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The DLR Artificial Skin
Step II: Scalability as a Prerequisite for Whole-Body Covers

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Abstract— **In human skin, the ability to spatially discriminate an individual indentation from two simultaneous indentations is tailored to the need of the specific area of application on the human body. While the spatial resolution is comparatively low over wide areas of the human body, there are no insensitive spots. In addition, the measuring range is tuned to the expected loads on the respective part of the human body. Within this study these observations are utilized to solve some of the key challenges on the way towards an artificial skin as a whole-body cover for robotic systems. To enable the reliable detection of collision events which are commonly of very short duration the reaction time of the artificial skin system has to be minimized. In order to do so, the goal conflict between the required number of taxels and the required high readout frequencies has to be solved. We present the DLR approach towards scalable transduction hardware and readout electronics as a basis for the acquisition of tactile information from future whole-body covers. First experiments with prototypes of the DLR Artificial Skin demonstrate the scalability of the transduction hardware with respect to size, spatial resolution and measuring range.**

I. INTRODUCTION

The task to cover an entire robotic system with an artificial skin poses multiple challenges. In our previous publication [1] we presented the first step towards robust yet sensitive transduction hardware. Within this study we build on these results and present the next step – our solution of the challenge of scalability. Next to the manufacturing of robust elastic transduction hardware, which is capable to span the 3D-curved surfaces of today's humanoid robotic systems, the design and implementation of a large area high speed readout system is crucial. If a human sized robotic system is assumed, the total surface area will be comparable to the extent of human skin of about 2 m^2. Covering such a large surface with transduction hardware with 1 mm spatial resolution would result in a huge overall number of taxels. Whereas the general demand of a spatial resolution of 1 mm, which is quoted since the early works of Harmon [2], may be justified for a dexterous manipulation of fine objects with robotic fingertips, no one will argue that at the back of a humanoid robotic system an equally high spatial resolution will be required. A direct scaling of high (spatial) resolution transduction hardware is not appropriate. One possible strategy to minimize the overall number of taxels is the utilization of taxels with a varying surface area. Thus, the spatial resolution of the artificial skin can be reduced where appropriate. In addition, the transduction hardware can be sub-divided in order to parallelize the readout process. The parallelization of the readout process can be achieved by the application of multiple modules of distributed readout electronics that are connected to a bus system, (see section V). At DLR both strategies are combined to enable the design of an implementable artificial skin as whole body cover. Figure 1 depicts a prototype

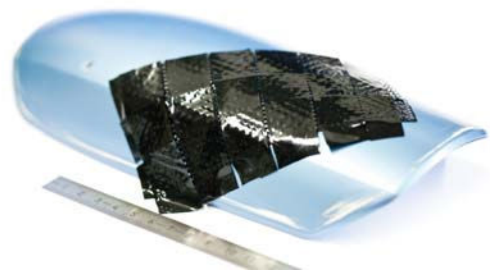

Fig. 1. Prototype of normal force acquisition tactile surface sensor with 3×5 taxels with a spatial resolution of 20 mm. The presented prototype is designed towards covering a large surface area as the depicted covering structure of the DLR Hand-Arm-System (upper arm cover).

of the DLR Artificial Skin with a spatial resolution of 20 mm for the application on the surface of the DLR Hand-Arm-System [3]. In current literature numerous approaches towards sensitive whole-body covers for robotic systems are presented, e.g. [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16]. The majority of these approaches are presented in form of laboratory prototypes in various stages of integration. Besides the mostly time consuming manual manufacturing processes, the covering of non-developable 3D-curved surfaces of modern humanoid robotic systems is one of the unsolved challenges. In addition, the design of high-speed readout electronics that enable the acquisition of tactile information from a whole body cover at high frequencies to date remains unsolved. Therefore, the task to develop a readout strategy that allows for a reliable detection of collision events irrespective of the location of the collision has to be addressed. Amongst the hurdles towards a fully integrated artificial skin the scalability of the transduction hardware has to be considered one of the key challenges. To the best knowledge of the authors there is no approach that can be scaled to fit all requirements of the different application sites on a humanoid robotic system. The goal for the DLR Artificial Skin is the design of a system that is capable to span the desired range of spatial resolution and offers adjustable transduction characteristics which are required to equip a humanoid robotic system from fingertip to the sole of foot.

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II. DESIGN GOALS

Taking human skin as a design metaphor, a spatial resolution which is optimized to the respective requirements of the site of application may be beneficial. The distribution of the spatial resolution of the receptive fields in human skin is presented in the so called Weinstein maps, depicted e.g. in [17]. According to the Weinstein maps the spatial resolution varies between 1 mm e.g. at the fingertips and 70 mm at the back of the human body. Figure 2 exemplifies

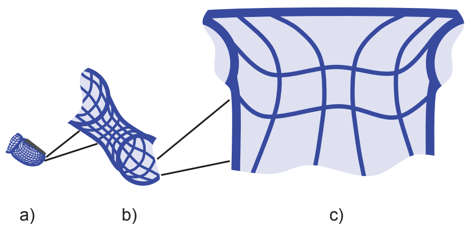

Fig. 2. Scalability of spatial resolution according to body site, (a) fingertip, (b) lower arm structure, (c) torso.

the variety of spatial resolution required on different body parts of a humanoid robotic system. To enable the reliable detection of a tactile stimulus, irrespective of the size of the indenting object or the contact location on the surface of the robotic system, the artificial skin must not have insensitive areas. In order to ensure that no insensitive areas are formed, the taxels have to be arranged carefully on the complex shapes of modern humanoid robotic systems. This task will be facilitated if the surface area of the individual taxels can be scaled. Moreover, a constant distribution of the sensitivity within the surface area of a single taxel is desired in order to achieve the same sensor output irrespective of the location of the indentation. Furthermore, the measurement range of the individual taxels has to be scalable in order to fit the requirements of the different application sites on a humanoid robotic system.

Whereas a resolution of single digit Pascals may be appropriate for an artificial skin on robotic fingertips, hundreds of Newtons and resulting pressures of 20 kPa will have to be accounted for at the same time, if an artificial skin would be applied on the sole of foot of a humanoid robotic system; (according to [18]: Ground contact forces of 480 N can be expected for a static single foot stance of the DLR biped robot TORO [19]). Figure 3 exemplifies the high variability of the expected load range at the different application sites on a humanoid robotic system. Therefore the measuring range of an artificial skin has to be scalable to fit the wide range of requirements on the different application sites on a humanoid robotic system.

An additional aspect of scalability is the goal conflict between the desired incessant surveillance of the entire surface of the artificial skin and the overall number of individual taxels. With respect to temporal resolution the desired minimization of the reaction time contradicts the desired high number of individual taxels. The time required for the readout of the entire surface, defines the achievable

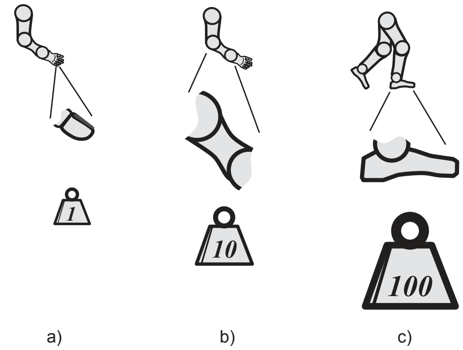

Fig. 3. Scalability of pressure range according to body site, (a) fingertip, (b) lower arm structure, (c) foot.

reaction time in case of a collision. Therefore, the required minimum readout frequency for the reliable detection of collision events is estimated.

Impact tests conducted in [1] reveal, that the initial peak of the indentation force lasts about 60 ms in a collision between a aluminium impactor and the proposed setup of the DLR Artificial Skin (a 2 mm thick tactile surface sensor on top of 16 mm damping layer) . The readout frequency has to be high enough to detect even shorter collisions. According to [20] the duration of the initial peak of the contact force in a collision between an aluminium impactor mounted on the tool center point of a lightweight robot (LWR III) and the forehead of a Hybrid III crash test dummy lasts between 5 ms and 10 ms.

High speed impact tests conducted by [21] reveal an even shorter duration of the impact (approximately 0.5 ms). For the tests the lower arm of the DLR Hand-Arm System [3] has been replaced with an aluminium profile being covered with a 3 mm thick layer of silicone rubber. In order to simulate high speed impacts the aluminium profile was hit with a baseball bat.

The deformable layers that are applied in all examples are crucial for the duration of the impacts. For the design of the DLR Artificial Skin (which incorporates an internal mechanical damping layer) a duration of the initial peak of the impact of 4 ms is considered the worst case scenario for impacts between a robotic system covered with an artificial skin and a rigid object. In order to ensure the reliable detection of an impact event, each taxel of the artificial skin has to be read out at least twice as often. Thus, in this worst case scenario, the minimum readout frequency for the overall artificial skin is 500 Hz. In general, the required readout frequency restricts the maximum number of taxels, which can be connected to a single readout electronics.

III. SENSOR PRINCIPLE

In the following, the DLR approach towards an all-polymer artificial skin as presented in [18], [1], [22] will be summarized. The DLR approach is based on the partitioning of the functional range of an artificial skin. Figure 4c) depicts the setup of the DLR artificial skin. Specialized layers are

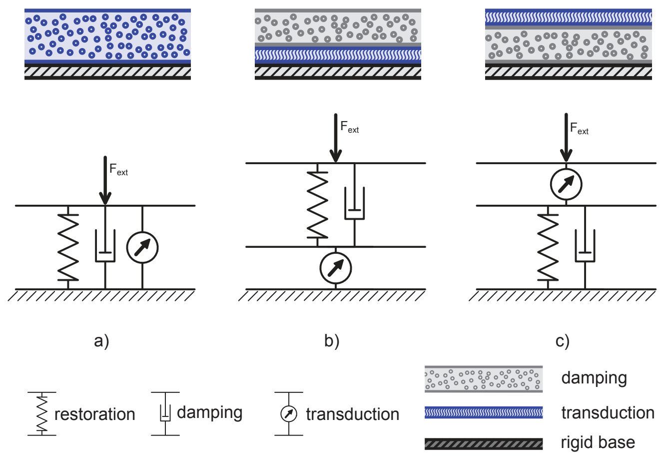

Fig. 4. The classical setup of tactile sensors (a) consists of a homogeneous material which provides mechanical damping, the transduction effect and the required restoration forces. A setup based on a superficial damping layer and an underlying transduction layer (b) is impeded by a reduced initial sensitivity as external stimuli are cushioned by the superficial damping layer. For the DLR Artificial Skin a functional partitioning of the setup based on an internal damping layer and a superficial transduction layer (c) is applied.

combined to achieve the desired overall characteristics of the artificial skin. The properties of the individual layer can be individually optimized without the need to make compromises. The transduction principle of the proposed

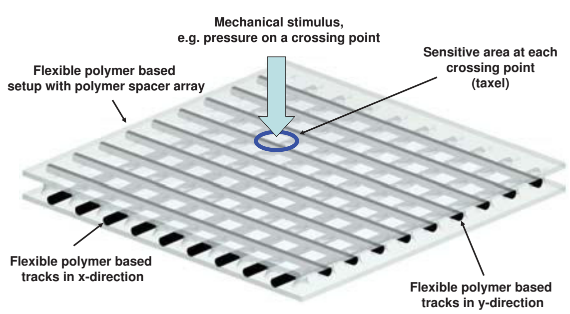

Fig. 5. The sensing principle of the DLR Artificial Skin is based on the acquisition of the change in electrical transfer resistivity at the crossing point of two orthogonally oriented polymer based circuit tracks. An external compressive force results in the deformation of the polymer sandwich foil. Consequently, the contact surface area between the polymer based circuit tracks is increased and the change in electrical transfer resistivity can be measured.

stretchable surface sensor is based on the acquisition of the electrical transfer resistivity between polymer based circuit tracks (PBCT) that are arranged in two orthogonal layers. At each crossing point between two electrodes, a sensitive area, a taxel, is formed. Figure 5 depicts the working principle of the tactile surface sensor. The mechanical structure of the tactile surface sensor consists of two polymer substrates, which are separated by polymer spacers. In order to further enhance the sensitivity the taxels are located within the geometrically defined voids between the spacers of the mechanical structure. In addition, macroscopic surface structures concentrate the external indentation force towards the location of the taxels. Thus, small external stimuli result in an indentation of the surface structure that is supported only by the top polymer substrate. Consequently, the taxel located below the surface structure is mechanically loaded. The deformation energy required to evoke a measurable sensor output is minimized. If an external mechanical stimulus occurs, the mechanical structure of the tactile surface sensor is deformed. Consequently, as the polymer based electrodes of the orthogonal layers come into mechanical and electrical contact, a change in electrical resistivity becomes measurable. A further compression results in an increase of the contact surface area between the polymer based electrodes and thus results in a further increase of the contacting area between the individual polymer electrodes. Hence, the measurable electrical transfer resistivity is further reduced. In case of high indentation forces, e.g. during a power grasp or a collision, the adjacent polymer spacers propagate the indentation force to the underlying mechanical damping layer. This all-polymer design prevents the mechanical destruction of the taxels, which was observed in a former study [23]. With the lateral functional partitioning a high sensitivity can be obtained without compromising the required robustness. Figure 6 depicts the principle of the lateral functional partitioning.

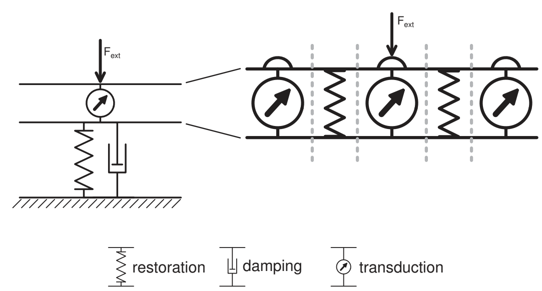

Fig. 6. The sensor setup consists of two polymer substrates that are separated by polymer spacers. Two sets of polymer based electrodes form an array of taxels at each crossing point. In order to increase the sensitivity, the taxels are located within the geometrically defined voids of the tactile surface sensor. Thus a lateral functional partitioning is realized. The transduction is spatially separated from the polymer spacers that provide the required restoration forces. In case of a collision, the polymer spacers propagate the impact energy to the underlying mechanical damping layer.

IV. THE DLR APPROACH TOWARDS SCALABILITY

For the design process of the DLR Artificial Skin we envisage a future touch sensitive full-body cover for humanoid robotic systems. In order to approach this goal, multimodal scalability is applied as a basic design paradigm for the DLR Artificial Skin. Here, multimodal refers to scalability with respect to

- size,
- spatial resolution
- measuring range and
- readout frequency.

A. Reduction of the wiring complexity

The first step towards whole body covers for robotic systems is the reduction of the wiring complexity, which is most commonly addressed by the application of matrix structures for the electrical connection of the individual taxels. Figure 7 depicts the basic contacting principles. The individual connection of each taxel, depicted in Figure 7a), prevents the crosstalk between the taxels and thus yields the best results with respect to signal quality. The major drawback of this approach is the multitude of required readout wires that contradicts the desired spatial integration into a humanoid robotic system. Figure 7b) depicts the most common approach, a matrix setup for the contacting electrodes. This setup requires a sequential connection of the individual taxels to the readout electronics and thus limits the readout frequency. Moreover, the matrix approach suffers from crosstalk between the individual taxels. Figure 7c) depicts a 4-wire connection of the boundaries of the sensitive surface. These so called "electrical impedance tomography (EIT) approaches"(e.g. by [24]) are based on the calculation of the location and intensity of indentations from the distribution of the currents that are acquired via the electrodes at the boundaries of the sensor. The EIT approaches generally lack the spatial resolution required e.g. for robotic fingertips. With respect to scalability, a matrix setup for the connection of the taxels offers the best compromise between the number of readout wires and spatial resolution.

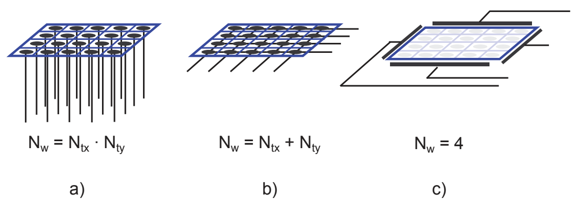

Fig. 7. General contacting principles for the connection of the taxels of an artificial skin. Individual contacting of the taxels (a), results in a minimal cross influencing of the taxels and thus enables a straight forward acquisition of tactile information. The arrangement of the taxels in a matrix configuration (b), results in cross influencing of the individual taxels requiring compensation in the readout circuit. The maximum reduction of the number of readout wires is achieved if the sensitive area is contacted at the edges only (c). While enabling minimal numbers of readout wires, this approach results in the reduction of the achievable spatial resolution and reduces the ability of the sensor to detect multiple simultaneous indentations.

B. Scalability of taxel size

The applied sensor principle is based on scalable manufacturing processes. Thus, the width of the PBCT and hence the size of the individual taxels can be adapted to the application site. For a detailed description of the manufacturing processes please refer to [18]. Figure 8 depicts two sensor prototypes with a spatial resolution of $1.25\ mm$ and $2.5\ mm$.

C. Scalability of the measuring range

Initial tests of the high resolution prototypes have revealed a quasi binary sensor output to external mechanical loading of the PBCT with circular cross section. To optimize the transduction properties and to enable a scalable measuring range, the cross section of the PBCT is altered from circular to triangular cross section of the PBCT. For the simulation of the transduction properties, the symmetry at the crossing point of the PBCT was used to minimize the computational effort, see figure 9. In order to adjust the measurement range the angle of the PBCT is varied in the simulation. Figure 11 depicts the dependency of the calculated surface area for different elevation angles of the cross section of the PBCT.

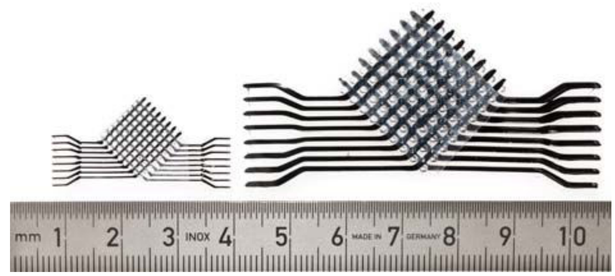

Fig. 8. Prototypes of the scalable tactile surface sensor of the artificial skin. The sensor on the left provides a spatial resolution of $1.25mm$, e.g. for the equipment of robotic fingertips. The sensor prototype on the right provides a spatial resolution of $2.5mm$, e.g. for the palms of robotic hands. The figure illustrates the scalability of the proposed sensor design and the underlying manufacturing processes.

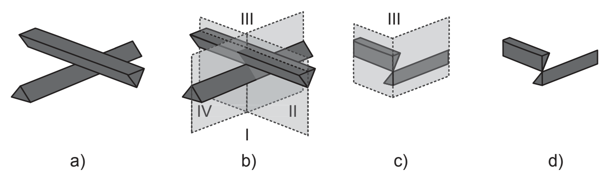

Fig. 9. To reduce the computational effort for the simulation of the transduction properties of a taxel (a), the symmetry of the setup (b) is used to reduce the model to a quarter of the taxel (c,d).

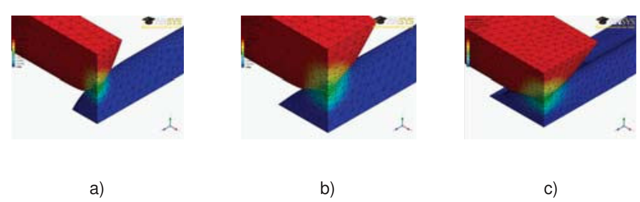

Fig. 10. The angle of the PBCT is varied in order to evaluate the adaptability of the transduction properties based on an alternation of the angle of the triangular PBCT. The simulation is conducted for an angle of $30°$ (a), $45°$(b) and $60°$.

V. SCALABLE READOUT SYSTEM

At DLR the approach towards a scalable readout electronics for a whole body cover of a humanoid robotic system is based on the works of [26]. The basic idea for the scalability of the readout system is based on the work of Speeter, [27], who already proposed a variable electrical connection of the individual column electrodes in 1990. For the DLR

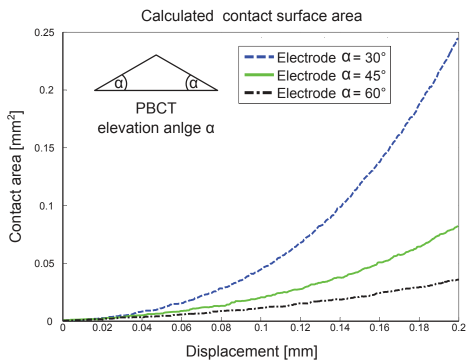

Fig. 11. The above figure depicts the results of a FEM analysis conducted in Krauß [25]. An external indentation force results in a deflection of the upper PBCT and thus results in a change of the contact surface between the triangular PBCT. Depending on the elevation angle of the PBCT the dependency of the contact surface area from the displacement in normal direction can be adapted. Thus, the transduction properties of the normal force acquisition taxel can be scaled to the requirements of the application site on a robotic system; figure curtesy of Krauß [25].

approach the strategy of Speeter is extended. The usually applied multiplexers are replaced by analog switches for both, the supply and the readout electrodes of the tactile sensor array. This setup allows the dynamic connection of individual row and column electrodes. Thus, the individual taxels can be connected to form variable receptive fields, see figure 12. Consequently, this allows the dynamic adaptation of the surface area of the receptive fields. One may argue that the readout frequency is increased at the cost of spatial resolution. For safe physical Human-Robot-Interaction (pHRI) and manipulation in human centered environments a fast collision detection is essential according to [28]. Combining fast collision detection with full spatial resolution of the tactile sensor results in long conversion times and demands, high bandwidth for the transfer of the collected data to the processing robot control systems. Here the restrictions of the envisioned spatial integration of an artificial skin system into a humanoid robotic system become apparent. The limited designed space prevents the introduction of high bandwidth bus systems that require bulky cables. In order to decide, whether a collision event between the cover of the robot and another object has occurred, in the first approximation only binary contact information from activated taxels is required. The interconnection of individual taxels of a tactile sensor array enables the reduction of the spatial resolution and prevents insensitive areas within the tactile sensor array. The clustering of individual taxels can be implemented in different granularity as shown in figure 12. This enables a combination of all taxels into one or in clusters of multiples of two. This setup increases the readout speed at the cost of a reduced spatial resolution. However, after the detection of a collision event, the processing unit is able to report this event to the robot control system with a reduced delay. Subsequently, the spatial resolution is increased step by step. The acquisition of the activation state of individual taxels at the maximum spatial resolution enables the precise determination of the extent of the surface area of the contact. The

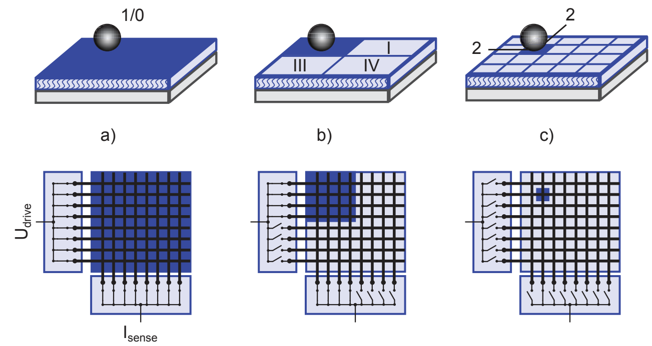

Fig. 12. Scalability of daisy chained analog switches controlled via SPI bus enables scalable processing units for tactile data acquisition. Thus, the minimization of the reaction time of the artificial skin to a contact event is based on a readout strategy that allows for the sequential increase of information depth.

readout electronics for the DLR Artificial Skin is based on digitally controlled analog switches instead of the commonly applied multiplexers for the connection of the tactile sensor array and the processing unit. The switches are configured via a Serial Peripheral Interface (SPI), reducing the wiring effort compared to binary controlled multiplexers, abetting the design of a processing unit with miniaturized dimensions for the envisioned spatial and functional integration e.g. in robotic fingers. Figure 13 depicts the second generation of

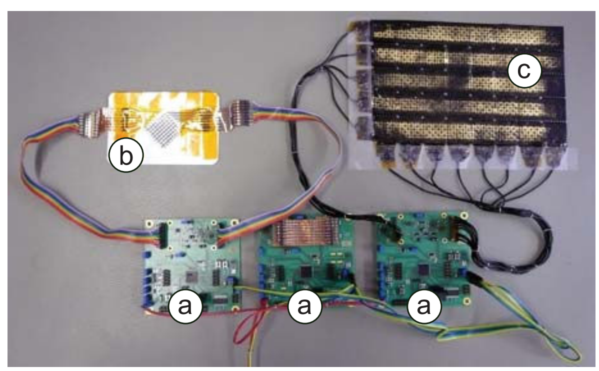

Fig. 13. Multiple processing units (a) connected to different types of tactile sensor arrays (b, high spatial resolution) and (c, large tactile area) for experiments with multiple processing units sharing the same bus for data transfer, first shown in [26]

the readout electronics for the DLR Artificial Skin as designed in [26]. Here, three readout modules (a) are combined to acquire tactile information simultaneously from different tactile sensor arrays, (b and c). The processing unit in the center of the setup is connected to an array of common resistors for reference. As shown in figure 14, analog switches controlled by SPI can be cascaded. For the second generation of the readout electronics the analog switches are combined with a microcontroller. The applied analog switches are packaged with eight switches per device and thus enable the direct interfacing of tactile sensor arrays with 8×8 taxels.

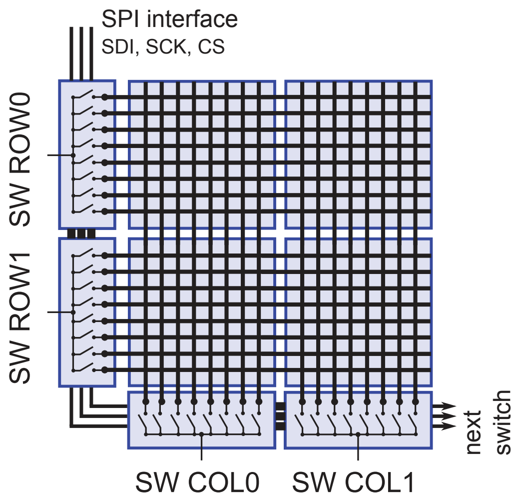

Fig. 14. Scalability of daisy-chained analog switches that are controlled via a SPI bus enable scalable processing units for the acquisition of tactile data from large area touch sensitive whole body covers.

In addition to the scalability of the number of rows and columns, a scalability of the measurable range of the transfer resistivity of the taxels is implemented in the processing unit using a digitally controlled sensing resistor. This variable sensing resistor enables on the one hand, the acquisition of a larger range of transfer resistivity of the taxels and on the other hand, allows the dynamic compensation of the variable length of the contacting electrodes and the resulting increase in resistivity in the PBCT within cascaded tactile sensor arrays. Thus, large area tactile sensor arrays based on a scalable number of rows and columns as basis for the design of a whole body cover for a humanoid robotic system become feasible.

Equation 1 shows the simplified composition of the time for the readout of one taxel. In this equation the time spans are t_{sw} the time for switching the analog switches, t_{st} the stabilization time of the amplifier and filter circuit (depending on the filter characteristics), t_{conv} the conversion- and readout time of the analog-to-digital converter, t_{proc} the processing time of the microcontroller and t_{tr} the transmission time required for the transfer of the tactile data to the robot control system.

$$t_{readout} = t_{sw} + t_{st} + t_{conv} + t_{proc} + t_{tr} \quad (1)$$

The data acquired by the processing unit is transferred via a Controller Area Network (CAN) based on CAN 2.0B standard at a transfer rate of $1\ Mbit/s$. For a whole body artificial skin based on multiple processing units on the same bus the extended identifier of the CAN 2.0B standard is applied. This enables the implementation of a decoder software that is capable to determine from which processing unit the tactile data originates. This determination is implemented by using the identifiers of the CAN messages. In addition, this enables a prioritization of the acquired data. Applying CAN for the data transmission results in a transmission time of $t_{tr} = 76\ \mu s$ for a single taxel at a resolution of eight bit. In contrast, the time for data acquisition for one taxel can be approximated as:

$$t_{acq} \approx t_{sw} + t_{st} + t_{conv} + t_{proc} \approx 15\ \mu s. \quad (2)$$

Thus, the maximum speed of the readout system is solely limited by the bandwidth of the CAN bus system as

$$t_{tr} > t_{acq}. \quad (3)$$

This limitation results in an overlapping acquisition of new data during the transmission of the previous data package. Hence, the theoretical time for the readout equals the transmission time:

$$t_{readout} = t_{tr} = 76\ \mu s. \quad (4)$$

The update rate of the sensor data is furthermore limited by the CAN interface of the control system. In the current DLR assembly an update rate of $5\ kHz$ has been achieved with one processing unit on the bus system reading a single tactile element: Multiple processing units sharing the same bus resulting in update rates of $5\ kHz$ divided by the number of processing units. A tactile array of 8×8 independent processed tactile elements is transferred in eight messages using the maximum payload of the CAN 2.0B standard. In this case data acquisition lasts

$$t_{acq} = 15\ \mu s \cdot 8 \cdot 8 = 960\ \mu s \quad (5)$$

and transmission time

$$t_{tr} = 131\ \mu s \cdot 8 = 1041\ \mu s \quad (6)$$

resulting in a theoretical update rate of about $960\ Hz$ in continuous sampling mode. A measured update rate of $409\ Hz$ was achieved in an impact experiment shown in figure 15, see [1].

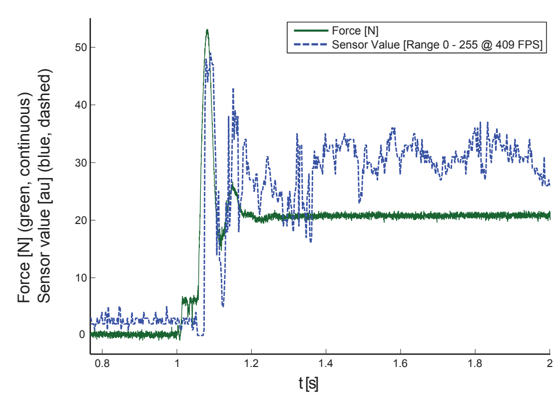

Fig. 15. Dynamic response of the tactile surface sensor prototype during the overload testing. The depicted graph illustrates the capability of the presented prototype to withstand the high impact forces ($50\ N$) and at the same time acquire tactile data at a rate of 409 FPS. The green solid line depicts the impact forces in Newton, acquired by the high speed force sensor of the testbed designed by [29]. The blue dashed line depicts the output of the tactile surface sensor in arbitrary units ranging from $0 - 255$.

VI. EXPERIMENTS

Initial experiments for the evaluation of the correlation between the external applied force and the electrical transfer resistivity of a single taxel were conducted with a test setup depicted in figure 16. PBCTs with different cross section shapes were applied to gold plated support structures. The lower part of the assembly is mounted on a load cell. Moving the upper part of the assembly with a linear stage downwards results in a deformation of the PBCT and thus increases the contact surface area which results in a decrease of electrical transfer resistivity. In this experiment different triangular cross section shapes of PBCTs are compared. The results are shown in figure 17. The comparison of PBCT with different elevation angles shows that the relation between indentation force and resulting transfer resistivity can be varied if different elevation angles are applied. The non-monotonic output observed for the elevation angle of 60° is most likely a result of the bending of the tip of the PBCT. Therefore for future development the elevation angle of the triangular shaped PBCTs is limited to a range of 30° to 60°. PBCT with an angle exceeding 60° tend to deform prior to polymerization of the PBCT. PBCT with an angle of less than 30° result in a large width and thus reduce the achievable spatial resolution. Figure 17 also demonstrates the high sensitivity of the taxels formed by intersecting PBCTs.

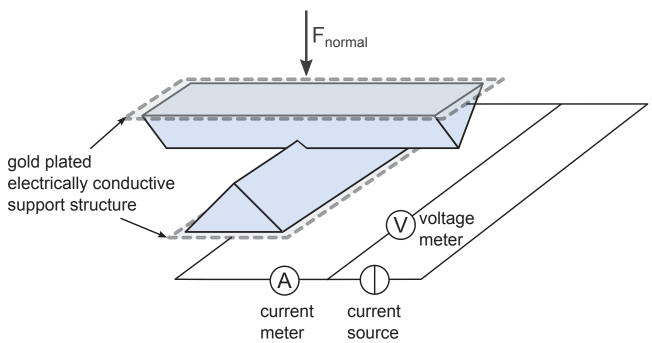

Fig. 16. Initial test of the evaluation of the transduction properties of two intersection PBCT with triangular cross section; Figure adapted from Schnoes [30].

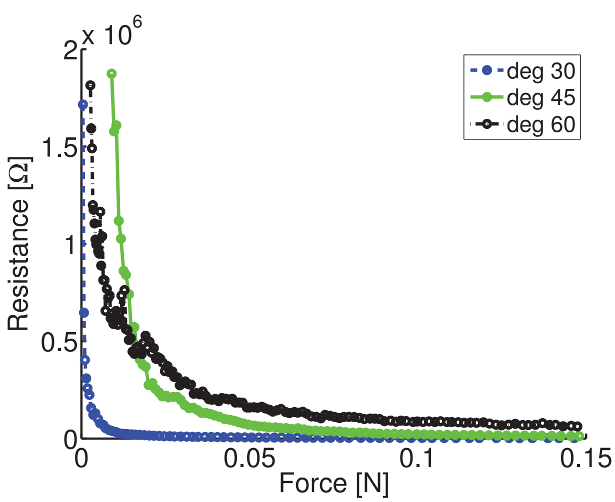

Fig. 17. The adaptation of the relation between the applied external load and the resulting change in transfer resistivity between two intersecting PBCT is demonstrated with triangular cross sections with an elevation angle of 30°, 45° and 60° as described in figure 11.

VII. CONCLUSION AND FUTURE WORKS

The DLR approach towards large area artificial skin as a whole body cover for robotic systems is based on multimodal scalability. The pursued strategy allows the manufacturing of an artificial skin that can be scaled with respect to size, spatial resolution, and measuring range of the transduction hardware. The same holds true for the design of the readout electronics that allows a cascading of the individual readout electronic units. The second generation of the DLR readout electronics for tactile data acquisition is equipped with analog switches and is thus able to detect collisions within the duration of the readout of a single taxel. This strategy solves the goal conflict between required high speed readout capabilities for the reliable detection of collision events and the desired large overall number of taxels of a whole body touch sensitive cover. The experiments conducted with the prototypes of the DLR Artificial Skin demonstrate that the design of the readout electronics supports the combination of multiple readout units and thus forms the basis for the implementation of a future whole body touch sensitive cover for robotic systems. Future work will be focussed on the optimization of the transduction properties of the DLR Artificial Skin. Therefore, the mechanic support structure, in addition to the adaptation of the elevation angle of the PBCTs, will be applied as a means of scalability to further tune the measurement sensitivity and range to fit the requirements of the respective application site on the robotic system. Furthermore, the experiments identified the CAN bus system to be the bottle neck in the data acquisition setup. Therefore, future works will concentrate on the replacement of the CAN bus system.

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