Electronic Skin: Achievements, Issues and Trends

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Electronic Skin: achievements, issues and trends

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Abstract

The skin is one of the main organs of the human body and as such it implements many different and relevant functions, e.g. protection of the inner body organs, detection of cutaneous stimuli, etc. Due to its complexity, the development of artificial, or better, electronic skin (e-skin) is a very challenging goal which involves many different and complementary research areas. Nonetheless, the possible application areas are many and very relevant: e.g. humanoids and industrial robotics, artificial prosthetics, biomedical instrumentation, cyber physical systems, for naming a few. Many research groups are addressing the development of e-skin and the research scenario is exciting and continuously evolving. Due to its very peculiar features, the development of electronic skin can be effectively tackled using a holistic approach. Starting from the system specification definition, the mechanical arrangement of the skin itself (i.e. soft or rigid mechanical support, structural and functional material layers, etc.) needs to be designed and fabricated together with the electronic embedded system, to move toward aspects such as tactile data processing algorithms and the communication channel interface. In this paper, we present and assess the achievements of our research group in this field focusing on the following aspects: (i) The manufacturing technology of sensor arrays based on piezoelectric polymer (PVDF) transduction; (ii) The mixed-mode interface electronics; (iii) The tactile data processing algorithms; (iv) The electronic embedded system. Future trends and research perspectives will be also presented.

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Keywords: E-skin; piezoelectric polymers; tactile data processing; electronic embedded systems

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1. Introduction

The development of electronic skin (e-skin in the following) is a hot research topic due to its relevant countless applications e.g. in robotics and in biomedical systems [1, 2]. The functions of e-skin are basically: 1) to protect the inner electronic system from damages due to interactions with the outside (e.g. impacts, humidity); 2) to convey the mechanical stimulus in a convenient way to the beneath distributed sensor arrays: the geometrical arrangement of e-skin patches, the geometry of the protective layer on top of the e-skin structure and the composition of the protective layer contribute to an effective implementation of this task; 3) to acquire and to pre-process sensor signals in a convenient way; 4) to extract in an effective and reliable way the meaningful and necessary information for the task at hand (e.g. automatic reflexes, contact type recognition, surface feature detection, etc.); 5) to transmit the information to the next higher level of the ICT infrastructure of the system (e.g. the local communication bus). Each of such operations can be organized in many other tasks which jointly concur to implement the extrinsic/cutaneous tactile system. What is more, from the previous considerations, it seems that the e-skin should be flexible (i.e. conformable to the system to be applied on) and stretchable e.g. to support joint movements, and processing must be implemented in real time for using the tactile information in the system control loop.

The different e-skin tasks are far from being properly addressed and still in their infancy even if many research groups are addressing the topic with numerous different approaches at each level of the problem.

Our research group is being addressing this topic since roughly 10 years in a holistic way, managing the seamless design and implementation of the mechanical and electronic systems of the e-skin. With reference to the above system organization, we mainly focused on the development of: 1) sensing arrays based on a technology exploiting piezoelectric polymers as sensing materials; 2) the interface electronics; 3) tactile data processing algorithms; 4) dedicated digital embedded electronic systems. In this paper, we will review main achievements in these areas. The paper is organized as follows: Section 2 describes the sensing material and presents a survey on the on-chip integration of tactile sensors. Section 3 presents tactile data processing algorithms. Research issues related to the effective implementation of an embedded electronic system for e-skin is illustrated in section 4 and a presentation of the current approach to tackle some issues in the field is then given. Conclusions and future perspectives are reported in section 5.

2. Tactile sensing arrays

2.1. Sensing material and large area sensor array technology

The first step in e-skin development is to identify the adequate *functional* material to enable certain sensing capabilities. As the functional skin requirements are debatable and ‘application dependent’, piezoelectric polymer films of Polyvinylidene Fluoride (PVDF) [3] have been chosen as meeting the target requirements of mechanical flexibility, high sensitivity, detectability of dynamic touch (1Hz-1kHz frequency range) and robustness.

Commercial PVDF sheets (100μm thick) from Measurement Specialties Inc. are stretched and poled. Stretching at temperatures below the polymer melting point and poling by the application of very high electric fields (~100V/μm) give the polymer sheets the symmetry of an orthotropic material [4]. Linear constitutive equations [4] are commonly used to describe the material intrinsic transduction of the mechanical stimulus into a charge signal, but care is required to account for the way the piezoelectric film is integrated into the skin, which also includes a substrate and a cover layer.

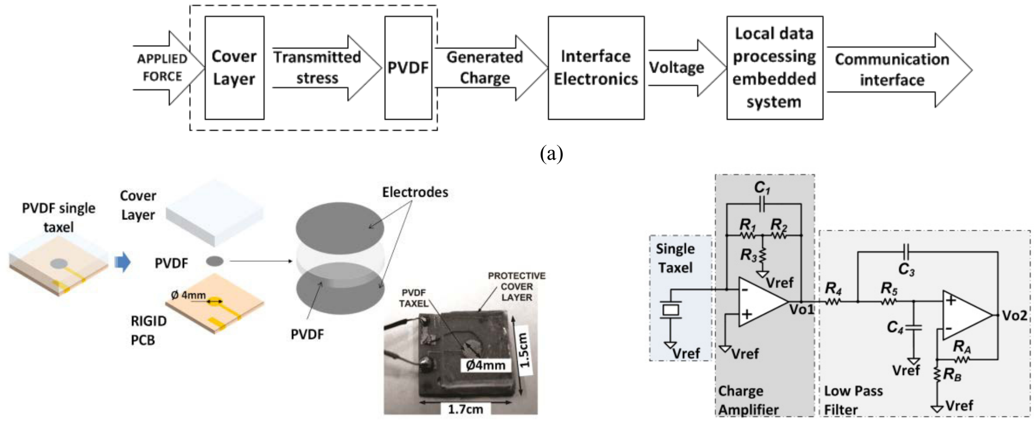


Fig. 1. (a) From the applied mechanical stimulus to skin communication interface. (b) Basic skin prototype based on a single PVDF transducer. (c) Schematics of the charge amplifier.

In the e-skin easiest concept, a PVDF circular *taxel* is provided of electrodes for charge collection and it is glued to a rigid substrate and covered by a protective layer (see Figure 1 (b)). This configuration was used to make preliminary choices (e.g. technology for patterning electrodes on PVDF, material and thickness of the protective layer, assembly technology) and to design the electronics. A Fujifilm Dimatix 2800 (DMP2800) *Drop On Demand* inkjet printer has been used for deposition and patterning of metal electrodes (Cabot Conductive Ink 300 (CCI-300)) on the PVDF polymer film, enabling scalability to large area manufacturing through a maskless approach [5]. A PDMS flexible elastomer has been chosen as cover layer and directly polymerized on top of the polymer film, starting from two-part silicone Sylgard® 184 (*Dow Corning*).

Charge, generated by the PVDF transducer as a result of the cover layer transmission of external mechanical stimuli (Fig. 1 (a)), can be directly converted to voltage by means of charge amplifier-based electronics [6], whose schematics is reported in Fig. 1 (c). For 2.5-3mm thick PDMS cover layer and 3-4mm diameter electrodes, charge typically ranges from hundreds of fCs to nCs, depending on the tactile gesture [7]. These values become an important design spec for the electronics. The same approach illustrated in Fig.1 has been extended to fabricate larger piezoelectric polymer sensor arrays, from a 16-

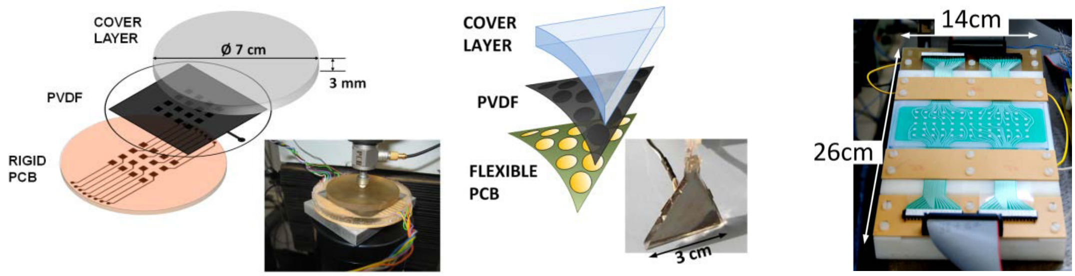
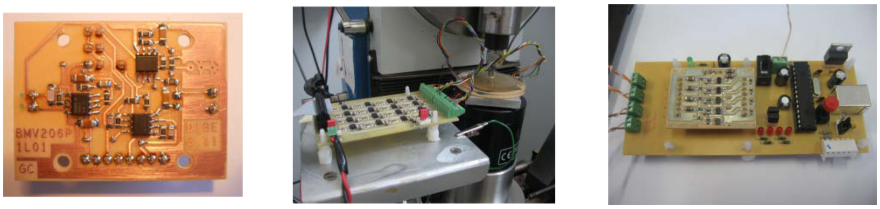


Fig. 2.Tactile sensor arrays based on piezoelectric transduction (PVDF). (a) 16-taxel array skin prototype based on a rigid substrate. (b) Flexible 12-taxel prototype, (c) Latest 64-taxel flexible skin prototype realized by SPES MEDICA (Genoa, Italy), at present integrated on a rigid support (not yet published).



(a) (b) (c)

Fig. 3. (a) Basic 1-channel charge amplifier, (b) interface electronics based on 16 charge amplifiers (analog output), (c) interface electronics based on 4 charge amplifiers, analog-to-digital converter, microcontroller for data transmission (digital output).

taxel rigid version (Fig. 2 (a)) to flexible 12-taxel (Fig. 2 (b)) and 64-taxel solutions (Fig. 2 (c) –results are not published yet), which have been designed with the requirements in mind of skin compliance to curved surfaces, scalability (to cover the entire robot surface), low cost and lightweight, robustness and reproducibility.

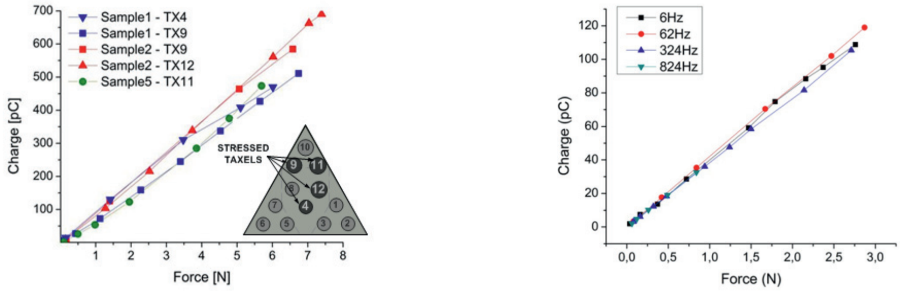
Ad-hoc Interface Electronics extends to multiple channels the concept developed for the single taxel prototype. Fig. 3 shows some implemented prototypes based on charge amplifiers for PVDF charge reading.

The overall skin system has been tested and validated in its different versions. As an example, Fig. 4 summarizes experimental results proving reproducibility and linearity of the 12-taxel flexible prototype illustrated in Fig. 2 (b).

2.2. Tactile sensor on-chip integration

A novel tactile sensing device that can provide an effective and advantageous solution to the large sensing area approach discussed above is the Piezoelectric Oxide Field Effect Transistor. The device is composed by a high trans-conductance MOS device with a large channel width-to-length ratio, and a thin film of piezoelectric polymer, like P(VDF-TrFE), deposited by spin coating on the gate contact [8, 9].

The direct interface between the polymer and the terminal contact allows for an efficient capacitive coupling between the transducer material and the electronic device dedicated to impedance adaptation and signal amplification. If the piezoelectric material is poled in the through-thickness direction, when a normal force is applied a voltage arises between the film surfaces, and a charge accumulation in the transistor channel is induced. In this way the transistor amplifies the signal generated by the thin film and decouples itself from the other circuitry with virtually infinite input impedance. The entire device is extremely compact and suitable to be integrated into an array of sensing elements with high spatial tactile resolution. The small size of the components allows for an autonomous transducing system embedding in the sensitive surface also the signal conditioning circuits and the digital converters. It is possible to maintain the human like tactile resolution, while also reducing the amount of cables and external circuitry for signal elaboration. A neuromorphic circuit that executes an Address-Event Representation (AER) digital coding is being developed to this scope [10]. It is a compact and robust circuit that can be embedded directly close to the POSFET itself, and its output signal can be managed by a tree organized arbiter taking advantage of the time multiplexing of the spike codification [11]. We use a Leak Integrate and Fire (LI&F) neuron that integrates the POSFET current and generates a pulsing output signal characterized by a fire rate proportional to the intensity of the applied force. In this way the input envelope is encoded in the time elapsed between two different spikes, and this allows to time-multiplex sensor data. At present, the data bus to the central computing unit is only wide as the number of bits to address the neuromorphic taxel that has fired.



(a) (b)

Fig.4.(a) Reproducibility of the skin: charge response of different taxels (the inset indicates taxel location), placed on TRIANGLES 1, 2, 5. (b) Linearity of a single taxel: charge response of the same taxel for different stimulus frequencies.

3. Tactile data processing algorithms

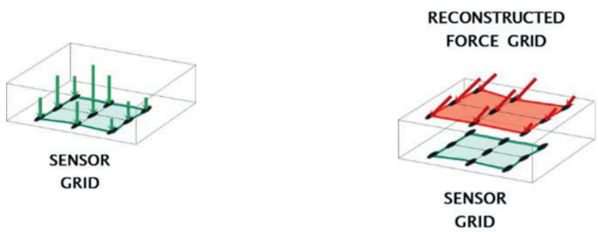
The e-skin allows a link between perception and action. Processing and interpretation of tactile data is the first step required to enable response to external mechanical stimuli. Two different complementary approaches have been pursued: the former is based on continuum-mechanics, which is application and transducer independent and aims at reconstructing the applied force distribution. In the latter, machine-learning technology has been used to recognize different touch modalities, avoiding an explicit formalization of the stimulus-‘sensor response’ relationship and applying empirical induction by learning-from-examples approach.

3.1. Continuum mechanics based approach

The problem we address is the recognition of tactile stimuli acting on the surface of the skin from the finite set of measurements from sensors beneath the cover layer.

This issue is rather general and may apply to a variety of contexts, hardware settings and tasks, where the e-skin is the scene of complex events, such as multiple contacts in separate regions. The main limitation is that the external surface where the stimuli occur must be relatively flat.

The main research scope is therefore to develop an algorithm for estimating the spatial distribution of



(a) (b)

Fig.5. (a) A distribution of forces (not shown) acts on the cover layer, which conveys mechanical ‘stress’ information to the sensor array located beneath. Only the pure normal stress component is recorded. (b) The proposed algorithm reconstructs the force distribution from sensor outputs.

contact forces as well as their intensities and directions starting from sensor data (Fig. 5). This requires the solution of an inverse problem where only *incomplete* information is available. As a matter of fact, the applied tactile stimuli are assumed to be received by the sensors as a pressure on their upper side (sensors only read the T_{33} stress component). The proposed method discretizes external forces at the nodes of a grid and the question is how to reconstruct 3-component point forces applied to the N grid nodes (equal in number to the number of sensors) starting from N sensor data.

This problem is in principle ill-posed. A solution is achieved through an optimization procedure accounting for the physical features of the problem by the use of the Moore-Penrose pseudo-inverse matrix [12] and of a vector depending on two continuous and adjustable scalar parameters. The eligible solution is the one which maximizes an *efficiency* functional, at best complying with the physical constraints.

The algorithm has been tested on single-contact problems with encouraging results, paving the way for its extension to the case of multi-contact stimuli.

3.2. Machine Learning based approach

The goal is to interpret sensor data to discriminate between a set of stimuli that the system is expected to recognize. Machine-learning techniques may prove to be useful when the tactile-sensing framework faces challenging assignments such as the interpretation of touch modalities. A reduction in the overall complexity of the pattern-recognition problem stems from splitting the modeling process into two tasks:

1) The definition of a suitable descriptive basis for the input signal provided by the sensor (or lattice of sensors), i.e. a feature-based description $\mathbf{f} \in \mathcal{F}$, where $\mathcal{F}$ is a feature space:

$$\mathrm{f} = \phi(\boldsymbol{\mathcal{S}}) \tag{1}$$

In expression (1), $\boldsymbol{\mathcal{S}}$ is the 3rd order tensor that characterizes sensor outputs [13].

2) The empirical learning of a model for the non-linear function, γ, that maps the feature space, $\mathcal{F}$, into the set of tactile stimuli of interest:

$$\gamma : \mathcal{F} \rightarrow \mathrm{T} \tag{2}$$

In general, T includes a finite number of stimuli, hence γ implies a multi-class classification task.

In principle, the literature offers a wide range of ML-based techniques to set up γ. In fact, the peculiarities of the tactile-sensing framework notably shrink the range of solutions that best fit the underlying 3-dimensional tensor problem. The crucial issue here is that most machine-learning techniques represent input patterns as n-dimensional vectors $\mathbf{x}$ that lie in some feature space $\mathcal{F} \subset \Re^n$. In the specific case of the tactile problem, that feature-extraction process would alter significantly the original structure of the signal provided by the sensor, since $\boldsymbol{\mathcal{S}} \subset \Re^r \otimes \Re^c \otimes \Re^d$. For example, one would lose the

Table 1.Classification problem

Classification problem	A	B	C
Classification error	13.7 %	19.2 %	11.4 %

relationship between the row space and the column space. Moreover, one could expect that the inadequacy of feature extraction (step 1) would reverberate into an increased complexity of the modeling process (step 2). The tactile sensing framework described in [13] tackles this issue by adopting a ML-based system for pattern recognition that is specifically designed to deal with tensor signals. The employed ML-based system derives from the theoretical framework introduced in [14], providing an effective methodology for tensor-based learning models, preserving as much as possible the natural structure of tactile signals. Table 1 gives the simulation results for the following binary classification problems, which involved three basic touch modalities:

- A: "sliding the finger" versus "brushing a paintbrush";
- B: "sliding the finger" versus "rolling a washer";
- C: "brushing a paintbrush" versus "rolling a washer".

In each experiment, the dataset included 260 patterns, evenly divided between the two actions; 56 patterns were used as test set. The performances are expressed as percentage of errors in the test set, overall confirming that the proposed framework achieved state-of-the-art performances.

4. Dedicated embedded electronic systems

In recent years, embedded electronic systems have substantially increased their presence both in industry and in our everyday lives. Hence, more and more effort is being dedicated to the development of systems which are designed for implementing specific and dedicated functions, and interact with the external environment through sensors and actuators [15]. Each embedded electronic system has specific design constraints. However, there are some common features which are expected from these systems, namely high computing performance, real time operation, low power consumption and possibly low cost, small size and long life cycle.

When considering e-skin where the electronic system must be embedded inside the skin itself, small size is crucial. Moreover, taking into account the human/e-skin or environment/e-skin interaction tasks involving tactile feedback, real-time performance is particularly important [16]. In the event of a failure, one needs to be able to recover the system to its operational state in the least amount of time and impact to the operational applications. Fault tolerance becomes a critical requirement that must coexist with real time operational requirements. An important aspect when pre-processing close to sensors is early detection and treatment of faults, in order to limit their effects on the whole system and avoid, as much as possible, the replacement of faulty parts. Fault-tolerance techniques such as active redundancy are widely adopted. Active redundancy can be implemented in both space and time domains [17]. In the space domain, critical components can be replicated into multiple copies to enhance error resilience. In time redundancy the computation or data transmission is repeated and the result is compared to a stored copy of the previous result.

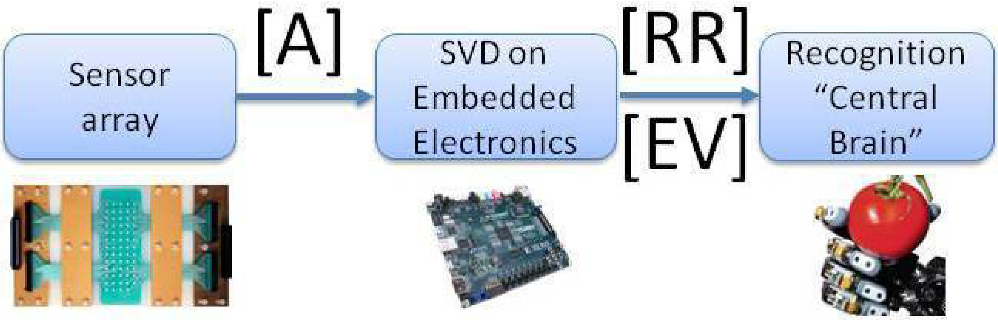


Fig. 6. The tactile system; A: input matrix; RR: rotation matrix; EV Eigen value matrix.

Table 2 shows literature data regarding the addressed requirements of the embedded electronic system used for e-skin.

The processing of data coming from the tactile sensing array concerns a huge amount of data organized as tensors (see Section 3). Fig. 6 shows the functional block diagram of the architecture of an e-skin patch. In the current implementation, the required data rate is around 640 kbps, considering 8×8 tactile sensor array, with 10 bit data resolution and 2 kHz of sampling rate (oversampled at 3 kHz). This means that the dedicated embedded electronic system has to sample and process 10000 data array of 10-bits per second.

Considering tactile data at each instant of time as organized inside a matrix, the dedicated embedded electronic system can reduce the amount of data to transmit by applying transformation algorithms like the Singular Value Decomposition (SVD) [23]. SVD is a stable and effective method to split the system into a set of linearly independent components, each of them bearing its own energy contribution; it is a numerical technique used to diagonalize a matrix in numerical analysis [24, 25]. SVD is an attractive algebraic transform for image processing, because of its endless advantages, such as maximum energy packing which is usually used in compression [26, 27]. Also, it is often employed to solve inverse problems, computing the pseudo-inverse of a matrix and multivariate analysis. Each of these applications exploits key SVD properties [28]. SVD is a robust and reliable orthogonal matrix decomposition method,

Table 2. Embedded electronic system requirements for e-skin.

Reference	Technology	Latency [ms]	Transductions method	Sensor bandwidth [Hz]	Special resolution [mm]	Size of sensor array
[18]	Flexible PCB	480	Polymer based FSR	78	18.5	16×9
[19]	PCB		Piezoelectric	80	15	10×23
[20]	Flexible PCB	20	Silicon based FSR	100	18	8×8
[21]	Foam layer PCB		Capacitive	80	15	4×4
[22]	Organic FET	480	FSR	3	2.54	16×16

becoming more and more popular in the signal processing area due to its stability [24, 25]. Several algorithms can be used to implement SVD [23] with a good accuracy. The Jacobi rotation is one of the most commonly used algorithms for computing SVD, due to the high degree of potential parallelism and convergence accuracy. In fact, it is based on recursive matrix rotation, a single rotation is obtained with 2×2 rotation matrixes where the rotation matrix $\mathbf{R}_{ij}$ is done by the four elements r_{ii}, r_{ij}, r_{ji}, r_{jj}; with $i \neq j$; i= (1, 2, …, n); j = (i+1, i+2, …, m), n and m being the number of rows and columns of the input matrix. In such a case different rotations can be executed in parallel. A trade-off is needed between the computational speed and the required hardware resources, according to matrix size, element accuracy and time between two data sequences, assuming 640 kbps as worst case (when n=8 and m=8) and considering a single embedded electronics for each data array.

5. Conclusions and future perspectives

The present paper summarizes our main contributions to the development of e-skin systems. We addressed such an issue in a holistic approach starting from basic building blocks (materials, electronics) to the fabrication of the whole skin system, which also includes embedded data processing.

Our approach is based on the employment of piezoelectric polymers such as PVDF, due to their intrinsic relevant features. Nanostructured piezoelectric polymers could be an interesting alternative for their promising reliability properties.

The embedded electronic system raises a number of issues; the interface electronics can be effectively implemented using either POSFET devices and a neuromorphic approach or a more traditional SoC implementation. The neuromorphic approach paves the way to the adoption of bio-inspired approaches which already proved relevant in vision systems. On the other hand, tactile data processing algorithms (either based on continuum mechanics or on machine learning) feature very promising results interpreting complex e-skin tactile interactions. The need for real time processing a huge amount of tactile data accounts for very high computing power. The electronic embedded system must supply real time performance and fault tolerance while asking for very low power consumption and resilience. We envisage the need for online circuit self-configurability to be able to adapt and address even more complex tasks in an autonomous way.

To be effective, the silicon system must be thinned and embedded into the e-skin structural material opening new issues in terms of reliability. Among other technology implementations, Organic FETs could be a viable, though long term, solution.

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