Electrical Characterization of 26 x 26 Ground Reaction Sensor Array Interfaced with Two Parallel Electronic Detection Channels

Qingbo Guo, Rajesh Surapaneni, Yu-Pin Hsu, Carlos Mastrangelo and Darrin J. Young
Department of Electrical and Computer Engineering, University of Utah
Salt Lake City, Utah, USA, E-mail: qingbo.guo@utah.edu

Abstract*—This paper presents the electrical characterization results of a 26 x 26 high-density ground reaction sensor array (HD-GRSA) interfaced with two parallel electronic detection channels. The system was developed for improving inertial measurement unit (IMU) positioning accuracy. The HD-GRSA is composed of 26 x 26 sensing nodes, which can measure dynamic ground force and shear strain associated with a ground locomotion gait. Each electronic detection channel consists of a front-end multiplexer that can sequentially connect individual sensing nodes from a 13 x 13 sub-array to a capacitance-to-voltage (C/V) converter followed by a 12-bit algorithmic ADC. The electronics were fabricated in a 0.35 µm CMOS process occupying an area of 7.7 mm^2 for each channel while dissipating a DC power of 3 mW from a 3V supply. The HD-GRSA demonstrates the designed functionality achieving a gait ground velocity resolution of approximately 95 µm$_{RMS}$/sec, limited by the electronic interference signals due to the long metal traces on the sensor array. Further performance improvement is expected by employing interference suppression techniques and better matching for critical wiring traces.

I. Introduction

GPS-denied environments call for alternative position tracking solutions. MEMS technology has enabled system integration of miniature low-power inertial measurement units (IMUs) based on accelerometers and gyroscopes. However, these devices suffer from an excessive output drift over time, thus inadequate for a long-term accurate position tracking. It was recently demonstrated the time drift of IMUs could be corrected by integrating with a GRSA [1]. The system combines a commercial IMU with a flexible error-correcting biomechanical GRSA. The IMU and GRSA are placed in close proximity within the heel of a personal boot as depicted in Figure 1, where the IMU can measure inertial information while the biomechanical GRSA independently measures dynamic ground force, shear strain, and sole deformation associated with a ground locomotion gait. During a fraction of the mid-stance of a human bipedal locomotion, the velocity of the heel is close to zero [2]. This critical information can be obtained by measuring pressure contours or contours centroid movement captured by the GRSA placed between the heel and insole of a shoe and in turn provides zero-velocity correction to the IMU, thus drastically reducing inertial error accumulation and improving position tracking accuracy. A prototype system incorporating a commercial insole-shaped pressure sensor array was implemented with an IMU mounted externally to a boot near its heel. The pressure sensor array consists of 99 sensing elements, where 54 elements were located in the heel portion. A loop-closing walk test over 30 minutes demonstrated a position error less than 4 meters [1]. To enhance the zero-velocity detection accuracy a 13 x 13 GRSA was developed to demonstrate a gait ground velocity resolution of 100 um$_{RMS}$/sec [4]. To further improve the performance, a high-density GRSA consisting of 26 x 26 sensing nodes were designed and fabricated. More data points available from the high-density array are expected to detect much smaller contact pressure profile change during the stationary contact of the heel, thus improving the accuracy of zero-velocity estimation during the mid-stance phase.

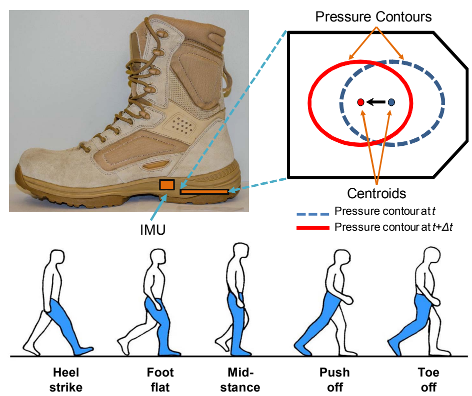

Fig. 1: Proposed personal navigation system employing high-resolution-gait-corrected IMU

II. Two Parallel Electronic Detection Channels for High Density Ground Reaction Sensor Array

Figure 2 presents a 26 x 26 HD-GRSA design employing a capacitive sensing technique described in [3, 4]. An array area of 70 mm x 71 mm is selected to fully cover a typical foot heel dimension. A sensing node schematic along with its equivalent electrical model is also illustrated in the figure. Each node is composed of two sensors, which can detect the z-axis pressure as well as x/y axes shear stress. For navigation, besides the normal pressure sensing it is desirable to obtain shear force for slippage detection and shoe rotation estimation. Each sensor can be dynamically configured by using electronic switches to achieve z-axis (single-ended) pressure and x/y-axes (differential) shear stress sensing. The minimum detectable velocity, MDV, achievable by the GRSA can be determined by using the following expression,

$$MDV = \frac{\Delta l}{DR * T_S}$$

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where Δl is the sensor pitch size, DR is the system dynamic range, and T_s is the processing time allowed during the mid-stance for the zero-velocity estimation. Therefore, given the sensor pitch size of approximately 2.7 mm in the prototype design, a system dynamic range of 60 dB (10-bits), and a processing time of 200 msec, a MDV of approximately15 µm/sec can be expected. The sensor array was fabricated by using the process flow outlined in [3]. A copper layer with a thickness of 8 µm was first electroplated over a 50 µm-thick kapton to form the array driving and sensing electrodes. A PDMS layer with a thickness of 10 µm was then spun on as the dielectric material, followed by depositing a 1 µm-thick parylene serving as an adhesion layer for the subsequent metallization. At this point, a 150 nm-thick gold layer was deposited and patterned to form the array top floating electrodes. The fabricated sensing nodes exhibit a nominal capacitance value of approximately 1.2 pF and 0.6 pF for the single-ended mode and differential mode, respectively, with a capacitance change of 10% and 1.4% under a maximum load for the corresponding modes.

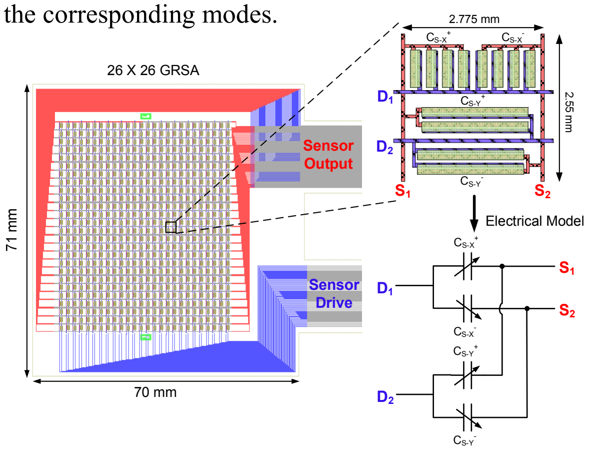

Fig. 2: HD-GRSA design, layout and sensor electrical model

Figure 3 presents the general architecture of the two-channel electronic sensing system for the prototype HD-GRSA. The HD-GRSA exhibits 104 sensing lines and 52 driving lines. Each sensor in the array can be accessed by configuring the MUX in the ASIC to select the corresponding sensing and driving lines as depicted in the figure. A selected pair of sensing lines is connected to a capacitance-to-voltage (C/V) converter followed by a 12-bit 66.7 k-sample/sec algorithm ADC. Other key building blocks implemented in the ASIC including digital timing & control unit and a driving circuitry.

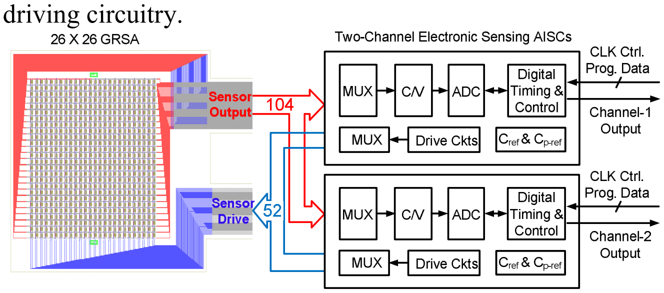

Fig. 3: Two-channel sensing electronic system for HD-GRSA

The design of the front-end sensing electronics, consisting of MUX, C/V converter, and programmable reference capacitors, is shown in Figure 4, where a half of the HD-GRSA sensing node model shown in Figure 2, i.e. a pair of differential sensing capacitors, C_s^+ and C_s^-, is used for simplicity. By properly configuring $\Phi_{X/Y}$ and Φ_Z, the sensing electronics can interrogate each sensing node along the z-axis or x/y-axes. When $\Phi_{X/Y}$ is closed, the sensor capacitance difference between C_S^+ and C_S^- will be converted to an output voltage. When Φ_Z is closed, C_S^+ and C_S^- will be combined together. The C/V converter will process the capacitance difference between the sum of the sensing capacitances and an on-chip programmable reference capacitor, C_{ref}. The capacitance difference thus represents the normal pressure information. During each reading, only a pair of sensors is selected for stimulation. The remaining sensors that share the same sensing lines are all grounded at their driving nodes. The grounded sensors thus form the parasitic capacitance at the input stage of the C/V converter. An on-chip programmable parasitic reference capacitor, $C_{p\text{-}ref}$, is incorporated to match with the array parasitic capacitance. This parasitic capacitance matching technique is not only critical for ensuring a proper operation of the C/V converter, but also for suppressing potential interference effect from the ground [5]. The capacitive sensor is interfaced with a switched-capacitor-based fully differential C/V converter. The converter is designed to alternatively operate between single-ended mode and differential mode to sequentially scan each sensing node in an array. A 10 msec array scanning time is chosen as a trade-off between power dissipation and number of frames needed to estimate a gait ground velocity, thus allocating 60 µsec to complete a sequential z, x, z and y sensing for each node. The switchable integrating capacitor, C_{I2}, is connected in parallel with C_{I1} in the single-ended mode. C_{I1} and C_{I2} are designed to be 0.7 pF, thus resulting in an integrating capacitor of 1.4 pF for the single-ended mode and 0.7 pF for the differential mode. The integrating capacitors value is chosen to ensure a proper signal swing level at the output of the C/V converter.

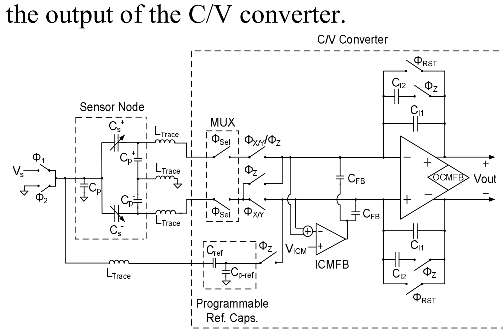

Fig. 4: Front-end sensing electronic design architecture

III. System Integration and Electrical Characterization of HD-GRSA

The electronics were fabricated in XFAB 0.35 µm CMOS process. A fabricated ASIC occupies an area of 3.5 mm x 2.2 mm and dissipates 3 mW power. Two ASICs were then mounted into two sockets on a custom-designed PCB and interfaced with the HD-GRSA to form a prototype system as shown in Figure 5. Individual sensing nodes from the sensor array were tested under applied normal pressure. The maximum normal pressure applied on a GRSA inserted into a boot during a normal walking condition is estimated to be around 320 kPa. Figure 6 presents the measured output voltage of the HD-GRSA versus applied normal pressure. Due to a misalignment in photolithography and other process variations, the fabricated arrays exhibited a certain variation in sensitivity as plotted in Figure 6. The general trend indicates the output voltage increases with the pressure initially and then reaches a saturation region. Based on the output voltage change, the PDMS layer thickness shrinkage can be estimated, thus determining the PDMS Young's modulus of approximately 2 MPa under a normal pressure of 320 kPa. This results is a close agreement with previously published data [4, 6]. In order to detect a small pressure contour change or contour centroid movement to capture zero-velocity information associated with a human bipedal locomotion, it is necessary to sense small pressure variation centered around the nominal pressure bias point of 320 kPa, which calls for calculating the slope (or small-signal Young's modulus) of the measured strain versus pressure profile. The calculation reveals the PDMS small-signal Young's modulus is approximately 20 MPa around a normal pressure bias point of 320 kPa. The shear characterization was also performed on the prototype HD-GRSA, deriving a shear modulus of approximately 550 kPa.

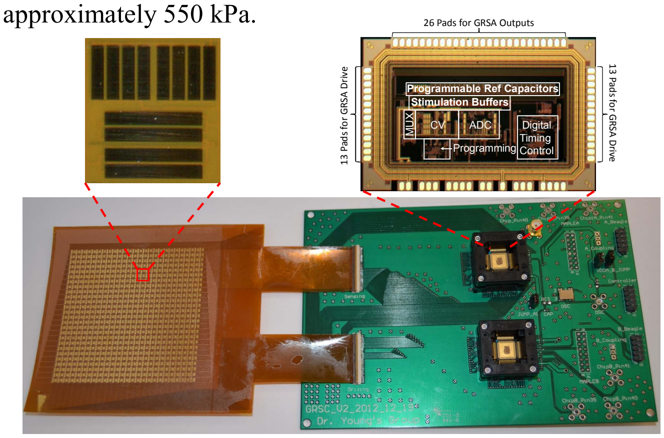

Fig. 5: Two-channel electronic detection system connected to HD-GRSA

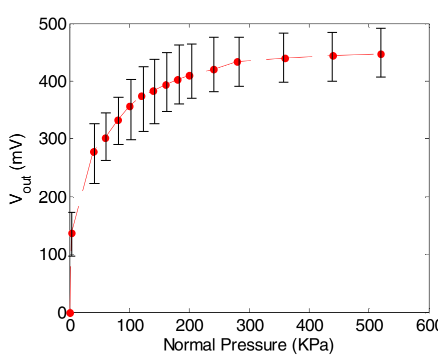

Fig. 6: Measured z-axis output voltage vs. normal pressure

It should be noted that any initial as-fabricated offset capacitance value between $C_{S\text{-}X}^{+}$ and $C_{S\text{-}X}^{-}$ and between $C_{S\text{-}Y}^{+}$ and $C_{S\text{-}Y}^{-}$ will manifest itself as an output voltage in the measured shear response due to the normal pressure effect and vice versa. This cross-axis coupling can potentially degrade the overall system performance. The as-fabricated offset capacitance value is mainly caused by the thermal expansion of the kapton layer during the fabrication process [3], which in turn introduces a misalignment for the photolithographical step to pattern the array floating electrodes. This misalignment, however, can be compensated by re-adjusting the mask accordingly. Figure 7 presents the output offset voltage measured in the shear mode from one quarter of the HD-GRSA, indicating a much reduced offset after mask adjustment. It should be also noted that the type A and type B sensors exhibit the same design but with an alternating interconnections [7]. Therefore, with a same misalignment the two types of sensor will produce a same offset magnitude but with an opposite sign, which is evident in the offset measurement plots shown in Figure 7 before the mask adjustment.

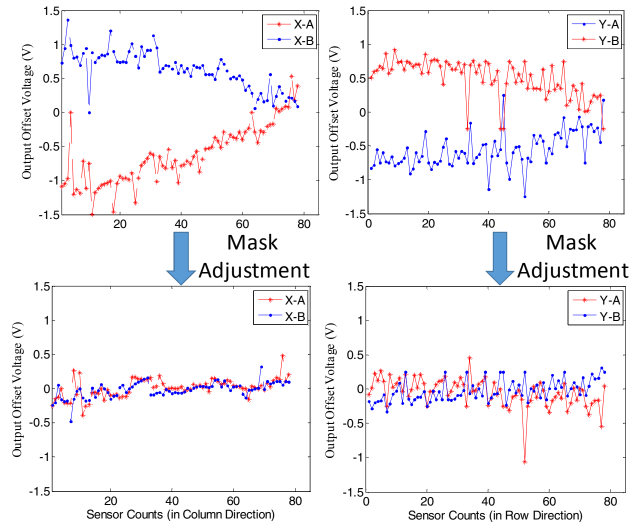

Fig. 7: HD-GRSA misalignment testing before and after mask adjustment

To emulate a standing heel pressure profile under a walking condition, a normal static force was applied onto a soft ball positioned over a HD-GRSA. The softball will deform with the increased normal pressure, which will enlarge the contact area. Figure 8 presents the measured GRSA z-axis output voltage profiles under different applied normal forces at 1.53N, 15N, 20N and 35N, respectively. It can be seen that the sensor array output voltage level and contact area increase with the applied force. The output voltage saturates as the PDMS enters into the saturation region at large force level, thus confirming the measurement results presented in Figure 6.

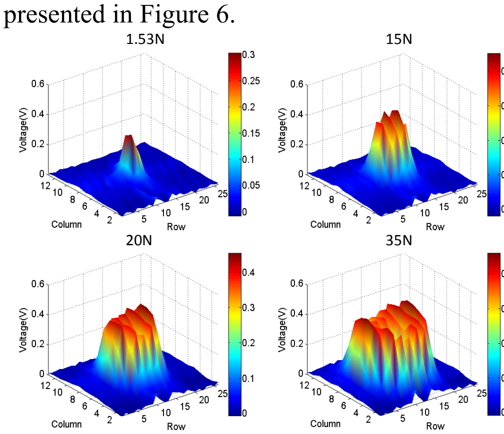

Fig. 8: Output voltage (pressure) profile under normal force applied on as soft ball positioned over HD-GRSA

The centroid position of the pressure contour can be determined by using the following expressions,

$$X_C = \frac{\sum_1^{n_y}(\sum_1^{n_x}(V_{xy} * n_x * \Delta l_x))}{\sum V_{xy}} \text{ and } Y_C = \frac{\sum_1^{n_x}(\sum_1^{n_y}(V_{xy} * n_y * \Delta l_y))}{\sum V_{xy}}$$

where x and y represent the coordinates of a HD-GRSA, V_{xy} is the output voltage from a sensing node located at x and y location, Δl_x and Δl_y represent the sensor pitch size along the x-axis and y-axis, respectively, n_x is the number of columns, and n_y is the number of rows in a HD-GRSA. Furthermore, assuming ΔV_{xy} is the interference/noise from each sensor and is uncorrelated with a nearly consistent value for the entire array, the centroid uncertainty thus can be estimated by using the following expressions.

$$\Delta X_C \cong \frac{\Delta l_x * \sqrt{n_x^3 * n_y/3} * \Delta V_{xy}}{\sum V_{xy}} \text{ and } \Delta Y_C \cong \frac{\Delta l_y * \sqrt{n_y^3 * n_x/3} * \Delta V_{xy}}{\sum V_{xy}}$$

Figure 9 presents the corresponding centroid position with its variation along the x and y axes over a 25-second time frame for the pressure contour profiles shown in Figure 8. Each data point in the plots presents an averaged value of 20 frames, equivalent to a time interval of 200 msec which is adequate for estimating zero-velocity during a mid-stance of a human bipedal locomotion. It is noted that one should calculate the vector sum of the velocity resolution along the x and y axes to determine the centroid velocity resolution. As a result, a vector centroid velocity resolution of approximately 95 μm_{RMS}/sec is determined, which is mainly limited by the electrical interference signals on the order of 12 mV_{RMS} due to the long interconnect traces on the prototype HD-GRSA.

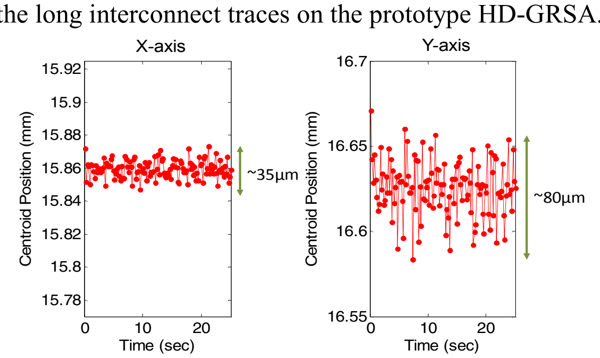

Fig. 9: HD-GRSA pressure contour centroid position and variation

Besides using a soft ball to characterize the HD-GRSA, the sensor array was also subjected to a normal standing test. Figure 10 shows the resulting 2D and 3D views of the pressure contour of a heel during the normal standing. Figure 11 plots the heel centroid position and variation over a time frame of 25 seconds with each data point being averaged over 20 frames. It can be observed that the resulting centroid position drifts by approximately 0.5 mm over the testing time period, which is caused by the heel position drift during testing. The gait ground velocity is determined to be approximately 170 μm_{RMS}/sec, limited by the heel movement and shaking during characterization.

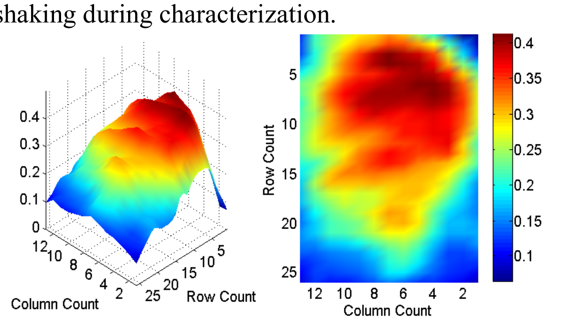

Fig. 10: Output voltage (pressure) profile of heel during normal standing

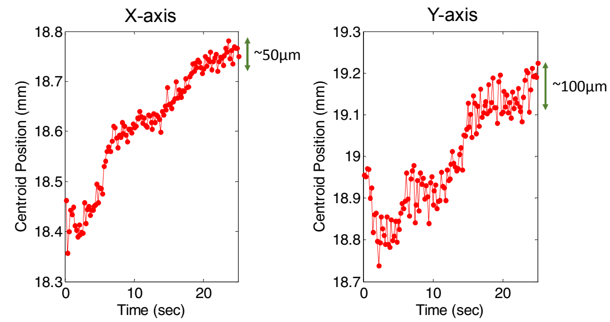

Fig. 11: Heel pressure contour centroid position and variation

IV. Conclusion

A two-channel electronic detection system was developed to characterize a prototype 26 x 26 HD-GRSA. Individual sensors in the array have been characterized for the vertical pressure and lateral shear stress sensing capability. Initial as-fabricated sensor array offset can be effectively compensated by a mask adjustment, thus greatly minimizing potential cross-axis coupling. Static pressure testing through a soft ball positioned over a HD-GRSA indicates a pressure contour centroid position uncertainty of ~8 μm_{RMS} and ~18 μm_{RMS} along the x and y axes, respectively, which corresponds to a gait ground vector velocity resolution of approximately 95 μm_{RMS}/sec. This performance is mainly limited by the large electrical interference signals due to the long interconnect traces on the HD-GRSA. An improved sensing performance is expected by employing interference suppression techniques. The HD-GRSA was also characterized under a normal standing test, demonstrating a gait ground velocity resolution of approximately 170 μm_{RMS}/sec.

Acknowledgement

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