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Biomimetic artificial skin for robots: A review

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ABSTRACT

Electronics skin (e-skin) for robots nowadays employs a variety of powerful data processing, complicated electronics, smart materials and structures and transduction techniques. It helps robots in avoiding environmental hazards by providing multiple modalities of sensations similar to the human skin. But, the successful implementation of e-skin in robotics has so far been slow to develop despite being extremely valuable in itself. This article reviews the current e-skin designs and open research questions in the field, focusing on the efficient use of e-skin in robotic systems. The use of e-skin in robotics has a few unique characteristics. For example, unlike other robot senses, the e-skin must be distributed throughout the robot body, much like human skin does. This calls for a distributed and decentralized control and simultaneous processing of several tactile encounters. Because of these constraints, making tactile sensor modalities a reality is difficult. Dealing with concerns including sensor location, electronic/mechanical hardware, signal acquisition techniques, automated calibration procedures and algorithms to analyze and interpret real-time sensor data are necessary to meet these obstacles. Since the performance of a system often depends on how its parts are integrated, we explore this topic from a system viewpoint. Researchers developing robots with touch sensors and system designers are expected to benefit from the survey.

Keywords: Biomimetic, artificial skin, robot skin, tactile sensor, electronic skin

1. INTRODUCTION

Exponentially advancing technologies in the recent decade have revolutionized the field of robotics. Previously, robots were only operating in industrial environments and they were controlled by humans. However, contemporary robots, e.g., rehabilitation robots, assistive robots and medical robots are operating in human environments and are autonomous. They make decisions on their own. For example, during the COVID-19 pandemic, assistive autonomous medical robots like Mitra (Robo Doc: How India's robots are taking on Covid patient care | Global development | The Guardian) in India, Tommy (Tommy the robot nurse helps keep Italy doctors safe from coronavirus | Reuters) in Italy and many others in different countries have helped patients and doctors with the care of the patients through their autonomous decision ability. The shortage of medical staff around the globe and their fatality rate has shown us that these robots with more capabilities would have saved a lot of lives of both the patients and the healthcare workers because robots don't die from infectious diseases but we humans do.

Environmental models are necessary for robots to make decisions. But perfect environmental models are impossible in most cases and they need to adapt to uncertainties. Adaptation can be facilitated if sensing modalities are increased because the more data the robots will have, the better the environmental model they will be able to build. Tactile sensing is a significant one of the many sensing modalities because, to manipulate an object, the robot has to make contact with it. Using tactile sensing currently, available robots can differentiate between objects by differentiating their textures (Heyneman and Cutkosky, 2012; Kampmann and Kirchner, 2014; Lee et al., 2019; Sankar et al., 2021; Yamamoto et al., 2012), temperatures (Lee et al., 2019; Mittendorfer and Cheng, 2011a; Wade et al., 2017), rigidity (Wade et al., 2017) and many other parameters. It can determine details like contact location (Assaf, 2021; Cirillo et al., 2017; Kampmann and Kirchner, 2014; Kawasetsu et al., 2018; Lee et al., 2019, 2021; Liang et al., 2020; Mittendorfer and Cheng, 2011a; Parvizi-Fard et al., 2021; Sankar et al., 2021; Schmitz et al., 2011; Scibelli and Krans, 2016), slip (Heyneman and Cutkosky, 2012; Kampmann and Kirchner, 2014; Lee et al., 2019; Lin et al., 2021; Scibelli and Krans, 2016), shear (Scibelli and Krans, 2016), bending (Lin et al., 2021), sharpness (Parvizi-Fard et al., 2021) etc. For the robots of the future, this tactile information is necessary for the robots to operate safely and efficiently in a human environment.

However, seldom implementation of e-skin in current robotic systems (such as ATLAS (Atlas TM | Boston Dynamics), AMECA and ARMAR-6) shows that although a wide range of touch sensors is available, tactile sensing has not yet become an effective presence in robotics. The dispersed character of the e-skin and the numerous tactile variables that must be determined, all provide obstacles. Contrary to vision, the aforementioned characteristics make it challenging to develop cutting - edge technology for the perception of touch. Many elements, which substantially bolster the efficiency of the use of information related to touch, would be highlighted from a holistic perspective.

The following is the paper's structure: The field is reviewed in Section II concerning conformability, sensor dispersion, optimal sensor location, wire routing and other physical or mechanical concerns. Section III surveys research in the areas of communication, interface electronics, hardware for electrical and electronic systems and associated fields. Section IV discusses research questions pertaining to improved levels of perception, such as feature extraction, data analysis and amalgamation of sensors. Section V includes an overview of the findings and suggested next steps.

2. MECHANICAL FEATURES

Whole body e-skin's mechanical property is an important factor for its efficient use. These properties are flexibility and conformability, skin stretchability, mechanical compliance, sensors' quantity, location and dispersion. Apart from that, it includes sensor shapes and layout for 3D coverage, wiring and weight of the skin. Although these features are expected of a whole-body tactile system, it was not addressed in the early stages of robotic skin development. Only in the late 2000s have researchers started addressing them consistently (Alirezaei et al., 2007; Hoshi and Shinoda, 2006; Lacasse et al., 2010; Ohmura et al., 2006; Someya et al., 2004). Research towards utilizing this feature is reviewed in this section.

Elasticity

Whole-body e-skins for robots should be pliable and elastic. It ought to adapt to the robot's arched exteriors hence pliability is necessary and in places like joints, the elasticity of the skin will aid the movement of the links connected to that joint because, a rigid e-skin would not be able to cover the whole body, especially the curved surfaces of the robot. Also, the elasticity of the skin will add an extra layer of cushion-like protection to the robot hardware. This will increase the durability of the robot. Pliable and elastic skins can be useful for use in prosthetics and wearable technologies made using e-skin.

The existing e-skins use either a non-modular or modular approach. In the non-modular approach, an array of flexible materials (Sankar et al., 2021; Lee et al., 2019; Wade et al., 2017; Lee et al., 2021; Kawasetsu et al., 2018) is used to cover the whole robot body. Types of the material depend upon the transduction method used for the collection of the tactile data. Capacitive (Chen et al., 2020; Gupta et al., 2016; Navaraj and Dahiya, 2019; Pagoli et al., 2022), piezoelectric (Gupta et al., 2016; Lin et al., 2021; Navaraj and Dahiya, 2019), piezoresistive (Lee et al., 2021; Su et al., 2021), magnetic (Kawasetsu et al., 2018) and resistive (Lee et al., 2021; Park et al., 2022; Parvizi-Fard et al., 2021) method has been used by researchers. In the modular approach, it is either pliable PCBs (Cirillo et al., 2017; Mittendorfer et al., 2015; Schmitz et al., 2011) or rigid PCBs (Heyneman and Cutkosky, 2012; Kampmann and Kirchner, 2014). Standard electronics components are mounted on these PCBs. The reduced size of electronic components makes it possible to fit multiple sensors and processors in a single module. An array of small modular circuit boards with these sensors and processors are used as robot skin. In a single module, alongside processors with signal conversion, processing and conditioning capabilities, there exist sensors with multiple modalities. Modular skins with different shapes such as – hexagonal (Mittendorfer and Cheng, 2011a; Scibelli and Krans, 2016; Mittendorfer and Cheng, 2011b), triangular (Schmitz et al., 2011), square (Cirillo et al., 2017) and rectangular (Kampmann and Kirchner, 2014; Liang et al., 2020) are available.

Layout and Sensor Shapes for 3D Coverage

An e-skin with a good design plays a significant role in efficient use. For the modular approach, choosing sensor module shapes carefully can aid in covering a certain 3D surface. Examples of such designs are robots' massive body portions covered by triangle (Schmitz et al., 2011) and hexagon-shaped (Mittendorfer and Cheng, 2011b; Scibelli and Krans, 2016), square (Liang et al., 2020) and rectangular (Cirillo et al., 2017; Kampmann and Kirchner, 2014) structures.

The triangulation method, which uses a collection of triangles to recreate three-dimensional surfaces, is used in computer graphics to approximate plane surfaces of any shape. So, the same concept is used for creating a module which covers the whole body of the robot. Similar to Hex-O-Skin (Mittendorfer and Cheng, 2011b), vision sensing has used hexagonal shapes for natural triangulation. The fluctuation in resolution in various directions is reduced because there is low variation in the x, y and z-axis sensor distances with Hex-O-Skin modules. Designing an e-skin with appropriate sensor module forms for wide areas can be done using algorithms and computer tools.

A good illustration is the Dymaxion map. To produce this map, the earth is projected over the top of a polyhedron. This polyhedron is then opened and deflated which produces a flat world map by slicing a two-dimensional plane into the necessary shape and joining or folding the shapes appropriately, a three-dimensional plane may be created (Demaine and O'Rourke, 2007). The above tactile skin implementation strategy for robotics begins with a CAD representation of a robot's 3D components. Using the technique, iCub, Nao and Kaspar - these humanoids' e-skin was created. The procedure can assist in choosing appropriate tactile sensing module forms and placement locations for the application at hand, with maximal area coverage being the goal.

Wire Routing

In robotics, wiring restrictions are a key barrier to the use and incorporation of e-skin (Cutkosky et al., 2008; Dahiya et al., 2010). The demand for more cables to address components and collect and transfer information and energy grows along with the number of tactile modules. Because of the existing drives and electronic elements, the numerous cables create issues such as routing wires via the joints. Wire count reduction is possible with intelligent routing and addressing. For instance, the number of wires in the e-skin by Lin et al., (2021) and Lianga et al., (2020) is significantly reduced from n x m to n + m by using the row-column layout instead of using wires from each sensor. Here, n and m denote the number of rows and columns respectively (Cirillo et al., 2017) needed 4n + m wires for n x m number of sensors.

The current injection method around the electrode on a piezoresistive material used by Lee et al., (2021) has reduced the number of electrodes and hence the number of wires. They used two distant electrodes to measure the change in resistance in a smaller region which decreased the number of wires. Kawasetsu et al., (2018) got rid of wires in the sensors by using magnetic sensors and data transmission methods. (Lee et al., 2019) used a conductive fabric to support the sensor material which eliminated the necessity for wires. Instead of wires, Sankar et al., (2021) used traces of conductive fabric in perpendicular to each other to form a row-column structure. There are other ways to tackle wiring-related problems, such as wireless data transfer and wireless powering of sensing gear. Wireless connectivity will make it simpler to create flexible sensing systems, among other benefits.

Weight, Thickness & Volume

Concerns about the skin mass, such as its weight, thickness and the amount of room required for the modules, are crucial for e-skin. Humans are a good example because the weight of the skin of a grown person's roughly 4.1 kg which is around 6% of body mass. A grown human weigh about 70 kg overall. Likewise, an adult human's skin surface area is approximately 1.8 m^2 and the range of skin thickness is 0.5 - 0.9 mm (Bartoshuk and Schiffman, 1977). Using this calculation as a guide, With the current design, it would take about 13 kg or 2600 tactile modules to entirely cover a humanoid with the Hex-O-Skin. After some design modifications, it can be reduced to 5.2 kg.

Hence, the humanoid that it should be covering should weigh around 217 kg or 87 kg with the modified design. Atlas (Atlas TM | Boston Dynamics), a humanoid robot by Boston Dynamics weighs about 89 kg. Hence, Atlas or any robot with similar weight can be covered with Hex-O-Skin and it would weigh near about 6% of the total body similar to we humans.

3. CONTRIBUTORS IN ELECTRICAL AND ELECTRONICS

The operational and constructional block diagram of an e-skin is depicted in Figure 1. The robot's skin's electronic architecture has been generalized to create the diagram. The system is split hierarchically into blocks that correspond to each block's functional responsibilities and control hierarchy. The stages show how sensing input is collected, how it is transferred to the upper stages and how instructions for controls are used for achieving the desired action. Within the lowest, hardware-dependent stages and the highest, Processing that requires a lot of computation, there exist differences in complexity. We will discuss a few limitations and options of the layouts in Figure 1 below.

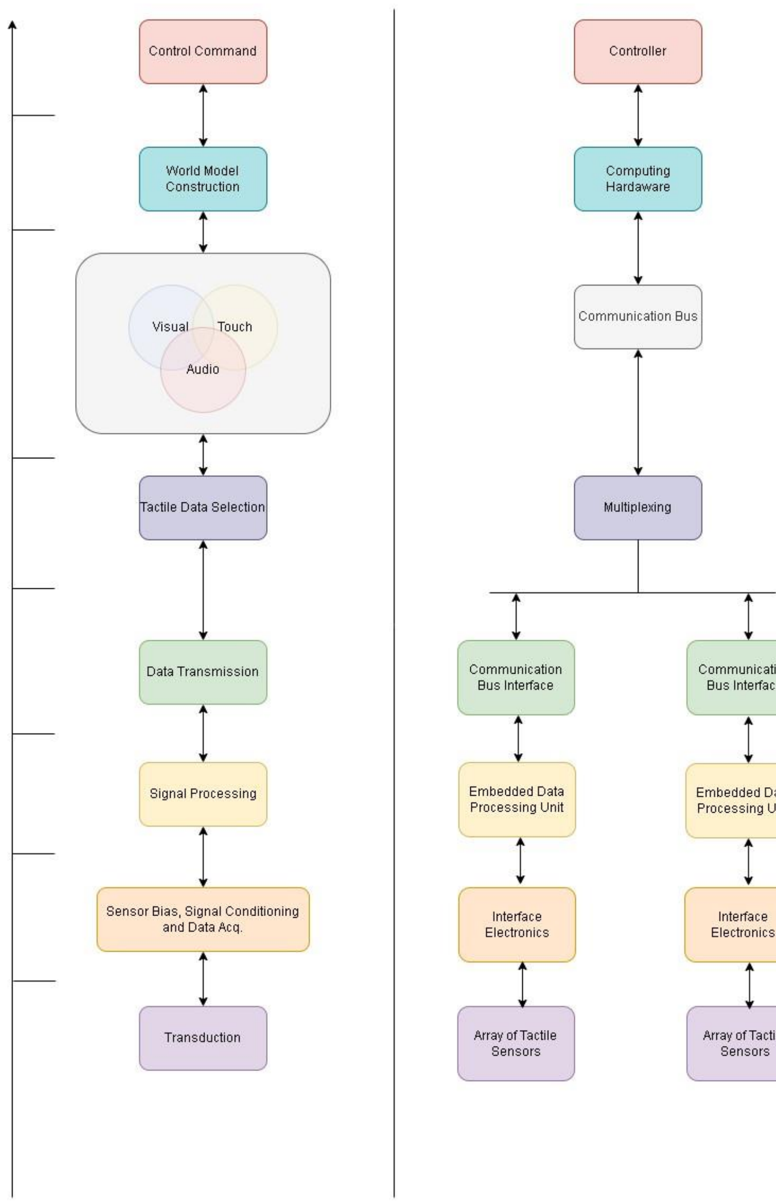

Figure 1 The operational (on the left side) and constructional (on the right side) block diagrams of e-skin.

The e-skin and its sensors

An e-skin's both operational and constructional block diagrams are shown in Figure 1. Blocks that correspond to the system's functional functions and the flow of sensory information and control are hierarchically separated within the system. The levels show the gathering of sensory information, the transmission of that information to upper stages and the instructions needed for the desired action. Between the lower, more computationally intensive levels and the top, more hardware-heavy levels, there are differences in complexity.

The levels presented in Figure 1 have a variety of design options and constraints. The anticipated reaction time of e-skin influences the choice of transduction technique. The skin's bandwidth is a reflection of the highest rate at which the skin can work.

A higher bandwidth means a faster reaction time. A few tens of Hz are the maximum bandwidth that resistive transducers can provide. Optical (Cirillo et al., 2017; Kampmann and Kirchner, 2014; Liang et al., 2020; Mittendorfer and Cheng, 2011b) piezoelectric (Lin et al., 2021), magnetic (Kawasetsu et al., 2018) and capacitive (Schmitz et al., 2011; Heyneman and Cutkosky, 2012) transducers are capable of producing signals with higher bandwidth, such as more than 1 kHz. Numerous occasions necessitate the simultaneous utilization of multiple modes of transduction. For instance, a collection of sensors based on various transduction techniques, e.g., piezoelectric or capacitive techniques, can monitor a number of characteristics, for example, temperature, applied force, strain etc. A multimodal e-skin should be able to measure several contact parameters using the same mode of transduction. Lessening the amount of sensing hardware is another benefit of multimodal transducers.

Electronics Interface

An operational block diagram of the e-skin's interfacing system is shown in figure 2. The elements of the block diagram include tactile sensor array block, sensor bias block, signal conditioning block and analogue to digital converter block. The output from the analogue to digital converter block goes to the data processor block for further processing of the data (Dahiya et al., 2008).

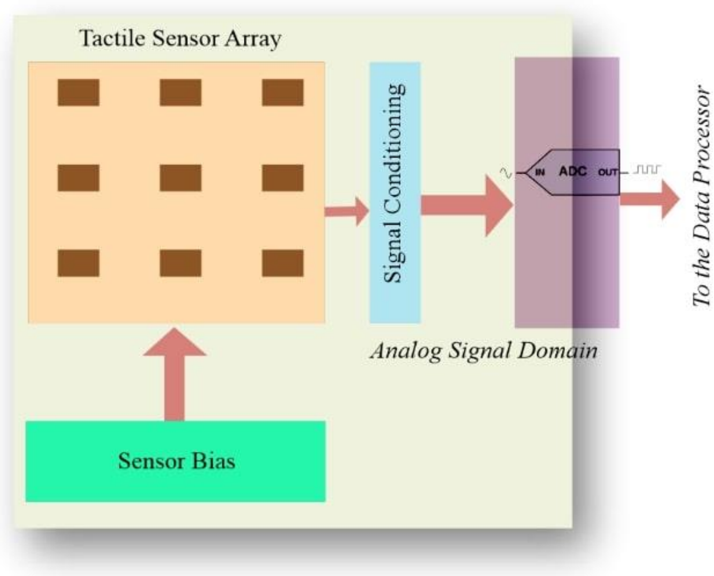

Figure 2 Operational block diagram of e-skin's interfacing system.

Sensors Bias: E-skins are of two types from the perspective of electronics: (i) active sensors and (ii) passive sensors. If an active device is involved (Gupta et al., 2016; Navaraj and Dahiya, 2019), a circuit for biasing the device is required for setting the operating point and eliminating the tactile sensor's switch-on time.

Signal Conditioning: Functions such as noise attenuation, signal amplification and filtering are implemented by this block (Cotton et al., 2007; Dahiya et al., 2011; Vidal-Verdú et al., 2011). Time-multiplexing with the help of an analogue multiplexer is done for each of these signal conditioning circuits (Dahiya and Valle, 2014).

Data Acquisition: Addressing the channel for signal conditioning and digitizing the analogue input (i.e., converting it from analogue to digital) are both components of data acquisition. For large skin area arrays, in particular, factors like wiring complexity have an impact on the interface electronics. In order to reduce complexity at the cost of a faster array scanning rate, the addressing can be fixed and serial (Mittendorfer and Cheng, 2011b; Schmitz et al., 2011). A different setup involves converting the observed signal into a frequency value, which is then digitalized and acquired using a digital counter.

Integrated Computation Unit

One factor for tactile sensing's slower adoption compared to other technologies in robotics is the difficulty in gathering and analyzing voluminous data from multiple tactile modules and multiple modes of the senses (Lee, 2000). Analyzing the sensor data near the sensor's position may greatly lessen the exchange of data between the transducers, the controllers and the computing device. Using a dispersed design, the processing speed of the robot can be increased and free up the robot's processor for more important work. Additionally, it can aid in scaling up the sensor array.

The embedded local signal pre-processing includes calculations like amplification, separating signals from various types of sensors such as force and temperature, linearization and temperature compensation etc. (Mittendorfer and Cheng, 2011a; Schmitz et al., 2011). A robot hand's slip sensor's (Lee et al., 2019; Liang et al., 2020; Lin et al., 2021) job is to sense the slip of an object and transmit the data to the controller so that it can change the strength of the grasp required for firmly holding the object. A robot's cognitive burden might be reduced by the incorporated local processing because it would no longer need to use vision to determine the object's stability and can hold the object with a precise force.

Local processing may be helpful when a collection of complicated information is retrieved (Sankar et al., 2021) and fed into the classifier for the contact touch modality. This information can include spatial resolution, duration and many others. For each iteration of the scan, the contact image must be computed while also solving the inverse issue in real time. These articles (Mittendorfer and Cheng, 2011b; Schmitz et al., 2011) present a modular tactile system that approximately resembles the lower part of the diagram that is up until the Tactile Data Transmission Level depicted in Figure 1.

The Transmission of Information

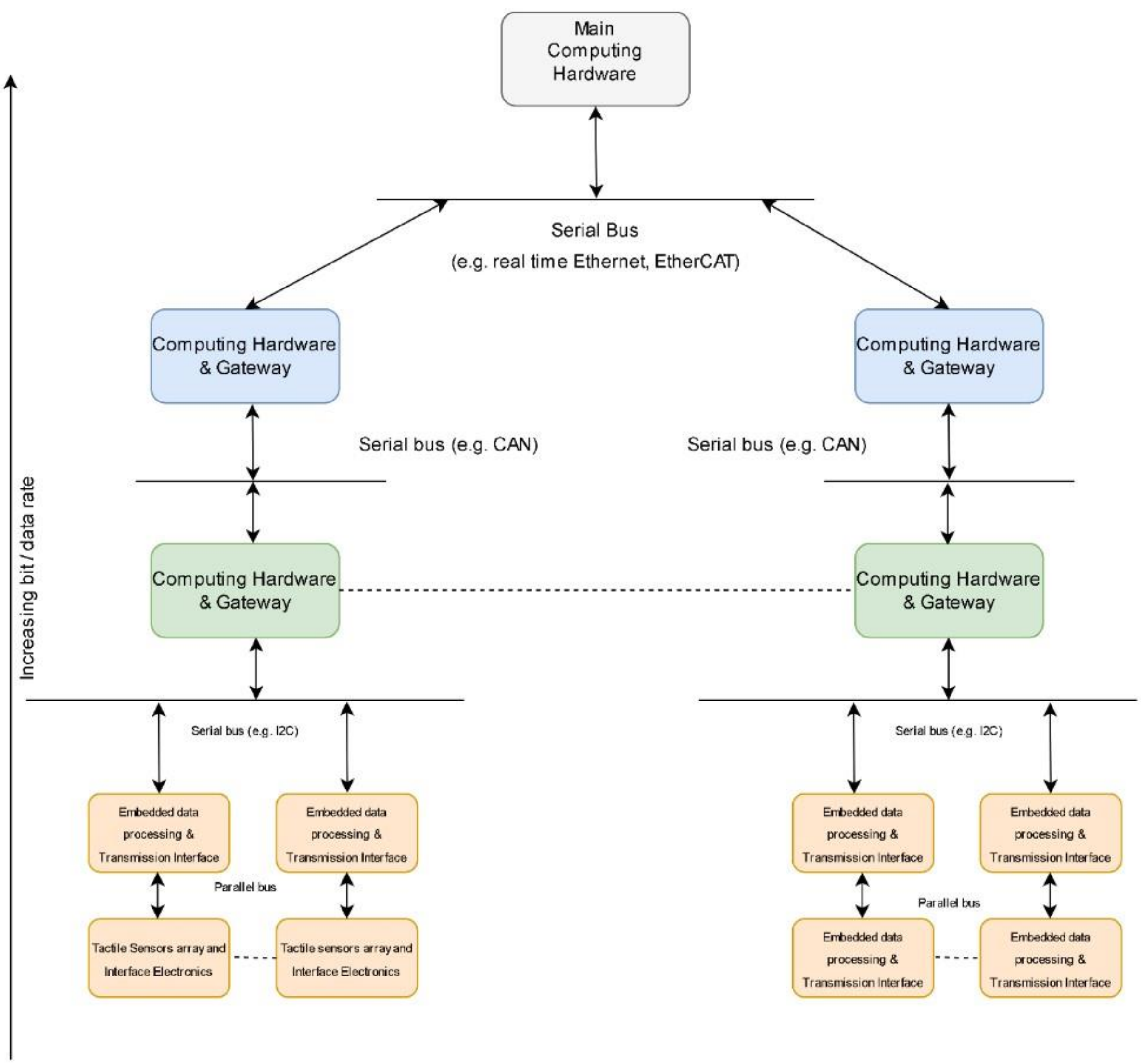

Figure 3 Data transmission architecture of e-skin.

Multistage data transmission architecture and the incorporated embedded computing unit can be used for transmitting the information gathered by the skin. First, raw data is gathered and then sent through the processor for tasks like extraction of features and many others. At last, the data is sent to the upper stages. The human haptic system is also organized in multiple stages.

In this topology, the communication bus is arranged hierarchically and star-like. The gateway between layers has local computer power to implement the necessary data processing methods (see Figure 3). The transmission to higher levels only involves significant traits. The protocols differ as one moves up the hierarchy (from the skin to the controller, for example) for reducing the quantity of wiring, serial communication buses are a good solution. In particular, the bus's bandwidth must grow to support an increased size of data and the complication and efficiency of the protocol must also grow.

Buses with low latency, small sized wiring are chosen at lower levels (I2C Bus). Longer wiring buses and more complicated protocols are preferable as one moves up the ladder. A similar architecture is described in (Schmitz et al., 2011). Here, a skin-like flexible system houses an integrated computing unit and an interface for data transmission (I2C). (Youssefi et al., 2011) shows a whole-body robot skin's performance, as well as the middleware, assisting the tactile structure concurrently (Baglini et al., 2010) presents a comprehensive analysis that gives a thorough examination of a networking system that utilizes 100 Mbit real-time Ethernet protocol enhancements.

4. INFORMATION HANDLING

Managing Data and Extraction of Features

By utilizing a communication bus hierarchy, both information routing through e-skin and feature extraction can be accomplished much like the human tactile system. The employment of control algorithms and classifiers will be influenced by taking tactile events in place of taking only tactile data into account. This could lower the volume of tactile data delivered.

To solve challenging activities such as balanced and secure grip, a variety of computational algorithms have been utilized to extract information from tactile input. For instance, the pose of the object has been determined using the particle filter technique using contact data among a grappler and the object (Jiang and Luo, 2022). In (Decherchi et al., 2011), it is shown how to recognize material by touching with the help of Support Vector Machines, Regularized Extreme Learning Machines and Regularized Least Squares.

Tactile information has been demonstrated to be helpful in determining bottle parameters such as "open/closed" and deformation qualities of objects (Chitta et al., 2011). On the basis of the information collected by robots, scratching various surfaces, machine learning methods are employed for the detection and classification of different surfaces (Sinapov et al., 2011). Different features from sensory data have been extracted using self-organizing maps (SOMs) (Johnsson and Balkenius, 2011). Using data gathered from interactions, objects are differentiated based on their size, shape, surface roughness, and rigidity. For differentiating objects on the basis of surface roughness, Bayes trees are used (Jamali and Sammut, 2011).

Sensor Fusion and Data Interpretation

Robotic tactile sensing now uses computational methods that were originally developed for computer vision. Robot touch sensors are dispersed throughout the 3D robot body; therefore, their information is more complicated than that from cameras. This has an impact on how tactile data is processed at higher computational levels (Figure 3).

Processing tactile data needs a considerable amount of work and is error-prone since e-skin's placements in space change as the robot moves. Creating increasingly complicated mental actions, for example, fast responses to abrupt inputs depends on this processing. To describe the touch inputs for different sections of the body, internal models must be created. Somatotopic internal maps serve these functions in humans. In robotics, similar arrangements are required. Some researchers utilize models based on artificial brain maps (Cannata et al., 2010), which are influenced by the somatosensory system of humans. Cannata et al., (2010) consider such mapping. Using surface parametrization techniques (Desbrun et al., 2002; Pinkall and Polthier, 1993) a two-dimensional surface model of the given three-dimensional surface is obtained along with its attributes (tactile modules positions, movements, variable denseness and other attributes).

To acquire the robot body's three-dimensional surface on the basis of touch sensation, extra transducers, such as transducers for sensing torque and/or force, a Computer-Aided Design (CAD) model and several interactions are required (Modayil, 2010), which also calls for extra constraints to resolve ambiguities. The simultaneous use of several sense modalities, such as tactile, visual and kinesthetic, may be necessary to build a realistic world representation. Consider, for example, an activity of distinguishing within two things which calls on tactile data (such as softness, texture and temperature) as well as visual information (such as colour and shape). To interact with their surroundings, humans blend sensory information from several perceiving modalities as well (Ernst and Banks, 2002). Artificial intelligence (AI) methods would be appropriate in this situation (fuzzy sets, neural networks).

5. CONCLUSION

Robots and biomedical devices will be able to detect their environment thanks to e-skin, which is made of a vast network of transducers along with electronic components integrated into elastic substrates. When embedded into assistive robots, it will result in improved precision and safety and additional modality. When made into clothing, it will significantly advance key facets of the service industry, it will contribute to advancing human prosthetics and improve human sensing. Current research demonstrates that a wide range of extremely effective sensing devices is possible in the fields necessary for the development of e-skin. It is challenging to use existing prototypes efficiently for many robotic activities since they frequently are awkward, energy-consuming and have poor resolution, precision and reliability. The design and implementation of e-skin into robots are the outcomes of numerous electronic hardware, constructional and computational compromises. These compromises are transducer modes, controllers for robots, integrated electronics, dispersed processing capability, circuitry, energy usage, fault tolerance, fabricability, functional reliability etc. Figure 3 summarizes some of the characteristics of tactile skin that are required for its efficient use. Before e-skin may be found everywhere in next-generation robotic systems, the serious research problems outlined in this work must be taken into account. The authors of this paper hope that the readers will see it as our initial attempt to outline the novel directions and difficulties associated with using tactile skin, as well as an invitation to participate in the exploration.

Author Contribution

Subrata Pandey – Mechanical Features, Contributors in Electrical and Electronics. Information Handling

Soumitra Kumar Mandal - Abstract, Introduction, Conclusion

Conference Presentation

This paper neither as a part nor as a whole has been published in any form in any conference or journal.

Ethical issues

Not applicable.

Informed consent

Not applicable.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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