

Measurement Optimisation for Complex Microsystems in Sport Applications

by

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Abstract

This paper is a research plan of a PhD candidature in the area of measurement optimisation for complex microsystems in sport applications. The research will be conducted at Swinburne University, in collaboration with The Australian Institute of Sport, Griffith University and CRC for Microtechnology. The project was commenced on the 27th of May 2002 and the expected completion date is on the 27th of May 2005. The purpose of the research is to investigate and resolve some of the issues with measurement systems in sport applications. The expected outcome of this research is to make improvements in current measurement system design and implementation. The proposed benefit to The Australian Institute of Sport is that better measurement systems with more accurate and useful data will be available to coaches at the highest level of competition to distinguish and enhance an athlete's performance.

1. Introduction

Designing a measurement system for sport application is a multi-discipline task. It requires knowledge in physiology, biomechanics, anatomy, sports science, sensor technology (in terms of its principle of operation, fabrication, packaging, and reliability), microelectronics, signal processing, data handling and software development. In order to create a measurement system that can provide accurate and useful information to the coaches and athletes, many design and implementation issues have to be examined. This paper summarises these issues and provides a background for the research objective to make improvements to the design and implementation of sport measurement systems. First, an introduction to measurement systems will be provided. Then the following topics will be addressed: parameter identification, sensor selection, calibration and testing, multisensing, identifying and characterising noise and interference, and control techniques. Finally, issues for measurement systems in sport applications will be discussed.

2. Industrial Implications

The implication of the research is that better measurement systems with more accurate and useful data will be available to analyse and enhance an athlete's performance. The technology will also be relevant to military applications to monitor soldiers and ambulatory healthcare applications to monitor the elderly, severely ill and disabled individuals.

3. Introduction to Measurement System

A typical quantitative measurement system consists of sensors, a processor, and an output module (Gardner, 1994). The sensors detect or sense the input signal, the measurand, which is the physical or chemical quantity to be measured (e.g. gas concentration, temperature, pressure). They convert non-electrical quantities into electrical signals. The processor is the mechanism that interprets these electrical signals, and converts them into an appropriate form that can be presented by the output module. Usually, the processor is comprised of a preprocessing unit that performs signal conditioning before passing the signal into the processor from the sensors. Some examples include amplifier, filter and analogue to digital converter.

4. Design and Implementation Considerations

4.1 Parameter Identification

The very first consideration in designing a measurement system is to identify the parameters to be measured. In sport applications, some typical parameters include force, acceleration and strain. Ideally, the parameter of interest is measured directly. However, in some cases, it is more practical to measure another parameter, and subsequently, derive the parameter of interest with the known relationship between the two parameters. That is, measure the parameter of interest indirectly. An example would be measuring respiration rate using a thermocouple placed at the entrance to the subject's nostrils (Compumedics, 2002). Once the parameters are determined, sensor selection has to be made.

4.2 Sensor Selection

There are many aspects that have to be considered in sensor selection. First, different sensors have different desirable and undesirable characteristics, which must be addressed for the particular application in order to achieve optimal performance.

Sensor characteristics include repeatability, linearity, sensitivity, resolution, accuracy, hysteresis, noise/interference susceptibility, dynamic range, operating temperature range,

offset, drift (sensitivity, baseline, offset), power consumption, ageing, frequency bandwidth, response time, recovery time and maximum sampling rate.

Other issues that are consequential in sensor selection include cost, fabrication, weight and size specifications of system, environment, etc. Thus, it is critical that all the specifications for the particular application are clearly described, so that the most suitable sensor is selected.

4.3 Calibration and Testing

Calibration is the process that is carried out to ensure that a sensor conforms to a known standard within a specified tolerance (Gardner, 1994). A calibration is a test during which known values of the measurand are applied to a sensor and the output readings are recorded. The resulting calibration record is plotted to produce a calibration curve, which allows the user to determine the error characteristics of the sensor and to adjust the transfer function accordingly.

The calibration process requires significant amount of time and labour per individual sensor, in addition to the expensive reference equipment. Thus, the calibration process contributes to a considerable increase in sensor production costs and set up time when the sensor is in operation.

By incorporating a programmable calibration facility at the sensor or sensor interface chip, the calibration of sensors can be automated and can be performed for a batch of sensors at a time, thus minimising the calibration time and costs.

Van Der Horn and Huijsing (1997) have proposed a calibration method and options for integration in the smart sensor concept. The technique does not require a large matrix of calibration data, which would need to be stored in a look-up table or converted into a correction formula. It utilises a step-by-step approach to correct the sensor transfer at each calibration measurement until the error is sufficiently small.

The principle of the method is to build up a polynomial curve from a number of calibration measurements. Each calibration point is used directly to calculate one programmable coefficient in a correction function, which can then immediately be used to correct the sensor output. The next calibration makes sure of this corrected signal and each succeeding correction is applied in such a way that the previous calibrations remain undisturbed.

In detail, the first calibration corrects the offset of the uncalibrated curve, as shown by the vertical shift from $f(x)$ to $f_1(x)$ in figure 1. The second is used to correct the gain (without affecting the offset calibration) by rotating the function around the first calibration point, as shown by the rotation around the origin from $f_1(x)$ to $f_2(x)$. The third calibration is used to correct linearity by “bending” the function in such a way that the previous calibration points stay fixed, as shown from the change from $f_2(x)$ to $f_3(x)$. Additional calibrations are made use of in the manner to further linearise the sensor

transfer function. The advantage of this technique is that no mathematical iterations are required to compute the coefficients of the polynomial factors. Conversely, the limitation with this method is that all the calibration points must be accurate as the polynomial curve is fitted exactly through these points.

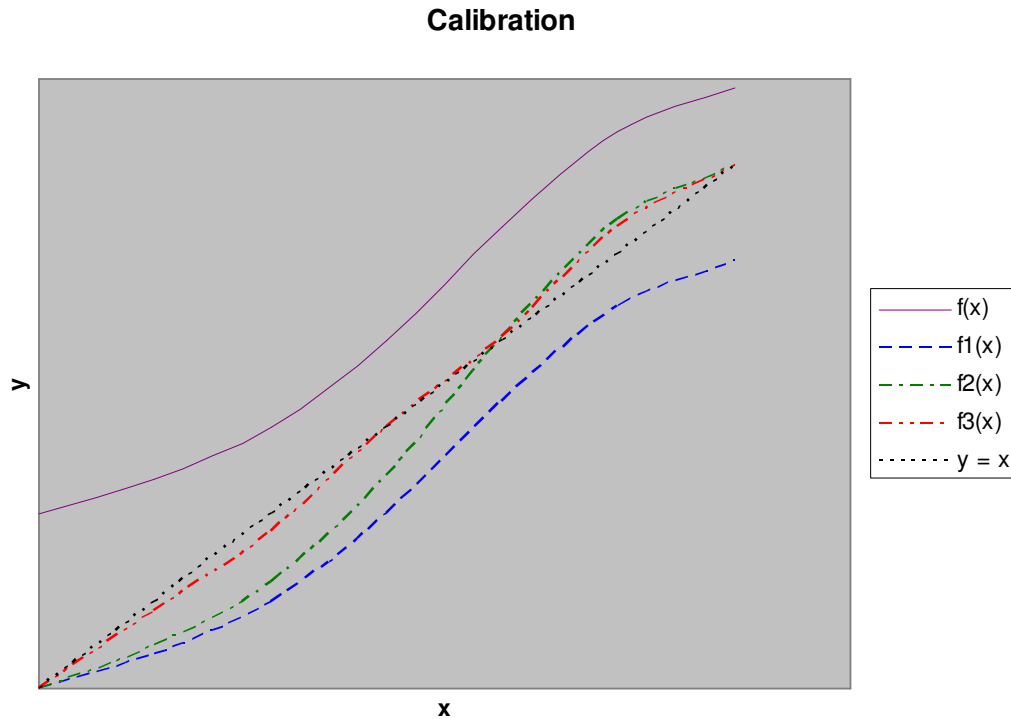


Figure 1: Diagram to illustrate the polynomial calibration proposed by Van Der Horn and Huijsing.

Good linearisation is obtained when the calibration points are selected in the following sequence: the first two calibration points are at the opposite end of the sensor range of operation and subsequent calibration points halfway between the two previous calibration points.

Furthermore, this method can be extended to two-dimensional polynomial calibration. This is necessary because sensors usually suffer from cross-sensitivity from another parameter (Van Der Horn & Huijing, 1997). In particular, many sensors are affected by the operating temperature, as their characteristics are temperature dependent.

For obvious reasons, sensors have to be tested to ensure that they are functioning correctly. It is desirable that a sensor has the ability to perform self-diagnostic tests to save time and money, and improve error detection efficiency. A complete failure is obvious to the user when the output falls below its operating range. However, in many

cases a sensor can fail to perform adequately but still provide a reasonable output (Gardner, 1994). For example, a faulty semiconductor sensor may produce incorrect output due to anomalies in its response, but the output signals are still within the operating range.

4.4 Multisensor Integration

Multisensor integration is often employed to correct systematic and random errors, as it has the advantage of providing redundancy and complementary information (Gardner, 1994). Undesirable dependent variables, usually temperature, affect sensor response and can be measured so that the systematic errors can be removed. Multisensing also allows the calculation of an average or discarding the particular anomalous reading, so that random errors can be eliminated.

4.5 Identifying and Characterising Noise and Interference

It is inevitable that noise and interference are inherent in the measurements. They corrupt the signals generated by the sensor and degrade the accuracy of the measurement.

The sources of noise and interference must be identified, characterised and quantified, as this will provide a basis to find suitable strategies to correct, or at least, minimise these errors.

Other problems include signal drop out with wireless measurement systems.

4.6 Control Techniques

Many control techniques are employed to process the sensor information and some of the more widespread ones include fuzzy logic, neural networks, adaptive filtering, Kalman filtering and characterisation with look up table correction. An introduction on the techniques that are most suited to sport measurement applications will now be discussed.

A neural network (Frank, 1996) is a collection of independent processing nodes that solve problems by communicating with one another in a manner roughly analogous to neurons in the human brain. Basically, each input to the neuron is multiplied by the synapse weight. The neuron sums the results of all the weighted inputs and processes the results with a typically nonlinear transfer function to determine the output. The network is trained by applying sets of inputs with known outcomes. The output from the network is compared to the known outcome, and the weights are adjusted to compensate for errors. Neural networks are particularly effective in systems that are difficult to define and are able to operate in a high-noise environment. Complex or numerous input patterns are among the problems that neural networks are capable to

resolve. In particular, neural networks are among the most common forms of control structures for multisensor integration (Luo & Kay, 1995).

The Kalman filter is a linear, discrete-time, finite-dimensional system, the implementation of which is well suited for a digital computer (Haykin, 1996). It is used in a number of multisensor systems when it is necessary to fuse dynamic redundant data in real time (Luo & Kay, 1995). The filter uses the statistical characteristics of a measurement model to recursively determine estimates for fused data that are optimal in a statistical sense. The recursive nature of the filter makes it appropriate for use in systems without large data storage capabilities.

The Kalman filter has been widely used in many applications such as video and laser tracking systems, satellite navigation, ballistic missile trajectory estimation, radar, and fire control. In particular, it has been extensively applied in inertial navigation, which is a technique well suited for athlete tracking.

There is a published world patent (Soehren, 2001) for a navigation system that tracks the motion of human foot travel. In essence, it is composed of three systems coupled together. It consists of a position estimator that employs a traditional inertial navigation technique using a triad of accelerometers and a triad of gyroscopes, an independent distance estimator using a motion classifier coupled to the motion sensors, and another position estimation using a Global Positioning System.

The distance estimator uses a neural network to analyse the motion information from the inertial navigation system and identify the type of human motion (such as walking forward, walking sideways, crawling, turning left, down stairs, stationary, or unclassifiable). Once identified, motion models specific for the motion type are used to estimate the distance travelled.

A Kalman filter is also integrated into the system, and it provides the corrective feedback signals for the inertial navigation processing with the distance estimate, and for both of these with the GPS data. It also provides corrections to parameters of the motion model (i.e. modifications to the neural network weights) based on the errors in the distance estimate. The accuracy of this system is not known, nor is there any experimental data found.

This patent is an illustrative example of the design and implementation process of a measurement system. It also highlights the idea that corrective algorithms and techniques are important in optimising measurement practicality with the limitations in sensor technology.

4.7 Issues for Measurement Systems in Sport Applications

For athletes in the highest level of competition, performance is measured to an extremely high resolution. For instance, running 0.001 of a second faster in the 100 metre sprint and jumping half a centimetre higher in high jump. Thus, a sport measurement system should ideally be able to obtain accurate and useful data without hindering an athlete's performance in anyway.

Many factors restrain the possibility of creating such a system. At the very least, the measurement system should be very small and light weight, not alter the athlete's biomechanics or physiology, with a fast set up time and still be able to provide accurate and useful information.

Size and weight are important constraints on the design of a measurement system, and this is the particular interest in building the measurement system using microtechnology. Biomechanical issues may include altering the centre of gravity of sporting equipment, such as a golf club, which can have significant effects. An example for physiology would be a marathon runner wearing a measurement vest that is significantly thicker than a typical tank top. This could increase the runner's body temperature and affect his/her performance. Moreover, safety issues must be addressed when the measurement system is applied in contact sports.

The set-up time for even the simplest sport measurement system can be orders of magnitude longer in duration than the event that is being recorded. In order to improve the reliability and ease of use of such systems a robust and rapid method is required in order to allow whole teams of athletes to be instrumented with minimal intrusion to normal preparation.

5. Conclusion

This research plan has summarised the design and implementation considerations required to create a sport measurement system. The next step is to exercise this knowledge by putting it into practical use. It is expected that there will be many areas that require significant development and this research work will contribute to knowledge in the field. Ultimately, it will benefit the athletes by providing them with useful feedback on their performance.

Acknowledgments

The author wishes to express his gratitude to The Australian Institute of Sport, Industrial Research Institute Swinburne, Griffith University and the CRC for Microtechnology for providing resources to this research.

References

Frank, R., "Understanding Smart Sensors", Artech House, Boston, 1996.

Gardner, J.W., "Microsensors – Principles and Applications", John Wiley & Sons, Chichester & New York, 1994.

Haykin, S., "Adaptive Filter Theory", Prentice-Hall International, Inc., New Jersey, 1996.

International Patent: WO 01/88477 A2, Soehren, W.A., Keyes, C.L. and Bye, C.T., "Navigation System, Method and Software for Foot Travel", Honeywell International Inc., 22 November 2001.

Luo, R.C. and Kay, M.G., "Multisensor Integration and Fusion for Intelligent Machines and Systems", Ablex Publishing Corporation, New Jersey, 1995.

Personal communication with Compumedics Pty. Ltd. (<http://www.compumedics.com.au>), 2001.

Van Der Horn, G. and Huijsing, J.H., "Integrated Smart Sensor Calibration", Analog Integrated Circuits and Signal Processing, Vol. 14, Kluwer Academic Publishers, pp207-222, 1997.