Flexible Pressure Mapping Platform for Mobility Monitoring Applications

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Abstract: The goal of the work presented here is the development, integration and testing of an innovative technological approach to be the basis for a new product and service for markets associated with the "Health" vector. Our research focuses on a Physiological computing approach, where a polymeric flexible detection system, working as the sensing element is used as an input channel, and a computing system is responsible for the physiological signals synthesis. The proposed solution provides a simpler, lower cost and larger scale manufacturing production of polymer based sensors, along with an electronic interface and the software design. The sensing platform consists in a flexible PCB (Printed Circuit Boards) manufactured using conventional technology (defining the electrical connections and the capacitors dimensions) together with two flexible polymeric membranes (TPU) printed with conductive ink (Plexcore®) for definition of the electrodes. A Capacitance to Digital Converter (CDC) is used to measure the capacitance of the sensors, and a graphical interface in MATLAB allows real-time visualization of data. Current results performed on the pressure sensors indicate the feasibility of the approach.

1 INTRODUCTION

Nowadays, humans are highly dependent on the use of computers and therefore, they become highly commonplace in work and leisure areas. The availability of good information processing capabilities and sensors is pushing for new applications relating physical monitoring. For this reason, the interest on Flexible Pressure Mapping Systems (FPMS) for use on non-planar surfaces grew tremendously (Engel J et al., 2006) (Kim & Ho, 1998) in areas such as aerospace, automotive, biomedical and robotics (Chiang, K. Lin, & Ju, 2007) (Cheng, Lin, & Yang, 2010) (Petriu, McMath, Yeung, & Trif, 1992) (Pritchard, Mahfouz, Evans, Eliza, & Haider, 2008) (Yeung, Petriu, McMath, & Petriu, 1994).

Flexible Pressure Sensors (FPS) are transducers that measure pressure distribution between two contact surfaces, with the particularity of being flexible. These sensors consist in a set of array of sensors elements to force or pressure that are embedded in a substrate. The force or pressure sensors are connected to electronic devices responsible for the signals reading sent by the sensors (several times per second) and communicates to the computer. Specialized software enables reading of data in real time providing an image in 2D or 3D graphics. Analysis tools acquire the pressure peak, the center of pressure or force, the output signal with respect to time and various statistical parameters, thus visualizing the magnitude and distribution of forces applied to the FPS.

Flexible polymer detection systems provide a better contact area and therefore more accurate readings thanks to its ability to fold/roll compared to traditional hard circuits. In medical applications a wide variety of configurations is needed and therefore it requires the pressure sensors to be flexible (bendable to a few degrees). Also, the sensitive area should be as small as possible. Depending on the spatial resolution required for the intended application, the diameter for the sensitive area of the sensor can range from 1 mm^2 to 1 cm^2 (Ashruf, 2002)). A high precision, reproducibility and selectivity are other essential requirements for the sensors. Flexible sensors have the capacity to follow all the movements, capacity to stretch to

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some degree (to measure correctly the applied forces) and have low thickness (thick sensors tend to provide erroneous readings (Ashruf, 2002)) which makes them ideal candidates.

The use of Physiological Computing systems in health care is necessary and presents significant advantages. For instance, FPMS offers the possibility of obtaining pressure readings measured in the contact surface, revealing information which is not readable to the naked eye. This technology is interesting since it enables reading, recording, processing and analysing the physiological physical states of the user and continuously monitor mobility, without the minimum disruption or loss of information. Data acquisition and display plays an important role in applications where for example, it is useful and advantageous to make an evaluation of a signal (measurement of pressure to prevent pressure ulcers in patients in wheelchairs or hospital beds) (Xsensor 2013).

In addition, an acquisition system can further contribute for health monitoring situations where is essential to follow patients during rehabilitation with the best action/prevention, diagnosis and treatment. This would also increase the autonomy of patients during rehabilitation, during the postoperative period; in medical facilities or in home environment, thereby reducing the length of hospital stay. The costs of surgery, treatment and rehabilitation are high, not to mention the collateral consequences at the social and psychological level. It is of clinical interest, as well as financial interest, to eliminate the gap between physiological data handling and human-computer interaction, to reach the most reliable diagnose for better action/prevention treatment, to increase the comfort of patients and eliminate some of the costs. Another element that deserves consideration is that these systems allow to perform intervention studies that assess the progress of treatment and rehabilitation, as well as the effectiveness of new treatments.

The objective of this study is to develop a physiological computing approach based on a flexible pressure mapping system for physiological sensing and software for Physiological data handling (see Figure 1). It will combine textile, polymers, electronics, and psychological studies to develop a support surface system able to acquire record and evaluate body pressure.

The importance of real time physiological data signal reading for prognostic for health monitoring devices is underlined in this paper. Experimental results on a prototype system are presented.

The paper is divided in six sections. After a brief introduction, the system overview, the details of the manufacturing process, the electronic interface, the software design and experimental results are presented. At the end, some conclusions are drawn.

2 SYSTEM DESCRIPION

The flexible pressure mapping system being developed has the form of a carpet with four equal sensitive areas as shown in Figure 2. The sensing zone is about 12x8 cm^2. The capacitive sensors (between 24 and 32 sensors) are placed in these regions. The capacitive readout electronics are placed next to the carpet. Each sensor element consists on a flexible Printed Circuit Board (PCB) for definition of the electrical connections and capacitor dielectric dimensions and two flexible membranes with printed electrodes. It is flexible and easy to handle. In addition, it will be integrated in complex atmospheres, allowing the monitoring of the balance during physical therapy sessions, indicating the regions of the foot that are exerting force.

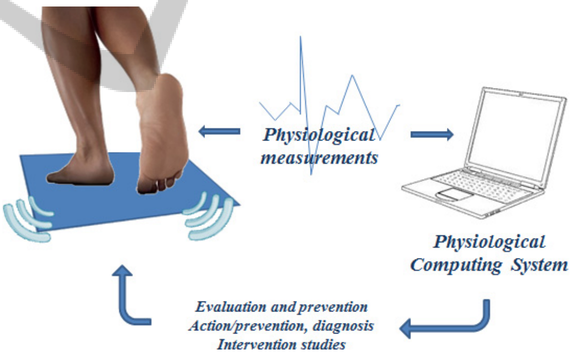

Figure 1: Block diagram of the physiological computing approach.

3 MANUFACTURING PROCESS

Three main steps are necessary to complete the proposed fabrication process: the fabrication of the flexible membranes with the conductive ink, the fabrication of the flexible PCB and an assembly step.

3.1 Flexible Membranes with Conductive Ink

TPU is a material that offers the elasticity of rubber, but with improved mechanical properties: good flexibility, strength and durability, excellent wear properties and elastic memory. Hence, polyester based Thermoplastic polyurethane (TPU), AVALON 65 AB grade, from Huntsman, was selected for the flexible substrate.

Due to their excellent properties (in terms of conductivity, inkjet printability and flexibility), conductive inks became an emerging technology, penetrating the sensors market and enabling new applications. Conductive inks are a growing market, representing a \$2.86 billion market in 2012 and forecasted to rise to \$3.36 billion in 2018 (Zervos, 2012). In this work, a conductive ink, *Plexcore®* OC RG-1100 grade (a Sulfonated polythiophene ink) from Sigma Aldrich was selected for the fabrication of the electrodes.

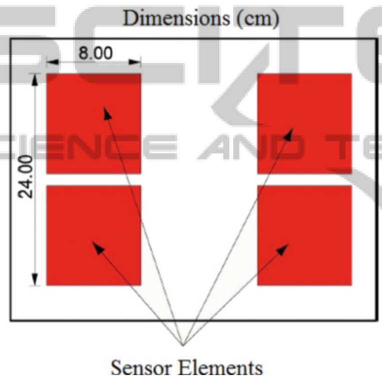

Figure 2: Sensorial platform scheme (the dimensions are in cm).

Printing of patterns with conductive inks on polymers surface enables the realization of "active polymeric materials". A high-definition printer (Xennia Carnelian) was used for printing and

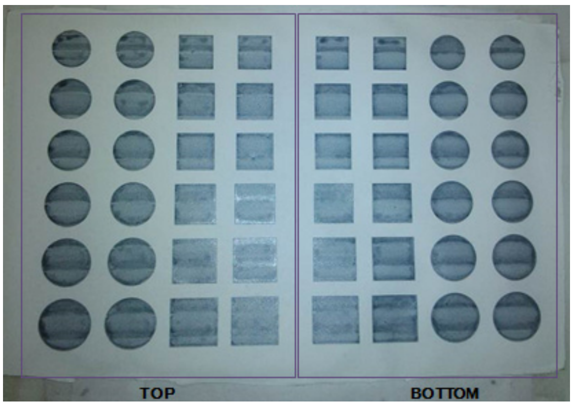

Figure 3: Inkjet printed flexible substrates (with conductive inks electrodes on a TPU substrate). The upper membrane is the mirror image of the lower membrane (Top on the rigth and bottom on the left).

definition of the electrodes of the capacitive sensors.

Inkjet Printing technology is a simple, low cost and large scale manufacturing production technique making it a very interesting approach due to both simplicity and cost of the solution. The conductive ink was printed in two TPU flexible membranes (see Figure 3); a substrate for the superior electrodes and another for the inferior electrodes.

3.2 Flexible PCB's

The flexible pressure sensors results from the combination of flexible PCB technology and flexible membranes with conductive inks. The flexible PCB's consists in a flexible substrate of polyimide (PI), 125 µm thick with copper on both sides (35 µm). The copper is subsequently machined to define the conductive lines, and then the substrate is open in certain regions to define the dielectric (air) of the capacitor. The platform has 24 capacitive pressure sensors. Multiple geometries were draw with increasing electrode size in the initial prototype.

This approach allows testing the several configurations, and selecting later the one that best suits the application. Figure 4, shows an image of the flexible PI substrate and respective conductive lines.

The sizes were selected to have a rest capacitance between 5-10 pF (5 pF for the smaller dimensions and 10 pF for the larger). The sensors are expected to have high sensitivity due to the low Young Modulus (as compared to silicon based pressure sensors) of the TPU. No mechanical reliability issues are expected since TPU has excellent mechanical properties.

Since the readout electronics requires an excitation AC signal, all the capacitors are connected to the bus excitation. Figure 4 (bottom side) shows the bottom of the flexible substrate. In

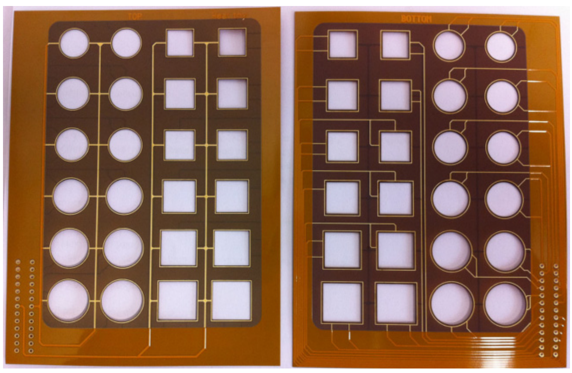

Figure 4: The top side (on the left) and bottom side (on the right) of the flexible polyimide substrate and the respective dielectric areas. The PCB size is 124 x 95 mm^2.

this case, the capacitors have an independent link which will be multiplexed for sequential reading of the capacitors. Noteworthy, is the ring around the dielectrics for electrical connection of the printed conductive electrodes. These rings enable the electrical connections to the capacitive electrodes.

3.3 Prototype Sensors Assembly

Finally, the flexible TPU flexible membranes were bonded with ELECOLIT 414 (a polyester-based, electrically conductive adhesive) in parts of the substrate to the flexible substrate of polyimide in order to manufacture the capacitive sensors (see Figure 5).

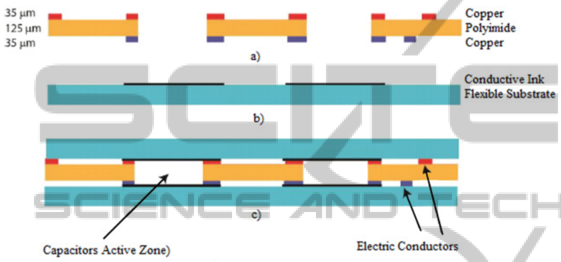

Figure 5: Sensor elements manufacturing process in which: a) the geometry of copper conductors and the capacitor dielectric are defined using a PCB flexible process; b) the electrodes of the capacitors are inkjet printed using conductive inks and c) the flexible substrates with electrodes are glued to the printed circuit board.

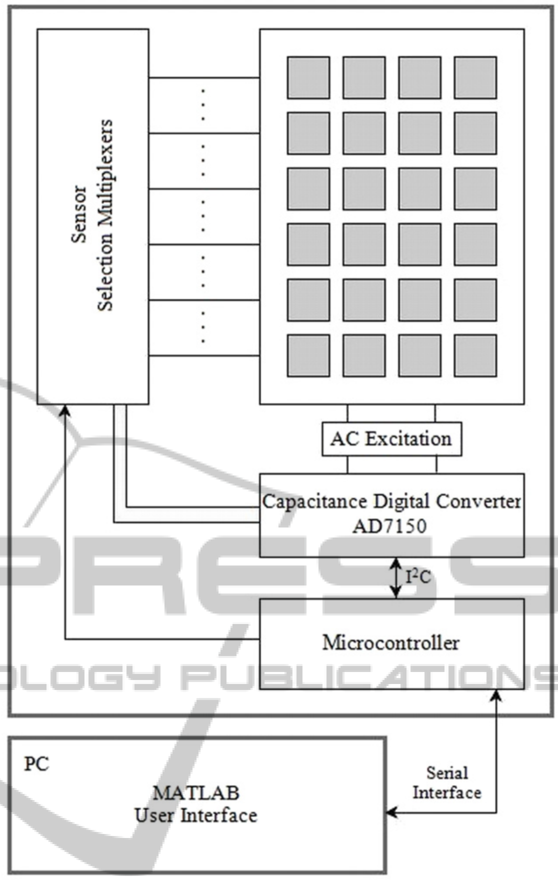

Figure 6: Capacitive sensors reading system block diagram.

4 ELECTRONICS INTERFACE

The reading circuit of the capacitive sensors has been designed considering the sensors and its manufacturing technology. Regarding the electronics, the capacitor sensor reading is performed using a 12-bit Capacitance to Digital Converter (CDC) AD7150 for each sensory zone allowing direct interface with the capacitive sensor. The converter consists of a second-order sigma-delta (Σ-Δ) modulator.

This low-power IC, 100 µA, has 2 input channels, with a conversion time of approximately 10 ms and 1fF resolution, for a dynamic range of 4 pF. The use of two multiplexers enables sequential reading of the 24 sensors comprising each sensory area with the two multiplexers connected to the two input channels of the converter. A microcontroller feeds and controls the multiplexers. When testing a particular sensor, the sensor is connected between the excitation bus and the modulator input of the CDC. The excitation signal is applied during the conversion and the modulator continuously acquires the load through the sensor. The digital filter processes the output of the modulator and the data can be read by the I^2C serial interface established with the microcontroller. The microcontroller allows the reading of the corresponding digital capacity value for each sensor, as well as configures the CDC. The CDC is connected to a computer, where the obtained values are recorded by a graphical interface implemented in MATLAB. This software provides real time readings and allows data manipulation.

5 SOFTWARE DESIGN

The software for data acquisition and display is implemented in the MATLAB graphical environment. At the current stage of this work, it is a very simple program providing:

- Serial communication with the microcontroller and setting of the converter parameters such as the

conversion mode, the converter sensitivity, the input dynamic range and others;
- Reading of the sensors capacity througth CDC;
- Real time values display, on a 2D graph, of the capacity variation as a function of the pressure for each of the sensors in each sensory area;
- Recording data on file for further detailed analysis.

The software allows testing all sensorial platform, however, at this time one sensory area of the prototype was tested, as depicted in figure 7 .

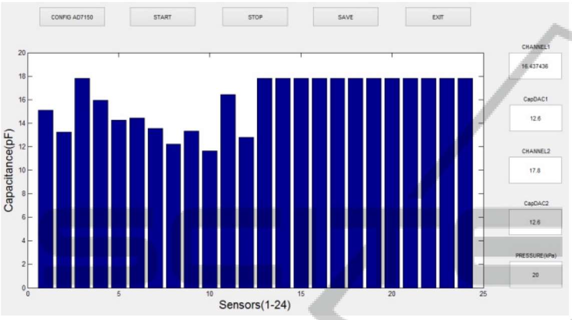

Figure 7: MATLAB graphical environment: Real-time prototype sensors acquisition.

6 EXPERIMENTAL PROTOTYPE

The assembled prototype (Figure 8) was placed together with the readout electronic PCB (Figure 9) inside a pressure chamber (Figure 10) and positive pressures were applied (ranging between 0kPa-100kPa). The pressure reading inside the pressure chamber was preformed through a reference pressure sensor (TECSIS P3297). Results are shown in Figure 11.

The assembled prototype sensor flexibility (bendable to a few degrees) is demonstrated in Figure 8. The sensing platform has the ability to bend, and it can be stretched to some degree (to measure correctly the forces applied).

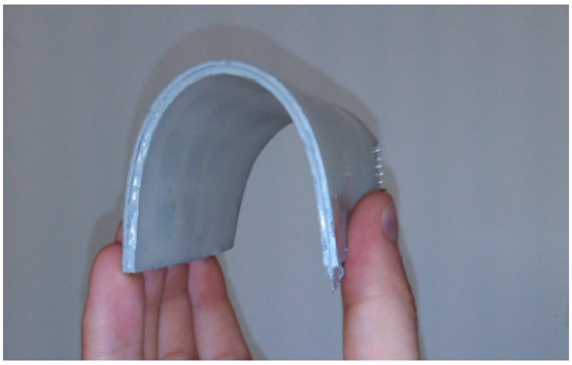

Figure 8: Assembled Prototype Sensors.

The sensors response to loads was also performed. The test consisted on placing weights on top of the sensors. For this purpose an acrylic plate with an area of 5.10 cm x 7 cm was used, as an interface surface between the load and the sensors, to ensure an equal distribution of the weight on all sensors. The capacity variation was measured for a weight range between 0Kg-19.2Kg. The sensor output was acquired at a sampling rate of 100 Hz and 1000 samples for each sensor. Several sensors were tested, and the average response of 5 sensors with circular geometry and different areas is present in Figure 12.

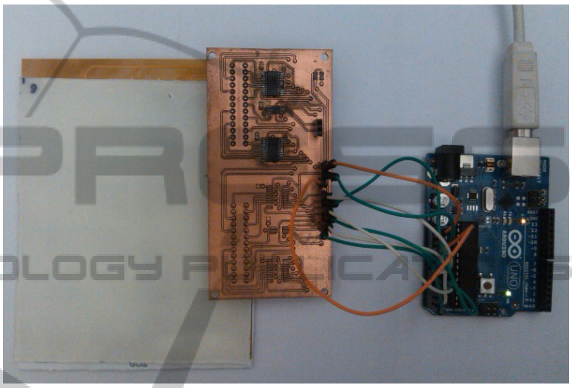

Figure 9: Assembly of the reading system.

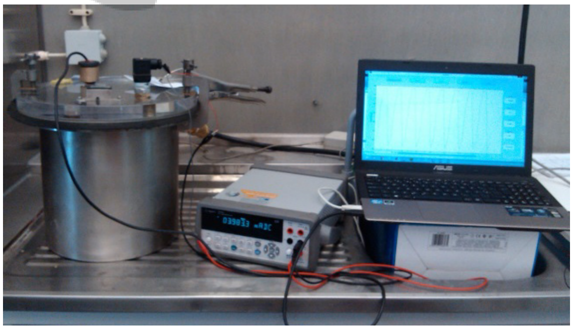

Figure 10: Capacitive sensor test setup.

7 RESULTS AND DISCUSSION

Figure 11 shows the static response of five sensors with circular geometry with diferent areas. The sensores capacity increases with the increasing pressure, however, contrary to what would be expected, higher sensor area (with 0.7 cm radius) had the lowest capacity variations (1.68pF) when compared to the smaller sensor areas (with 0.5 cm radius) with a capacity variation of 2.955pF. This unexpected behaviour is due to cross-coupling between the sensors, i.e., when one of the sensors is actuated, the surrounding sensors are also changing (with much less variation). Since the smaller sensors are the ones that have higher cross-coupling (these sensors are the ones with longer electrical connections and therefore with larger coupling capacitances to the neighbouring sensors), they end up showing a higher variation than the larger sensors. This same behaviour was observed on the loading tests (Figure 12) and this problem is already being addressed in a future redesign of the system (sensors plus electronics circuits).

Figure 12 depict the variation of sensor capacitation with load. It can be observed that the sensors capacitance increases with the load, but once again, the sensor with higher area didn't present more capacitance variations. The 0.7 cm radius sensor area showed the lowest capacity variation (1.88pF). The largest variation was seen on sensors whose area is between the maximum area and the minimum area, with the sensor electrodes radius - 0.65cm the range of higher capacity (3.015pF).

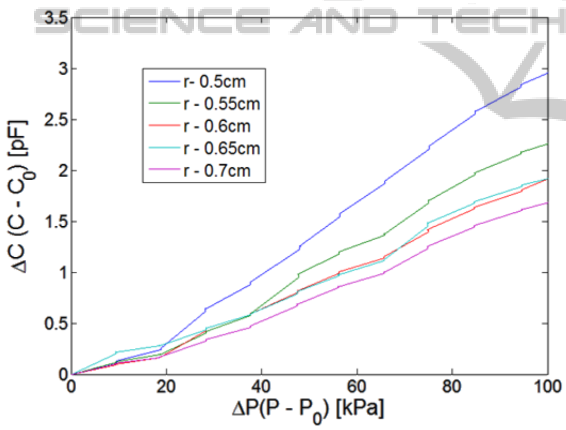

Figure 11: Pressure sensors static response.

Results for the rectangular sensors were not possible due to high parallel capacitances that increase the total sensor capacitance and the system is not capable of handling these high values (it saturates). The actual electronic readout and assembly process (glue used for contact) increases the parallel capacitance increasing all sensors in general, but, since rectangular sensors have larger areas, they show higher parallel capacity influence.

Regarding the system response time, tests results have demonstrated that the developed reading system is capable to follow the expected physical movements (average response time of 0.5 seconds) during therapy sessions. This acquisition time (0.5s) is insufficient for some type of exercises (especially if fast movements are involved), but for simple equilibrium exercises it might be sufficient. The acquisition time is expected to be improved in the next prototype.

The developed software has shown the ability to read, record, process and analyse the physiological physical states of the user and continuously monitor mobility, without the minimum disruption or loss of information. Overall, the measured response is in according to what would be expected (increasing pressure results in a capacitance increase).

This study had some limitations: at this phase, the capacitive results are higher than it was predict, which implies improvements in the electronic readout circuit in order to eliminate the parallel parasitic capacitance. In the next phase, the multiplexing strategy will be improved, in order to reduce the cross-coupling influence. The process control will be essential to achieve high reproducibility and desirable sensor specifications.

Nevertheless, pressure is not the most representative and the most appropriate for testing validation. In the future, the experimental testing will be performed with the sensor platform in contact with the human body and its performance will be compared to the existing pressure mapping platforms (Novel 2013)(PPS 2013) (Xsensor 2013).

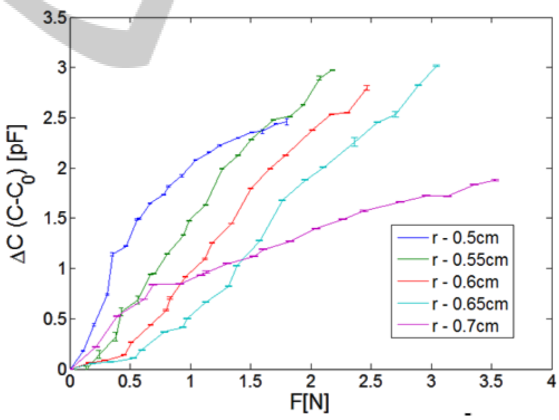

Figure 12: Sensor response to loads.

8 CONCLUSIONS

This article described the design, fabrication and experimental results of a flexible pressure mapping system and its readout electronics interface and software. Development of a better and efficient sensor, capable of being integrated into complex atmospheres, overcoming some of the difficulties found in Physical Rehabilitation, and able to measure balance during physical therapy is essential.

At this phase, the obtained results are very promising and encouraging. The solution presented here enables a high density of capacitive flexible sensors with a simple and inexpensive process. Nevertheless, there are some issues that must be improved in the next prototype.

These devices can help the ubiquitous management of the state of health of a patient, thus enabling a better performance/prevention, diagnosis and treatment. The developed sensors can help humans to benefit from the interactions between physiological data and computer. In the near future, with the development of science and technology, we will the development of new technologies with the ability to make the connection between humans and computers.

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