Tactile Sensing by the Sole of the Foot
Part II: Calibration and Real-time Processing

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Abstract

This paper introduces prototype experimental apparatus and the calibration and real-time signal processing required to investigate stability in standing, walking and running of humanoid robots using pressure sensing at the sole-of-the-foot contact. The system can provide very good spatial or temporal resolution and these can be traded off against each other dynamically to accommodate the instantaneous requirement, for example, sparsely sampling the whole sole during static balancing vs. densely sampling the impact region during walking or running. Dynamic variation in sampling policy during different phases of the gait is foreseen so as to optimise utilisation of the total sampling bandwidth available. Periodic signals like walking and running would be sampled repetitively, achieving by accumulation both high spatial and high temporal resolution.

Keywords: Tactile sensing, force/ pressure sensing, humanoid robots, real-time processing

1 Introduction

We aim to characterise and understand the role played by tactile sensing by the sole of the foot in stabilising bipedal standing, walking and running [1-3]. By measuring and understanding the spatial and temporal pressure patterns that are generated during the various phases of human and simulated-human standing and locomotion, we expect to learn how better to control these activities when they are attempted by humanoid robots [4-8] equipped with human-like sole-of-the-foot sensing capability. The literature on human balance control indicates that success will depend on incorporating the pressure sensing by the sole into the actuation algorithm [1-2]. Dynamic adaptation of the sensing and control system so as to customise what is measured spatially and temporally, and how actuation should be adjusted in response, appears to be crucial to bipedal balance for standing, walking, and running, possibly even more so for the former than the latter.

Our prototype apparatus, shown in figure 1a, and our initial experiments, illustrated in figure 1b, were introduced in [9]. These experiments are briefly summarised in the introductory sections of this paper. In the later sections of this paper we describe calibration procedures and issues, new experiments that demonstrate dynamic reallocation of sampling between the spatial and temporal domains, and signal accumulation and averaging over multiple cycles to achieve high resolution in both domains.

2 Apparatus

The apparatus allows static and dynamic loads to be applied to the system, as illustrated in the previously cited figures 1a and 1b. The sensor per se, shown in figure 2, is an x-y-addressed force-sensitive resistor array sold by TekScan[1] for medical diagnosis of foot problems. The sensors are inexpensive, but TekScan's monitoring hardware and software are both prohibitively expensive and generally ill-suited to the experimental scenarios we contemplate [10-17]. We therefore designed and built our own monitor. It uses analog current multiplexers controlled by a single board computer (SBC) to select which of the 960 tactile elements in the sensor array is monitored by the SBC's analog-to-digital converter at any instant.

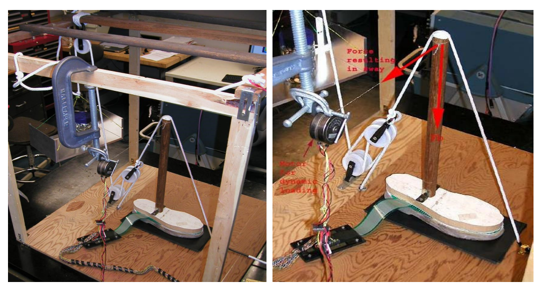

Figure 1: (a) (left) Overview of the apparatus; (b) (right) detail of the foot, leg, static and destabilising loading mechanisms.

Figures 3-6 show the physical and electrical features of the sensor. Individual tactile pressure-sensing elements are addressed via a left-right and front-back grid system, most easily seen in figure 3. The grid is centre-fed so the sensor can be trimmed to fit a shoe. The columns are split, allowing in principle twofold parallel access, but we have not implemented it.

On the SBC's low-level side it controls the analog current multiplexers - selecting the tactile element

[1] TekScan Corporation, South Boston MA, http://www.tekscan.com

desired at each instant - and on its high-level side it communicates with a PC via a serial link. The PC generates the scan sequence that the controller will execute - single tactile element, full raster scan of all tactile elements, low resolution raster scan of all tactile elements, foveal pattern scanning, etc. - so as to trade off the available spatial and temporal resolutions, whose product is limited by the sampling rate of the controller's analog-to-digital controller.

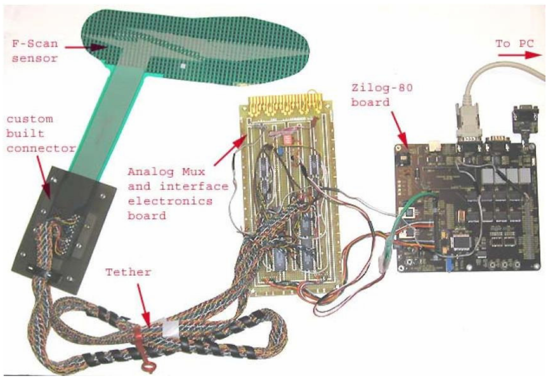

Figure 2: Sensor array, multiplexer, single-board controller.

The PC also supports the user interface, including implementation of the sampling policy either directly or by downloading a programme (which may include dynamic adaptation features), whatever analysis is applied to the sensor data before display, and a false-colour-mapped display of the pressure map.

In this prototype design, destabilising disturbances are generated by a stepper motor (figure 1b) - controlled by the PC's parallel port - that oscillates the tension in a string attached to the knee. The next step in our ongoing programme will be to reverse the sign: to analyse the dynamical behaviour of the pressure map so as to recognise and characterise disturbances and to generate control signals whereby, e.g., a pair of motors will restore stability after a disturbance.

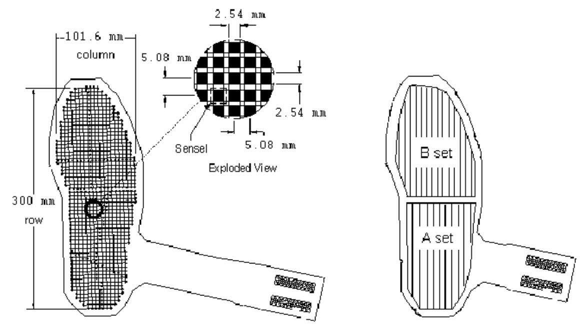

Figure 3: Dimensions and layout of tactile elements. Note that parallel scanning of two elements could be implemented in principle using two ADCs.

3 Calibration

The system is calibrated end-to-end by applying known forces to the whole sensor surface or to smaller groups of tactile elements and measuring the response over a range of input values. This end-to-end calibration allows us to model element-to-element variations due to manufacturing variations, but it does not account for effects such as hysteresis, which is significant in these sorts of pressure-sensitive devices. Nor does it account per se for problems like drift and temperature sensitivity, so the full calibration procedure addresses these separately.

The conductance vs. pressure of each tactile element is approximately linear in the mid- and high-ends of the operating range, but deviates significantly at the low-end, as illustrated in figure 4. The first stage amplifier receiving the current through the addressed tactile element is quasi-linear in the logarithm of the resistance of the addressed element, resulting in the convenient output characteristic seen in figure 5.

Figure 6 illustrate the extent of observed hysteresis and figure 7 illustrates the variation between two randomly selected tactile elements. The hysteresis is sufficiently large that there is no good reason to

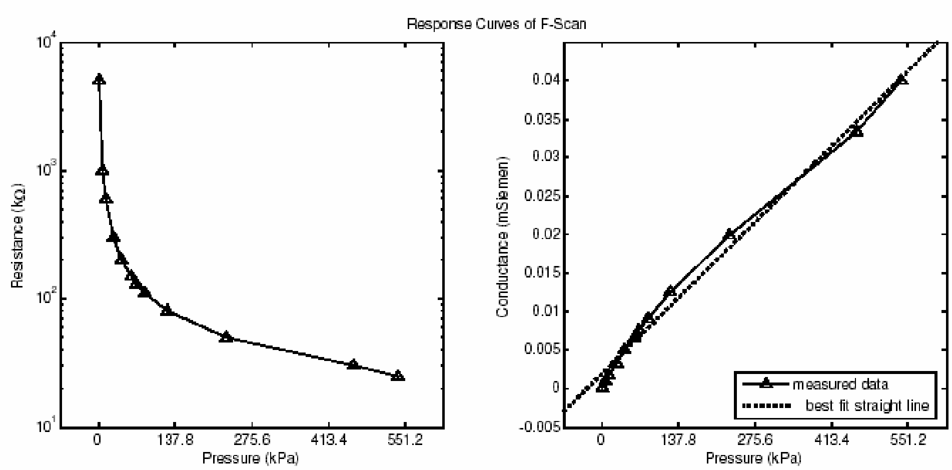

Figure 4: Response curves of a single sensor element.

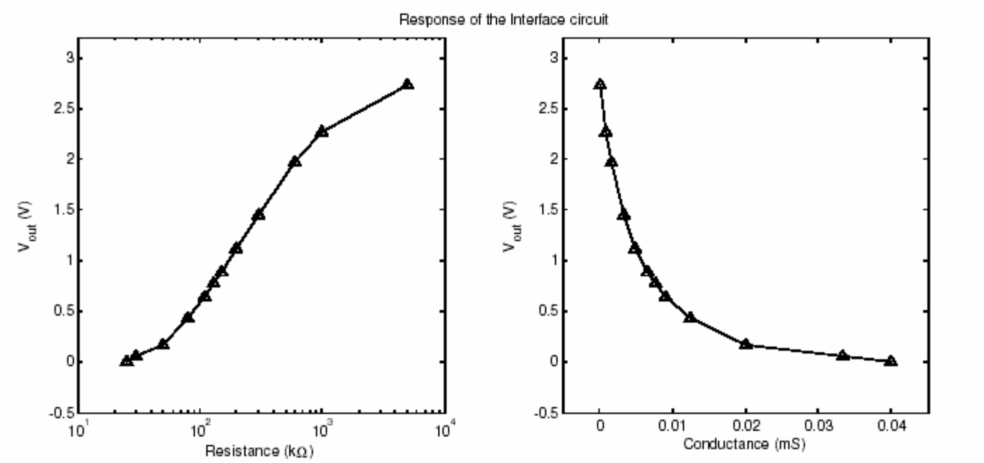

Figure 5: Response curves of interface circuit.

laboriously calibrate individual tactile elements. Figure 8 shows a rational function fit to the end-to-end calibration; we use this function to adequately relate the digital output of the SBC's analog-to-digital converter to the force applied to a tactile element. An absolute error might be as large as 30 kPa, but relative to the anticipated standing and ambulating pressures of a human or a near-human size hominoid robot, this is no more than 20%, which, after spatial and temporal averaging, is more than adequate for the intended applications.

4 Signal Processing

Figure 9 shows the impulse response of the tactile elements to a dropped rubber ball. Sampling of single tactile element can be completed in 0.3 ms, which allows the capture of fast signals, e.g., the impact of the heel strike in walking or running, or push-off with the toe over small regions of the sensor. Inasmuch as the appropriate small area of heel or toe region can be found iteratively over several cycles, this temporal capability seems quite adequate, though future experiments with humans or a running robot may make it necessary to rethink this.

To expand on this point, recall that when studying a periodic signal, such as a walking or running gait, high temporal and spatial resolution can be achieved by sampling and summing over several step periods. Potential difficulties with this approach include the variable period of actual walking and running, e.g., in response to terrain variations, or just fatigue in the human case, or its robotic equivalent as batteries run down. Variation in period can be largely corrected by marking the precise heel strike and toe push-off points and re-scaling time relative to these points in each cycle. Then multiple foot plant periods might be combined to provide an average high spatial and temporal resolution picture. Deviations of individual cycles from this average, i.e. residuals, would be indicative of effects like terrain-induced cycle-to-cycle gait variation and monotonic trends like fatigue.

4.1 Heel Strike and Toe Push-Off

Walking and running gaits include - by definition - a phase where one foot is in flight. During this phase the load on the sensor may be zero and may possibly even be negative - which would be seen as zero by the sensor we are using - depending on the accelerations and the nature of the foot-shoe contact. At the instant when the foot strikes the ground, the transient load increases significantly at the point of contact before being distributed over the foot. At lift-off at the end of the cycle the load may again increase as it is supported by a smaller area - the front of the foot - before finally it is precipitously reduced to zero as the foot leaves the ground.

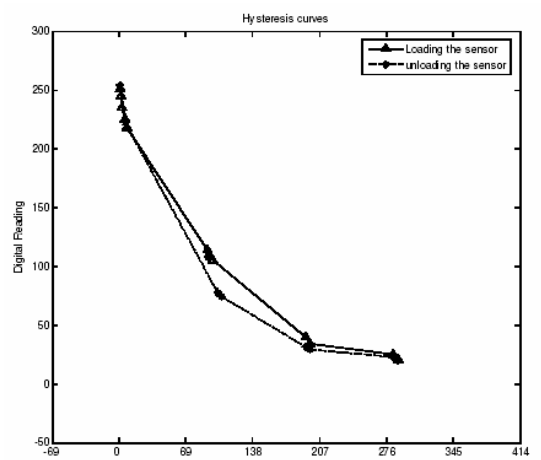

Figure 6: Hysteresis variation in tactile element.

To produce the high spatial and temporal resolution of the foot during the stance phase requires the start and end time of the stance to be located precisely. The sample time when sampling a single tactile element is about 0.3 ms, which is fast enough for most contemplated applications. But to achieve this sampling rate the point of contact must be known, so that sampling can focus on a small predetermined area. For idealised walking and running gaits the heel strike is the first instance of contact. This means that a known small number of tactile elements are loaded initially before the load is distributed to the foot. If fewer than 10 of these can be identified, then a scan with a total cycle time under 3 ms can be made, providing the required accuracy for finding the start of the stance phase. This "3 ms criterion" is obtained experimentally from the ball-bounce experiments illustrated by figure 9. It corresponds well in order of magnitude to estimates based on the human mass and spring stiffness of a typical running shoe. (It is well-known - and easily derived using only freshman physics - that the contact time of an idealised "bounce" is independent of impact speed. It is given quantitatively by half the oscillation period of the equivalent mass-spring system, i.e. half the square root of the ratio of spring constant to the mass.)

In a similar manner, the end of the stance phase can be precisely determined by locating the toe-off instant. But sampling to locate the end of the stance period is more challenging than for heel strike, as the sampling of the whole of the foot will be in progress - with consequent decreased temporal resolution - whilst the foot begins to lift off the ground. More favourably, during heel strike all the full sampling bandwidth can be dedicated to the heel-strike region, as the load then is essentially zero over the entire foot.

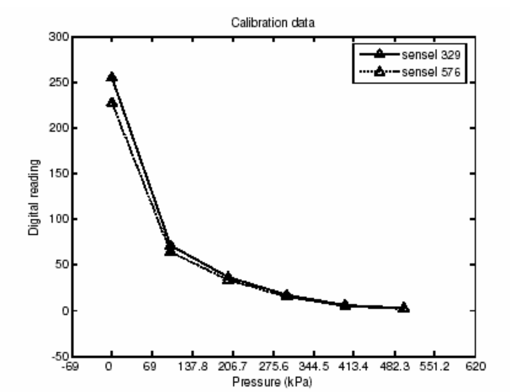

Figure 7: Variation in element-to-element calibration.

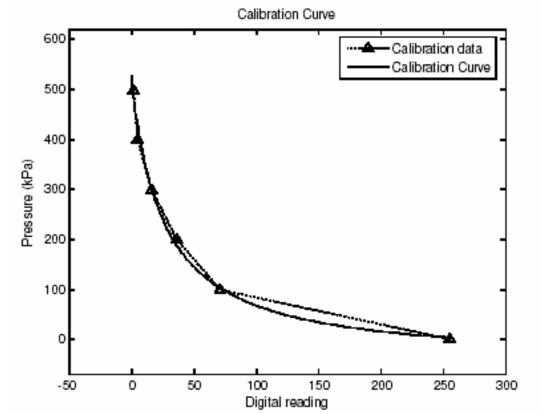

Figure 8: Calibration curve fit to a rational function (ax +b)/(x+c).

4.2 Sampling During Stance

Having determined the start- and end-points of the stance period, all stance data can be re-scaled as described above and the residuals examined to understand cycle-to-cycle differences due to e.g. terrain or fatigue.

As noted above, building a high spatial and temporal resolution view of the stance requires that the different regions of the foot be sampled for different relative times over different stance periods. A naïve approach would raster scan the array, adjusting the scan phase to be out of phase with the stance phases. But this is not optimal. During several phases of the stance large parts of the array are unloaded, as is seen in figures 10 and 11. These phases in which little interesting is happening can be exploited in the scanning strategy. If a low temporal and spatial resolution load pattern is known already, this can be used as a mask to direct sampling attention to the active regions only. This is shown in figure 12 for heel strike. If no initial load mask exists yet, it can be constructed in the first few strides of the gait. As the higher temporal and spatial resolution sampling is completed, a higher temporal and spatial resolution mask can also be applied to further reduce spending bandwidth sampling uninteresting regions.

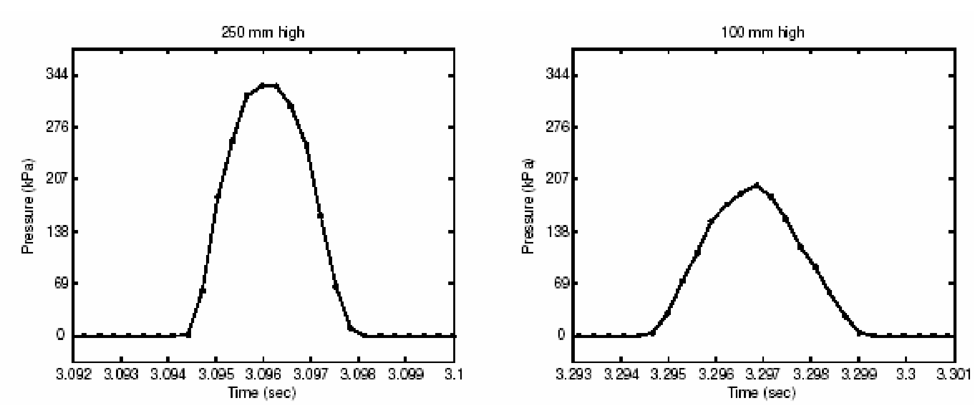

Figure 9: Impulse response to a rubber ball dropped from two different heights.

Variation in the duration of stance cycle will cause uncertainty that must be overcome by applying a mask with a conservative temporal extent. For example, if the stance period varies by 100 ms from cycle to cycle, then as the stance is near completion the uncertainty in the standardised time can be as large as 300 samples. The unloaded masks must be adjusted to ensure that requisite sample points are not overlooked under these circumstances. Depending on the statistical distribution of the actual stance periods, an aggressive mask - not too rapidly adjusted for the stance period delay - might still be applied on the assumption that any missed points will probably be seen during stance periods that are closer to the mean.

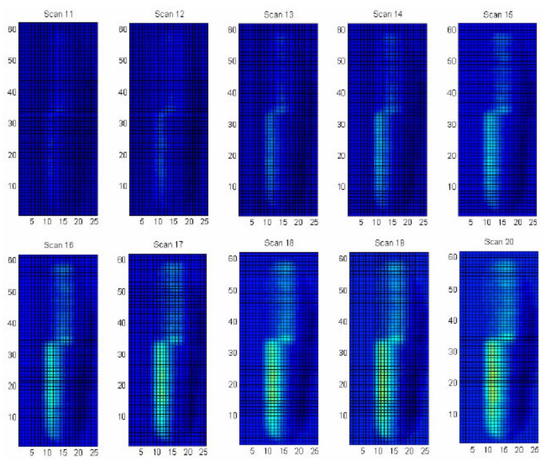

Figure 10: High resolution view of a lightly loaded foot with pressure changes during lateral sway. Note the large unloaded regions (dark blue).

As the high resolution sampling of the stance develops, current samples can be correlated with this reference so that an estimate of the current standardised time can be given. With the hardware limitations of the first-generation prototype it is unlikely that these strategies could be implemented well enough to actually improve performance significantly, but we are certain that given only time and money we could improve bandwidth at least up to the underlying limitations of the TekScan sensor without excessively straining our electronics acumen.

4.3 Force Image Processing

At present the first few moments of the pressure distributions seem to be entirely adequate for conveying the essential features of the data statically and dynamically. In future an image processing approach might be investigated for extracting higher spatial frequency information from the signals, e.g. walking and running surface tilt, unevenness and texture. Identifying these surface features might allow the control strategy to be adjusted for different surfaces. It might also help to identify the danger signals of incipient slip, incomplete foot support, etc.

An additional challenge that is introduced, if image processing techniques are adopted, is that each "pixel" is sampled at a different instant and the scan patterns are not generally progressive, so additional signal processing must be applied to obtain an inferred-time interpolated image before analysis. An advantage of a time-interpolated image will be that there is no inherent image frame time at which the image is taken, so the inferred-time interpolated image can be synthesised for any instant. The quality of the time-interpolated image will not depend on the instant selected, as the sampling occurs continuously and asynchronously, in contrast to the rigidly raster-scanned and framed signals from e.g. video cameras.

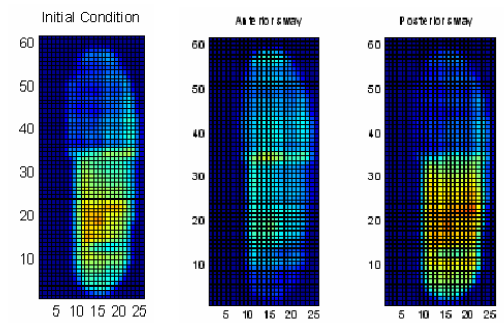

Figure 11: High resolution view of a heavily loaded foot with pressure changes during anterior and posterior sway. Posterior sway resembles a heel strike scenario. Note the large unloaded or lightly loaded regions (dark blue).

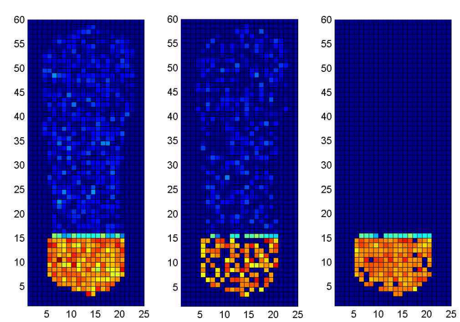

Figure 12: (a) (left) Simulated pressure profile during heel strike; (b) (centre) sampled force profile using random scanning; (c) (right) sampled force profile sampling only loaded region (right). Sampling only the loaded region during heel strike allows a high resolution force image to be captured quickly during a small number of steps.

5 Conclusions

This paper introduced a prototype apparatus for investigating the pressure distribution underfoot. The sensor system can be used to investigate balancing, walking and running. We expect future experiments will yield insight into the actuation and control mechanisms involved in human balancing, walking and running, and their implications for the design and control of humanoid bipedal walking robots.

The measurement system bandwidth dictates that either high spatial or high temporal resolution pressure images can be obtained at any instant. However, spatial and temporal resolution can be traded off dynamically, even on a timescale that allows adaptation inside the duration of a single step, to accommodate the requirements of any particular application. The quasi-periodic nature of walking and running allows both high spatial and high temporal resolution to be obtained by sampling over multiple cycles, thus overcoming the trade-off limitation.

Limitations of the 960 tactile element commercial transducer on top of which our sensor system is built include substantial element-to-element variation and substantial hysteresis. Their combined distortion can be as high as 20%. But software compensation is straightforward and, with clever real-time adapting sampling schemes implemented, there are more than enough elements to characterise the dynamics of the pressure distribution over the sole of the foot during standing, walking and running on any not-too-pathological surface.

6 References

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