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Adaptive sensor data acquisition for gait analysis

Wolfgang Kilian[a,*], Markus Hill[b], Stephan Odenwald[b]

[a]*Technische Universität Chemnitz, Circuit and System Design, Reichenhainer Str. 70, 09126 Chemnitz, Germany*
[b]*Technische Universität Chemnitz, Sports Equipment and Technology, Reichenhainer Str. 70, 09126 Chemnitz, Germany*

Abstract

In this paper a method is presented that uses one sensor configuration for both static and dynamic loading conditions to capture plantar pressure distribution values. In the gait analysis, different phases are from interest. The phases produces highly different signals and with conventional sensors and static data acquisition systems it is often difficult to achieve high precision measurements. An advanced programmable amplifier can be used to adapt the full resolution of the measurement system dynamically to the needs of the gait analyses. With the proposed system, it is possible to precisely measure the gait phases without changing any hardware. While the system is performing it is energy efficient as it only consumes power if needed. Furthermore, it is highly integrated and space saving. Thus, ideally suited for mobile outdoor applications. The technology used in this example can be applied to many different general sensor measurement questions in sports engineering.

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Keywords: adaptive gait analysis; data acquisition; mobile

1. Introduction

In gait analysis two phases are mainly distinguished, namely stance phase and swing phase. While in the swing phase, there is no contact with the ground and nearly no pressure is distributed to the foot, in the gait stance phase different kinds of pressure distributions occur. The stance phase is commonly divided into certain time instances and starts with the heel strike at which point the contact with the ground is made. It continues with foot flat, mid stance and the heel rise. The contact with the ground finally loses at the toe off phase [1]. In every moment of the stand phase the ground reaction force between the foot and the floor is different. For example, shortly after the heel strike the peak force can rapidly increase to over 100% of the body weight and can go later below 100% because of the acceleration that occurs while the body is in motion. The values for the vertical ground reaction forces can be approximately 100% ± 20% of body weight [1]. As stated in the literature, e.g. [2], the pressure measurement for all phases is equally interesting. Thus, the system must be capable of measuring a small range of interest and also the full amplitude. For this kind of measurement pressure sensitive insoles are used frequently [3–5]. In this case force sensors are located at different areas of interest. The sensors cover only a small area and the ground reaction force

* Corresponding author. Tel.: +49-371-531-39828 ; fax +49-371-531-839828.
E-mail address: wkilian@hrz.tu-chemnitz.de

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leads to a pressure on the specific sensor that depends on the time instances of the stance phase.
With an analog digital converter (ADC) directly connected to a standard amplified sensor the available resolution is fixed to the maximum pressure range and the available effective resolution for smaller pressures is frequently not sufficient. To increase the measuring range resolution, it is possible to use different amplifiers. As a result, that means the hardware needs to be replaced for each new measurement. To overcome these problems, the system has to be capable to measure small or high dynamic signals without the need to change the hardware. To achieve this, the measured values must be preconditioned before feeding to and being converted by the ADC. This means the signal get amplified and shifted to the given input range of the ADC. While this is possible with discrete systems, it is also a frequent requirement to have a highly integrated and mobile device. To amplify sensor signals commonly operational amplifiers (Op-Amps) are used and modifying the gain is easily done by changing external components. Changing the components around the Op-Amp can only be done in the design phase of the printed circuit board. Thus, finally the value is fixed. This can be avoided by implementing programmable analog circuits. Today also Op-Amps with integrated programmable gain amplifiers (PGA) are common and can be used. With every integration step that can be made in this design level, it is possible to achieve a smaller and most of the time less power consuming device.

2. Requirements

In sports engineering often sensor data acquisition should happen in real environment, in real situations. Frequently the scientists just use the laboratory system that is available and try to adapt them with huge effort to the system so that it fits into an in field measurement setup. If the data are collected with common laboratory equipment the subjects may be distracted or disturbed by wires, heavy data loggers or even uncomfortable sensors. Sometimes this cannot be avoided if extremely high precise or fast data is needed. However, often the trade-off between usability but not that fast high-speed precision is more than acceptable. To find out what is most important, technical parameters were defined and prioritized in our working group. The group came very fast to the conclusion that the common definitions are highly dependant on the situations we want to measure. Since the situations and thus the requirements can change during the measurement it becomes even more complex. For example, in the gait phase it is important to detect high peaks very fast, whereas in the stand phase precise measurements of pressure distribution is more important.

Beside the pure technical facts like speed, resolution and low energy consumption some other important features must be realized to increase the acceptance and usability for the system.

The solution must be small, lightweight, battery driven and easy to adapt to different sensors. Because the system is to be used outdoors a ruggedised design is important and it must be very easy to handle. Following these parameters it was obvious that a fast and while the measurement is running adaptable system seems to be the best solution.

3. System Design

Many insole sensor technologies are known and widely used. Generally, it is possible to distinguish between insoles with high sensor count like the Pedar-X system and insoles with low sensor count such as WalkingSense[1], SurroSense RX Insole[2] or Parotec[3]. However, if a high sensor count insole is used usally the sensors are grouped together to reduce the amount of data that must be evaluated. In many cases it is possible to achieve comparable results with both insole systems [3,4,6].

3.1. Measurement fundamentals

Most of the time it is not possible to measure the physical parameters like pressure or force directly. They must be converted to a voltage change which can be recorded. Thus, sensors that convert the physical values to better usable parameters like changing resistance, capacitance or inductance are used. To finally convert these values in the next

[1] Kinematix SA, formerly Tomorrow Options, Sheffield, UK
[2] Orpyx Medical Technologies Inc., Calgary, Canada
[3] Paromed Inc., Atlanta, GA

step to a changing voltage that can be processed many methods are well known. In our case, we decided to convert the change of resistance to a voltage change. This is done by creating a so-called half or full bridge [7]. The half bridge can be handled as a voltage divider Fig. 1 With R_G as the resistive sensor element, V_E for powering the bridge, V_O the voltage value that is converted and R_1 as fixed known value.
V_O is defined as:

$$V_O = V_E \cdot \frac{R_1}{R_1 + R_G} \tag{1}$$

With known V_O, R_G can be calculated as:

$$R_G = R_1 \left(\frac{V_E}{V_O} - 1 \right) \tag{2}$$

The idea behind using such a bridge is to increase the usable measurement range, to decrease influences of the environment or in case of a full bridge, both. The current that flows through the resistors leads to a voltage drop that depends on the resistor values. To calculate the resulting voltage equation Eq. (1) can be used. Equation Eq. (2) is used if V_O is measured and the resistance of R_G should be calculated. More detailed information about the bridges was proposed by sly[7] and Hoffmann[8].

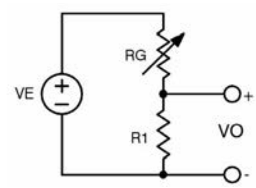

Fig. 1. Voltage divider [7, p.6]

In Fig.2 the pressure voltage level for a typical resistive sensor is shown.
It is divided into three parts, the full-scale, the interesting area (IA) 1 and 2. In the full-scale a high dynamic overall measurement ($dP = 6000\,mbar$) with a voltage range of $dU = 1.4\ V$ is needed.
The IA_1 is medium dynamic pressure ($dP = 300\ mbar$) with medium static load ($P_{static} > 1200\ mbar$) and medium dynamic voltage change ($dU = 0.2\ V$).
The IA_2 is the range with medium dynamic pressure ($dP = 300\ mbar$) in a high static load ($P_{static} > 5300\ mbar$) condition with very small voltage change ($dU = 0.05\ V$).

The following calculations are given as example to show the influence of the resolution and the sensor linearity. Most side effects such as noise, dynamic resolution, static resolution and precision etc are ignored for simplicity. However, further detailed explanation that deals with problems like this was given by sly[7] and real measured values with a Pedar-X system were described by Ramanathan et al.[5].

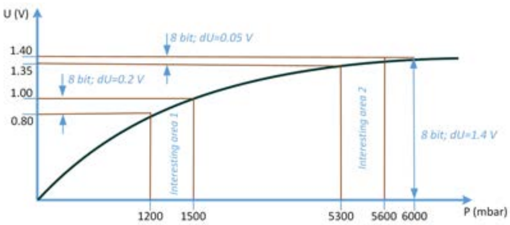

Fig. 2. Output voltage over pressure, Three measurement ranges marked and the maximum voltage that is usable.

3.2. ADC Resolution

The resolution of an ADC is regulary given in *bit*. Common values are 8, 10, 16 bits. The count of steps the ADC divides the analog value in digital parts is defined as $steps = 2^{RES[bit]}$ and give a rough estimation, how precise the ADC can convert the analog value to a digital one.
Assuming, that the voltage difference dU is amplified to the full-scale resolution of the ADC the resulting voltage resolution per bit can be calculated with:

$$LSB_{fs} = \frac{dU}{2^{RES[bit]}} \tag{3}$$

This is the smallest part of the signal that can be determined by the ADC. In an ideal linear sensor case the full scale pressure resolution is given by:

$$P_{res} = \frac{dP}{dU} \cdot LSB_{fs} \tag{4}$$

With an 8bit ADC the LSB_{fs} is calculated with Eq. (3) to $LSB_{fs} = 0.0056V$ and give a pressure resolution Eq. (4) $P_{res} = 23.44\ mbar$ This may be enough for qualifying the overall gait phase. If it is considered to examine the stand phase, because of the high offset pressure the non linearity from the sensor must be taken into account. As shown in

Fig. 2 the sensor voltage change per pressure is significantly lower in high load conditions than in low load conditions. Assuming again the values given in Fig. 2 and that the resolution is still set to fullscale $dU = 1.4V$ the resulting pressure resolution in the area is

$$\text{P}_{res} = \frac{300\,mbar}{0.05\,V} \cdot 0.0056\,V = 33.6\,mbar \quad (5)$$

and this is in relation to the 300 *mbar* less than 4bit effective instead of the expected higher resolution.
The nonlinearity of the sensor leads to a significantly lower voltage/pressure ratio and even completely newly invented sensors show such behaviour [9]. To get the correct results from the sensor, linearisation must be done. It is possible to do this in software, but the ADC resolution will be still the same. Since the steps in the signals are greater than expected, it can lead to huge artefacts in the resulting recorded values.

To solve this problem commonly ADCs with higher resolution eg. 10, 12 or 16 bits are used. While a better pressure resolution with this can be achieved, there are other drawbacks. It increases the power consumption [10] or reduces the overall conversion speed [11] and thus the maximum usable measurement frequency. To compensate these effects highest quality ADCs are again necessary, which increases the overall costs of the system.

Beside this, even with a 12 bit ADC and the conventional approach, in the given example only $P_{res} = 2.05\,mBar$ resolution in the IA_2 can be achieved Fig. 2.

To overcome the stated problems a dynamic adaptable measurement system is proposed. In the following chapter the possible advantages are shown.
If the ADC range is adapted by removing the given static offset and amplification to the voltage range a resolution better than $P_{res} = 1.2\,mbar$ in the stand phase IA_2 can be achieved with the same 8 bit ADC.
In table 1 the values that can be achieved with and without adaption are compared. Additionally the values for a 12 bit ADC are stated. It is assumed that $dU = 1.4\,V$, thus the full-scale resolution is given with:
$dU_{fs}(8\,bit) = 0.00547\,V$
$dU_{fs}(12\,bit) = 0.000341\,V$

Table 1. Comparision of the different pressure resolutions.

IA	$dU[V]$	$dP[mbar]$	$P_{res}[mbar]$	$P_{res}(adapted)[mbar]$	$P_{res}(12bit)[mbar]$
fs	1.4	6000	23.4	23.4	1.46
1	0.2	300	8.2	1.17	0.51
2	0.05	300	32.8	1.17	2.05

IA is the area of interest where fs is the full scale and IA_1 and IA_2 are the areas described earlier. The voltage span in the areas is given with dU and the related pressure span with dP. P_{res} shows the unoptimised pressure resolution, $P_{res}(adapted)$ the resolution with adaption. To give a comparison with a 12 bit ADC $P_{res}(12bit)$ can be found in the last column.
It can be seen that the adapted ADC gives always an equal, better or much better resolution compared with the unoptimised ADC.

To fulfill the requirements the system design must consist of a fast gain adaptable sensor amplifier and the ability to focus on small parts of measurement ranges. To be able to save energy and to minimize data traffic it is helpful to have adjustable speed (at the expense of resolution). To increase the usability a flexible sensor management should be provided.

4. Implementation

A programmable amplifier with integrated ADC and offset compensation is proposed. With such devices it is possible to measure both gait phases without changing any hardware. Highly integrated solutions are already available on the market. To measure the stated different areas of interest we are using a three-stage amplifier. Each stage is equipped with programmable gain and offset. With this solution it is possible to adapt the full resolution of the measurement system dynamically to the needs of the gait analyses.

In Fig. 3 system (1) shows the structure of a commonly used approach as discussed earlier. System (2) shows the implementation with a Semtech ZoomingADC SX8724C. This device consists of all the required functionalities and provides not only one PGA with adaptable offset, but it is even possible to adapt the signal within three stages. All the stages can be programmed as needed. The device provides the functionality to compensate the sensor offset up to 15 times full-scale. The gain can be selected from 1/12 to 1000 and the ADC has a resolution of up to 16 bit. In the device a signal multiplexer is integrated and with the help of this 3 differential or up to 6 single-ended signals can be connected. [12]

To simplify the first implementation and to evaluate the proposed functionality an already available sensor sole is used.

The insole made by IEE [4] consists of eight IEE Sensors type HD-FSR/HD002. A small resistive compensating element is also integrated. It is placed near the pressure sensors and the way that it is connected helps to compensate environmental influences.

One other important thing that can also be seen in Fig. 4 is the grayband surrounding the mean line, it represents the series scattering for the sensors. As the influence of the scattering is much higher by higher pressures, the resulting voltage change can highly differ between every single sensor. This is even more important as the steepness in this area is flatter than on lower pressures. To compensate this effect the proposed system is ideally suited. Every single sensor with its own pressure/voltage ratio can matched to the systems ADC.

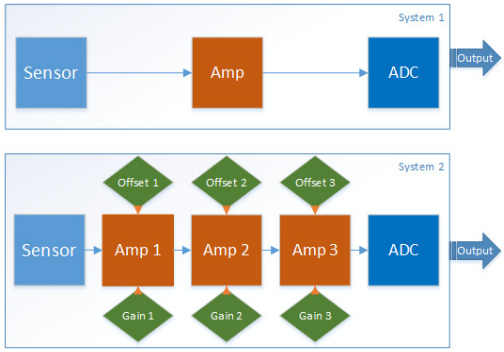

Fig. 3. Sensor signal conditioning

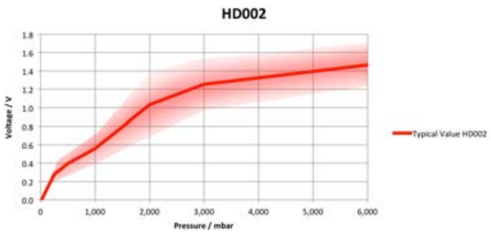

Fig. 4. Pressure/Voltage HD002 IEE[13, p.25]

With the low power consumption and the easy to use interface it is ideally to be connected to a tiny micro controller or if it is necessary to process the collected data in real-time in place it can be used together with a small, but power full highly integrated embedded computer. This is what we have done to examine the capabilities of the data acquisition IC. The device we built is called Dialogg Fig. 5 and integrates beside the described ZoomingADC many more sensors. The collected data can be processed directly on the system, thanks to the powerful dual core Intel Atom processor. After processing, the data can be wirelessly streamed in real-time to other systems or even collected on a tiny database. With this system it is possible to collect the data in the field within real ambient conditions.

5. Other use cases

Beside the usage for the gait analysis system, due its flexibility, the concept can be used in many different applications. As long as the physical values can be converted to a change in resistance the system can be adapted as needed. For example, it fits very well to strain gauges that are used in force sensors, load cells or directly applied to different materials. One common problem that exists is drift and creep [14]. Afterwards, with the proposed method the sensor data acquisition can be adapted as the needs changed.
We could already use the benefits of this research in cases where sensor prototypes have a very large stray in electrical resistance. Because of the prototypical realization the initial resistance fluctuated with every sensor by about 30%. If this fact is ignored, the effective resolution can degrade or it is not possible to cover the whole measurement range. Even in applications where the measurement ranges at the beginning are just estimates and not completely known it is helpful to have an adaptable system. An overall measurement can be done to figure out the really interesting parts.

[4] IEE ZAE Weiergewan 11, rue Edmond Reuter, Contern, Luxembourg

With this knowledge in the next setup the measurement range can focus on the interesting area and even the data rate can be selected as needed. With the possibilities of this system the overall amount of data can be reduced, making the evaluation in the next steps easier and lowers the power consumption again.

6. Conclusion

With the proposed system it is possible to measure completely different phases in the gait with the resolution and speed as needed, without changing the hardware. At the moment the amplification is set by fixed values. There are further steps necessary to make the system more usable. One step is to fully automate the process that adapts the sensor interface to the needed values depending on the pressures that occur.

Although the system is flexible, fast and can handle up to eight channels in sequence it is a completely low power design. The ability to switch to different speeds and resolutions can be used to reduce the energy consumption even more. This can be done for example by scanning all channels with a low resolution very fast. If there is no valid data (swing phase) nothing is captured. If the system is combined with more sensors like gyroscopes or acceleration sensors, one can predict the next gait phase and it is possible to configure the system according to this.

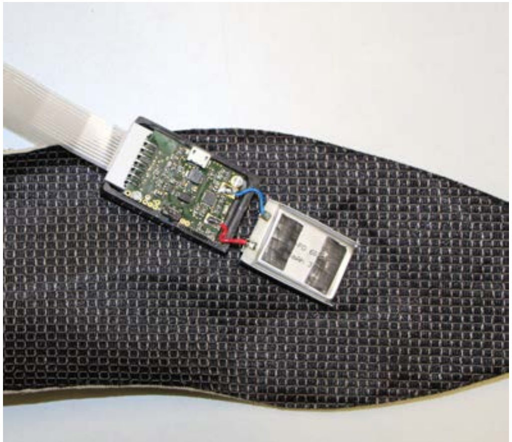

Fig. 5. Dialogg

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