the Velostat. The voltage difference is subsequently measured at all other adjacent electrode pairs, allowing for the detection of changes in the electric field due to touch.	[13]	
Uniform Electric Fields	The uniform electric field method involves the use of electrodes placed on the sides of the Velostat material. This technique involves the creation of two uniform electric fields with orthogonal directions within the piezoresistive film. Changes in the local conductivity of the film caused by touch can be projected to the boundary, enabling the determination of the location.	[14]	

Depending on the sensor connection method, a multiplexer (MUX) is needed as the number of probes exceeds the analogue inputs. A MUX is a device that selects between several input signals and forwards the selected input to a single output line and is typically controlled by a set of digital inputs. When choosing a MUX, it is important to consider the number of inputs and outputs required, the data rate, the switching speed, the voltage and current ratings, and the cost. There are many different MUX options available on the market, with varying characteristics and features. For example, the ADG706 [22] and the ADG732 [23] are 16 and 32-channel MUXes, respectively, with fast switching speeds.

C. Communication

In general, there are two types of communication; wireless and wired. During our search for other work, the communication methods mostly were 2.4GHz based (e.g. transceiver [6], Bluetooth [13], Wi-Fi [24]) and wired (e.g. ethernet [7], USB [25]).

The type of data being transmitted can significantly impact the choice of communication method. Raw sensor data, for example, will require higher data rates to be transmitted effectively. In cases where data processing is performed on the microcontroller itself, the data rate may be lower due to the added processing time.

Serial communication methods, such as UART, are generally insufficient for transmitting raw sensor data. However,

TABLE II

A LIST TO COMPARE MICROCONTROLLERS WITH FAST ADCS BASED ON SAMPLE RATE, RESOLUTION, CONNECTIVITY AND THE AVAILABILITY OF AN EVALUATION BOARD. ADAPTED FROM [19].

MCU	**CPU**	**Sample rate, Resolution**	**Sufficient Connectivity**	**Eval. board**	**Comments**
NXP LPC4370	1 Cortex-M4 + 2 Cortex-M0	80 Msps, 12-bit	✓	✓	LPC-Link2 can be used as an LPC4370 evaluation board.
TI TMS320F2823x	TMS320C28x	12.5 Msps, 12-bit	✗	✗	Mostly used for production devices.
ST STM32H7	Cortex-M7 + Cortex-M4	7.2 Msps, 16-bit (2x interleaving)	✓	✓	Arduino Portenta H7 has WiFi + Bluetooth.
ST STM32F303	Cortex M4	18 Msps, 12-bit (4x interleaving)	✓	✓	Very popular STM32F3DISCOVERY evaluation board.
MCHP PIC32MK	MIPS32	15 Msps, 12-bit (4x interleaving)	✓	●	Complicated ADC subsystem, many modes and channels. Expensive evaluation board.
AD ADSP-CM4xx	Cortex M4	5.26 Msps, 16-bit (2x interleaving)	●	✓	No full-speed USB.

✓ means adequate, ● means mediocre, ✗ means undesirable

the inclusion of full-speed USB implementation in most microcontrollers allows the transmission of higher data rates.

For wireless communication, the use of a radio module may be necessary, such as those from Murata. These modules can be integrated into evaluation boards and utilize Serial Peripheral Interface (SPI) for communication [26].

Because our goal is to create a high-performance testing framework, it may be desirable to implement a hybrid communication solution that allows for both wired and wireless connections with a constrained data rate.

D. Data Processing and Visualisation

Data processing is a crucial component in the operation of sensors. Various methods can be employed to improve the output of the sensor. A common approach is to first calibrate the sensor using a reference location and pressure, and then apply a smoothing filter to remove noise from the data. However, some studies use advanced techniques, ranging from matrix operations to extensive machine-learning models.

Cross-talk removal has been studied thoroughly by Medrano-Sánchez et al. [27] and concluded that several algorithms can recover the true value of the array. Their algorithm can be easily tuned to find a compromise between error and computation time.

Often the resolution from sensor arrays is limited. Jesus et al. [28] have used a resolution enhancement method to enhance the resolution. This method was originally researched by Pradeep Gaidhan [29] and aims to generate a higher-resolution image from multiple lower-resolution images and can also be applied to improve the resolution of sensor arrays.

The research conducted by Mutlu et al. [2] focused on the use of machine learning techniques for the classification of sitting posture. The authors demonstrated that their system was able to accurately detect subtle differences in the posture with a high degree of accuracy. Their work highlights the potential of machine learning for sensor array systems.

Most of the studies make use of a single program to do the processing and the visualisation, such as Labview [6], [12] or Matlab [30]. Gala et al. [24] used a web interface based on PHP and MySQL to visualise the data, making it usable from a different (mobile) device. We would like to improve the web interface to make it a cross-platform application so that it can be used by anyone, without prior technical knowledge, on any device. The framework Electron [31] would allow the visualisation application to work on multiple operating systems, without having multiple codebases. Similarly, Capacitor [32] would be able to achieve the same thing, but for mobile platforms.

IV. IMPLICATIONS AND CONCLUSIONS

In this methodological review, we presented every component needed to make a Velostat-based tactile sensor array. Research around the sensor connection is solid but would benefit from deeper analysis around adjacent electrodes since it has not been used frequently before. Our findings around the digitalisation hardware seem promising and with the current advances in embedded computing power, there might be a possibility to run all the signal processing on the device and thus only use the connected device to visualise the data. But no conclusion can be taken before conducting more thorough testing of the current algorithms.

The methodological conclusions of this review are twofold: on the one hand, no clear option to improve the tactile resolution is available yet, and more research needs to be conducted. On the other hand, creating a versatile and performant testbench is possible, but data processing might be the area where trade-offs will be made to create the system real-time. These findings highlight the ongoing challenges and potential solutions for advancing tactile sensing technology.

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