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In-Sole MEMS Pressure Sensing for a Lower-Extremity Exoskeleton*

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***Abstract* – The control system for the Berkeley Lower Extremity Exoskeleton (BLEEX) requires ground contact pressure information to operate safely and effectively. Commercially available in-sole sensors do not have sufficient bandwidth, accuracy and reliability for such a system. We have designed and prototyped an in-sole ground contact sensor that uses MEMS pressure transducers placed in an array of hermetically sealed cavities. This system provides a robust method to monitor ground contact pressures.**

***Index Terms* – Pressure Sensing, MEMS, Exoskeletons, Ground Contact Pressure.**

I. INTRODUCTION

A lower-extremity exoskeleton robot can be used to increase a person's payload capacity and endurance. The Berkeley Lower-Extremity Exoskeleton (BLEEX) is an example of such a device. The BLEEX system senses the wearer's intended movements and provides additional force. The system is self-powered, robust and durable. It utilizes hydraulic actuation and a high-speed control network [1]. Providing ground contact pressure information to the robot's control system would provide more reliable control in rugged environments. For example, if the robot can sense what phase of gait the wearer is in, a more intelligent response can be provided. If the robot simply amplifies all forces it senses, events such as hitting a toe on a rock could be worsened by the exoskeleton. Multi-site plantar pressure sensors have been used to detect gait phases for clinical purposes [2].

A number of in-shoe systems exist for monitoring contact forces and pressures in clinical environments. The most commonly used method places force sensitive resistors around the foot/shoe interface [2]. The accuracy and reliability of these sensors is limited [3,4]. The relatively slow response time of the sensors in these systems precludes their use in real-time control applications, as is required for the BLEEX. In addition, they are not robust or reliable enough to be used in the demanding environments required for the proposed application. Load cells can provide multi-axis force data and are more accurate and reliable. However, they are too large and heavy to allow multi-site data collection.

In this paper, we present the design of a novel, in-sole ground contact pressure sensing system consisting of an array of hermetically sealed Micro-Electromechanical Systems (MEMS) pressure transducers. The general concept will be described, as well as the design of the pressure transducers, electronics, and packaging. The design provides an accurate and robust method for monitoring contact forces at multiple points on the sole.

II. DESIGN

A. Concept

The system design concept is depicted in Fig. 1. A two-piece sole is placed in or under the wearer's shoe or boot. This sole contains an array of hermetically sealed cavities. It is constructed of two rubber parts, an upper sole and a lower sole, to allow sensors and electronics to be placed inside the cavities. Each cavity contains a MEMS pressure transducer and front-end signal processing electronics. As the sole comes in contact with the ground, the cavities are compressed, causing an internal increase in air pressure. This pressure is measured by the transducers. Power and signal wires are placed throughout the sole. Data acquisition and control electronics are placed on the robot, external to the sole.

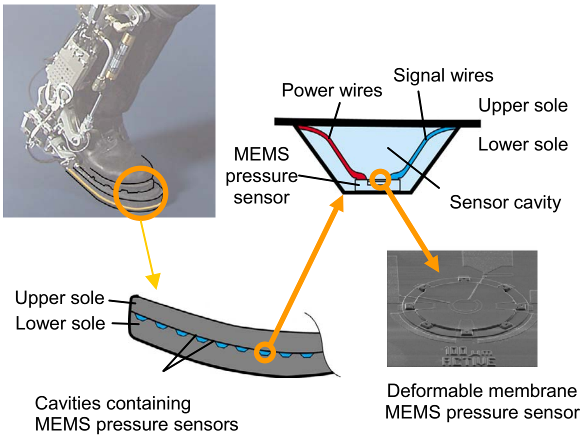

Fig. 1 In-Sole ground contact force sensing concept using MEMS pressure transducers arrayed in hermetically sealed cavities.

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B. MEMS Pressure Transducers

A number of different MEMS pressure transducer designs were evaluated (see Fig. 2) but the principle of operation was similar for each. Piezo-resistive traces were etched onto a flexible drum-head diaphragm. A reference cavity is machined below the cavity that is maintained at a constant pressure. As the pressure above the diaphragm is increased, the diaphragm flexes, changing the effective resistance of the traces. The traces were placed in a half- or full-Wheatstone Bridge configuration so the change in resistance could be correlated to a resulting analog voltage signal. The size and shape of the diaphragm and the trace configurations were varied. Fig. 2 shows 15 designs on a 3- x 6-mm MEMS die.

Fig. 3 shows a microscope image of a full-bridge design, along with a drawing describing the transducer's principle of operation. In the full-bridge designs, two sets of traces experience tension and two experience compression when the membrane is flexed. In the half-bridge designs, two of the traces are off the membrane, typically resulting in a less-sensitive device. Fig. 4 shows pressure versus voltage data for the device type shown in Fig. 3, which was one of the better performing designs.

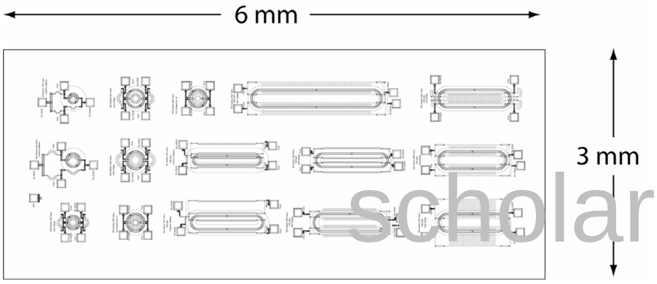

Fig. 2 MEMS die with transducer designs. The 3- x 6-mm silicon die pictured here contains 15 different pressure transducer designs.

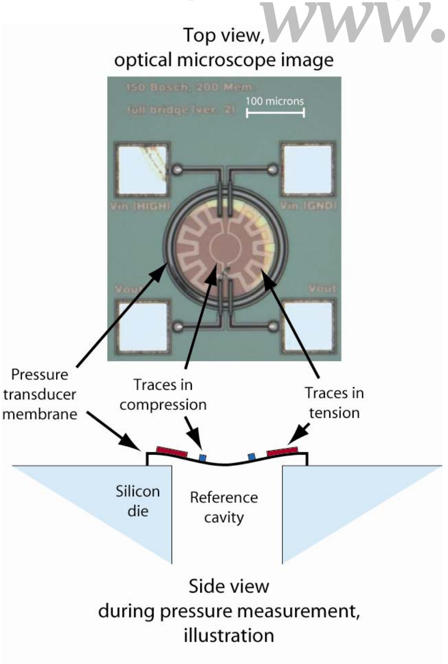

Fig. 3 One of the fifteen transducer designs fabricated. The transducer shown here is a full Wheatstone bridge configuration with two traces in tension and two in compression.

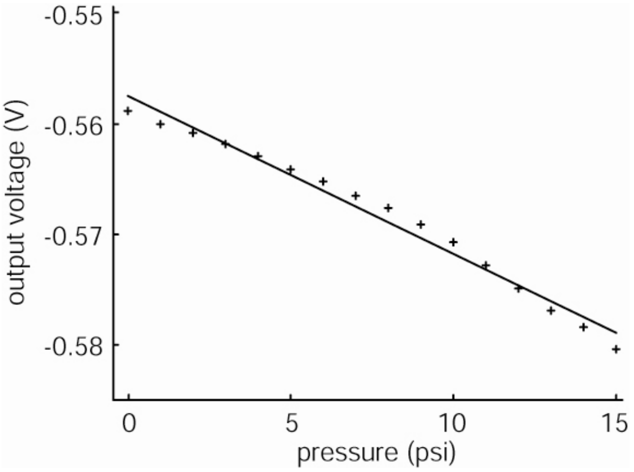

Fig. 4 Output voltage vs. pressure difference across the transducer membrane for the transducer type shown in Fig. 3. Also shown is a linear fit to the data.

Although the data shown in Fig. 4 is approximately linear (root mean square deviation from a linear fit is 4.3% of the range), a quadratic model fits the data much better (root mean square deviation from a quadratic fit is 1.1% of the range), and will be simple to implement in the post-processor. Repeatability of the measurements is excellent, with subsequent measurements showing a standard deviation of 0.2 mV. The measurements show excellent stability as well, typically changing by 0.1 mV or less within the first minute after the pressure is changed. The current generation of transducers has shown good reliability and robustness with measurement repeatability being maintained after thousands of pressure cycles.

The significant non-zero offset of -0.558 V is due to residual stress in the membrane and limits the resolution with which measurements can be made using the current generation of transducers. In order to address this, the next generation of transducers has been designed to have on-die trim resistors, allowing a much lower offset, and hence a higher measurement resolution, to be achieved. Other changes in the next generation of transducers include optimization for measurement sensitivity, ruggedness of the membrane, and ease of packaging.

C. Cavity and Sole

The cavity containing the transducer must be carefully designed to provide good sensitivity while ensuring that the electronics are not crushed as the cavity is compressed. Finite element analyses were performed to assess the pressure and displacement characteristics for a number of designs. The results of these analyses are summarized in Fig. 5. Cavity dimensions were selected based on the expected geometry of the sensors and electronics and appropriate air pocket size, while the thickness of the sole and boundary constraints were varied. Various rubber-like materials were also compared using similar analyses (not shown in figure).

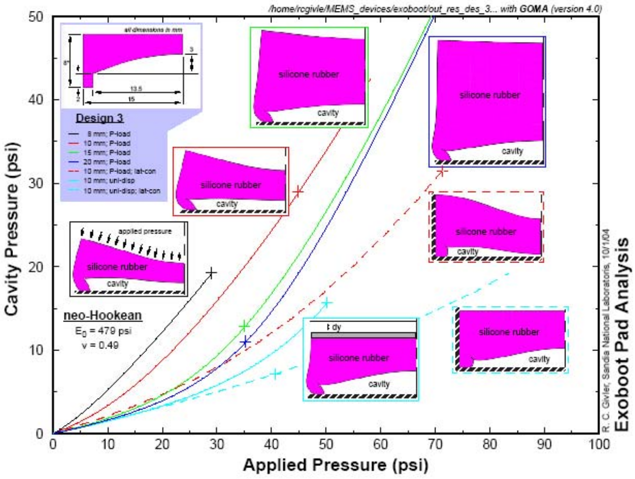

Fig. 5 Finite element analysis of various sole thicknesses and boundary constraints for pressure cavities. Material properties and some representative displacements are shown on the plot.

Fig. 6 Sole prototype. The lower (top) and upper portions of the sole are shown. A flexible circuit board has been placed in the upper sole.

A prototype sole with cavity dimensions chosen based on the results of this analysis was constructed (Fig. 6). The dimensions chosen correspond to the cavity that was most sensitive to external loads while not collapsing enough to harm the components under the maximum expected pressure (70 psi). The sole has an upper and lower part. The lower sole contains the cavities, while the upper portion contains areas for flexible circuit board routing. This prototype contains 8 cavities, placed at locations that would indicate the wearer's gait phase. Rings surrounding the cavities were added to improve sealing. When all sensors and electronics have been appropriately packaged, the two sole pieces are sealed together with an adhesive. This completes the seal around each cavity and provides a package that is waterproof and robust to rugged terrain. The adhesive has been tested over thousands of cycles in the sole with no delamination.

D. *Flexible Circuit Board*

A major design challenge for the system is providing power and signal connections to the sensors and front-end electronics in a flexible sole. Flexible wire routing can be provided but care must be taken to ensure that the wires are not strained excessively as the sole flexes as this can lead to fatigue failure. For the prototype described here, a single-layer flexible circuit board was designed so that all electrical traces could be placed on the neutral axis of the substrate (see Fig. 6). The board itself is placed on the neutral axis of the sole. The board has 1 oz. copper traces with a 0.003" polyiamide film on either side. Plastic stiffeners are placed in the areas where the sensors and electronics are mounted to provide stability. The board terminates with a zero-insertion-force (ZIF) connection that interfaces with the data acquisition board described below. The board is predicted to last over 2 million cycles with the current design and has been tested over thousands of cycles.

E. *Data Acquisition Electronics*

By realizing the MEMS pressure sensor as a half or full-bridge strain gauge circuit, sensor pressure was expressed as a small analog differential voltage. Since the design required several pressure sensors, some attention was given to designing a data acquisition circuit that could condition and sample several small differential voltages and send this pressure data to the Exoskeleton controller. It was required that the performance of the data acquisition circuit be sufficient that any delays in gathering and delivering the data to the controller not be so large that the control suffered. Initial prototyping efforts indicated that the data acquisition effort was less challenging than the development of sensors with a consistent signal quality.

For an 8-sensor implementation, the data acquisition required a simple front-end circuit to interface with each MEMS device and an 8-bit processor to collect the data using eight analog-to-digital converters. The front-end circuit amplified the differential voltage from the MEMS device and shifted it up so that it was centered at half the supply voltage of the processor. The processor sampled each of the eight signals with 10-bits of resolution and subsequently sent the combined data packet using the processor's universal asynchronous receiver-transmitter (UART). When sampling continuously and sending data at 115kbaud, the prototype was capable of sampling eight sensors and sending over 300 packets per second, implying a maximum delay of less than 3.3 milliseconds, a sufficiently small delay for control purposes. A 32-sensor system was also built to investigate multiplexing the sensors for measurement. Results of this test validated that the system was scalable; a 32-sensor system required four times as much time to sample, and the packets took four times as much time to send.

III. CONCLUSIONS

While the system described in his paper provides an accurate and lightweight way to measure ground contact pressures, the most important and unique feature is its robustness. It is specifically designed to function in harsh environments for a large number of cycles. As discussed above, each of the major components of the system have shown good reliability. The entire packaged system is currently undergoing reliability studies.

The use of small, lightweight MEMS pressure transducers allows sensing at a much higher spatial resolution than the proof of concept prototype described above. Using unpackaged integrated circuits or placing the signal processing electronics outside of the sealed cavities would allow an array of smaller, more closely placed cavities to be created.

Fig. 7 shows the final, sealed prototype package which is currently undergoing full characterization and long-term reliability studies. The next generation of MEMS pressure transducers are also currently undergoing characterization.

Fig. 7 Top (left) and bottom view of packaged sole. The bottom portion of the sole is semi-transparent and allows viewing of the flexible circuit board and electrical components.

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