INTELLIGENT AGENT BASED SOFTWARE ARCHITECTURE OF A WEARABLE ELECTROTACTILE FEEDBACK SYSTEM FOR BALANCE IMPROVEMENT

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Abstract

An electrotactile feedback system (EFS) is a specific form of biofeedback using electrocutaneous stimulation and can help people with problems of pressure estimation caused by a sensation loss in their feet to maintain their balance and reduce the risk of falls. In this research project embedded software has been designed and tested on a wearable EFS that tackles the problem of improving balance control for impaired individuals. The program has several inventive features. An intelligent agent was implemented to process information from the sensor system and taking an action in the form of electrocutaneous stimulation. In a training routine the force sensor system is calibrated and COP information obtained. Furthermore the software detects individual parameters of the wearer by testing the sensation threshold for electrocutaneous stimulation. The system uses artificial intelligence (AI), in form of a simple reflex agent (SRA) to prevent harmful or unwanted feedback. A preliminary test was performed to test the repeatability of the sensory threshold detection and showed a high repeatability. The developed software has several novel components and can be integrated in innovative wearable EFS that can be used by people with sensory impairment to improve their ability of controlling their balance and thus preventing falls.

Keywords: *Biomedical Engineering, Electrotactile Feedback, Intelligent Agents*

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1. INTRODUCTION

1.1 Background

Reduced sensory input in the feet can lead to balance instability when standing still or walking [1][2][3]. Balance is dependent on the processing of information from the vestibular system, visual perception and somatosensory system, including mechanoception and proprioception. These are processed in the human brain enabling body positioning to be altered in order to achieve stability. Impairment of the somatosensory system is a common disorder and is a result of morbidities that damage the sensory nerves. The reduced or non-existing sensation in the feet can lead to balance instability and consequently, increase falls risk and injuries of affected individuals [4][5][3][6]. It was found that accidental falls are the fifth leading cause of death amongst the elderly [7].

1.2 Motivation

Biofeedback in the form of an Electrotactile feedback system (EFS) has the potential to help people with sensory loss in their feet to lower their risk of a fall by giving them feedback on their current balance situation as a reference. The centre of pressure (COP) of the body measured under the feet is a commonly used indicator to analyse the quality of balance. By giving feedback about the magnitude of the COP displacement with electrocutaneous stimulation based on the forces measured under a user's feet the subject may improve his ability to actively control the body posture to countermeasure possible falls. There is only limited research dealing with the programming of algorithms that incorporate the technical and individual variables of an EFS and the use of artificial intelligence to optimize the feedback. This fact limits the progress of development of wearable EFS.

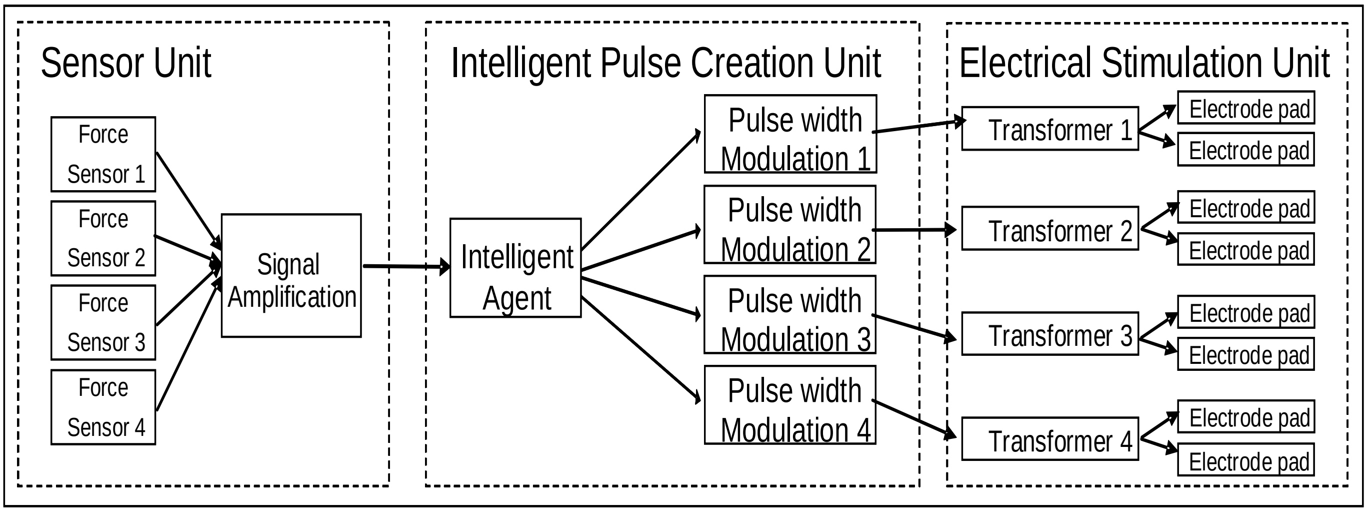

Fig 1: Block diagram of the developed electrotactile feedback system

2. THEORY

2.1 Electrotactile Feedback System

A wearable EFS was developed (Fig.1) consisting of a sensor unit (SU), an intelligent pulse creation unit (IPCU) and an electrical stimulation unit (ESU). The Sensor Unit of the device consists of four piezoresistive force sensors for the detection of pressure, An operational amplifier amplifies the sensor response and forwards the signal to the IPCU. The pulse had a frequency of 17 Hz and a maximum amplitude of 100 V. When the device is in operation the pulse frequency and pulse amplitude are fixed, and only the pulse width changes. The IPCU receives the data from the SU and processes the information in an intelligent agent (IA) (section 2.2.) where the pulse width is modulated and amplified in the ESU. The pulse lies within a range of 50-500 µs. The pulse controls a transformer which is part of the ESU. The transformers amplify the pulse from the IPCU and transfer the pulse through electrodes to the skin. The loop connected to the skin is galvanically isolated from the rest of the system.

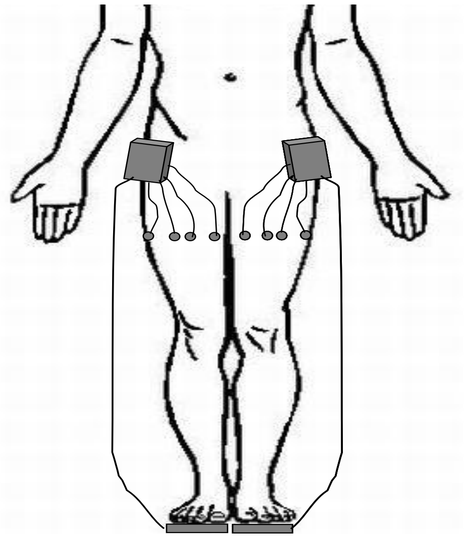

Fig. 2: Schematic diagram of the prototype

The developed EFS can be installed on a person by placing two devices on the left and right leg (Fig. 2). The force sensors are integrated onto an insole that can be placed in a shoe. The sensors are connected with a housing that contains the amplification part of the SU, the IPCU and the ESU. Leads are connected to the box allowing electrode pads to be placed at the user's upper leg.

2.2 Intelligent Agents

Artificial intelligence involves the design and study of intelligent agents. Intelligent agents are autonomous entities that detect changes in their environment and trigger an action based on condition-action rules [8](Fig. 3).

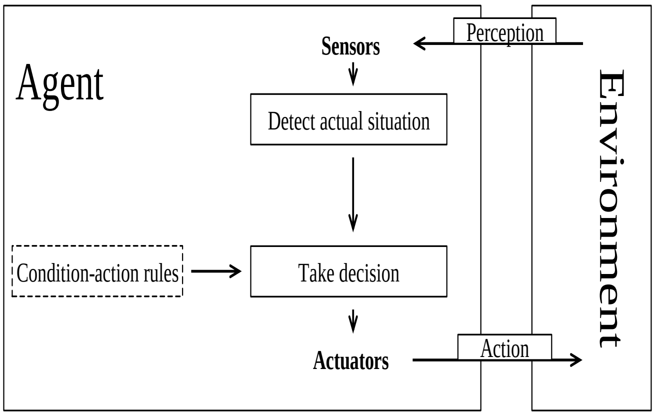

Fig. 3: Principle of simple reflex agent

There exist several types of agents which can be considered in the design of an EFS. Most intelligent agents need high processing power between the perception of a sensory input and the performance of an action. On the other hand a simple reflex agent (SRA) uses a rule base that is trained or defined before the agents starts to interact with the environment [8]. This allows the implementation of a fast decision making process. For the developed EFS the rules must be based on the parameters of the system which includes the force sensor validation, centre of pressure detection and identification of sensory thresholds. Further all actions, in form of electrical feedback, must stay in a comfortable range of stimulation.

3. METHODS

3.1 Piezoresitive Force Sensor Validation

Different piezoresistive force sensors, even when of the same manufacturing, can have a high variability if the same load is applied. While the linearity of change of resistance measured against different loads is quiet stable, the resistance for the same load on different force sensors and under different conditions can vary significantly. A possibility to calibrate force sensors is by putting controlled loads on them and recording the force-resistance or force–voltage curve [9]. Theoretically this is necessary before every use of a force sensor, as it changes its resistance over time based on temperature and location [10]. However this procedure is very time consuming and, is therefore not practical. By detecting the minimum and maximum force sensor value and assuming an almost linear behaviour between them, the time for calibration can be reduced significantly. The software developed in this work allows detecting the minimum and maximum force sensor values and incorporates this information in the calculation of the feedback.

3.2 Centre of Pressure Measurement

The centre of pressure is commonly used to describe the quality of balance [11]. The COP can be detected via force sensors allocated in a shoe insole [12]. Feedback about the COP can be supportive for improving the ability to actively controlling balance when it is limited, e.g. due to impairment [3]. As the goal of the device was to help people with impaired ability to stand stable by actively controlling their centre of balance, the software developed in this research is able to detect the COP in a stable situation for a user and store this information to detect when a person becomes unstable. The COP was obtained with a simple learning algorithm by measuring the force distribution under people’s feet [13] and the information is saved in a knowledge base. Several indicators of balance can be derived from the COP such as the displacement in the anterior-posterior (AP) and the medial-lateral direction (ML).

3.3 Threshold Procedure

The range of comfortable sensation differs between each individual. This is due to the sensitivity of a person [14], the placement of the electrodes [15] and the skin condition [16] leading to a higher or lower resistance for the current to pass through. By detecting the thresholds of the person before electrotactile feedback is applied it can be assured that the feedback is always in a comfortable range. An appropriate method for the detection of thresholds is the method of limits [17]. The software developed in this work implemented the methods of limits in the calibration procedure for detecting the thresholds for comfortable sensation.

3.4 Pulse Characteristics

The frequency for electrotactile feedback usually was set within the range between 2 and 100 Hz [18][19] and the pulse width was set between 0 and 1000 µs [20]. The program was able to deliver those pulse characteristics. The developed device was designed to create a bipolar pulse to avoid reddening of the skin which is associated with the use of a unipolar pulse skin [14].

4. FINDINGS

4.1 Software Architecture

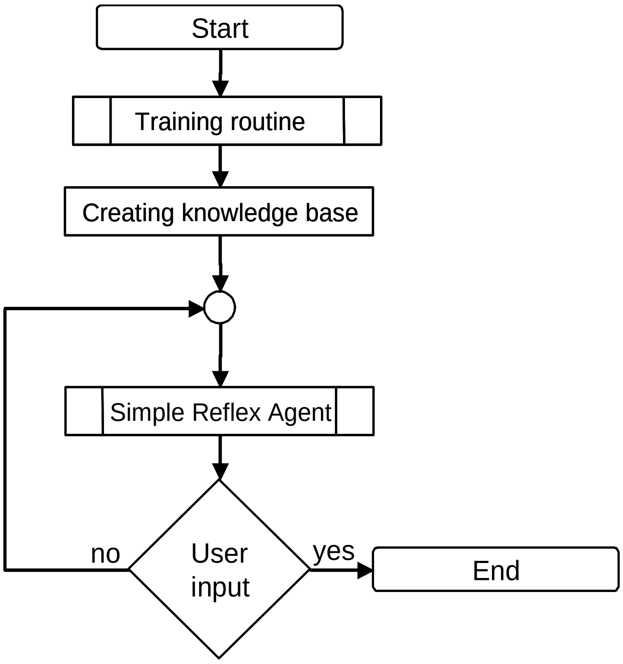

Fig. 4: Flow chart of software architecture of the EFS

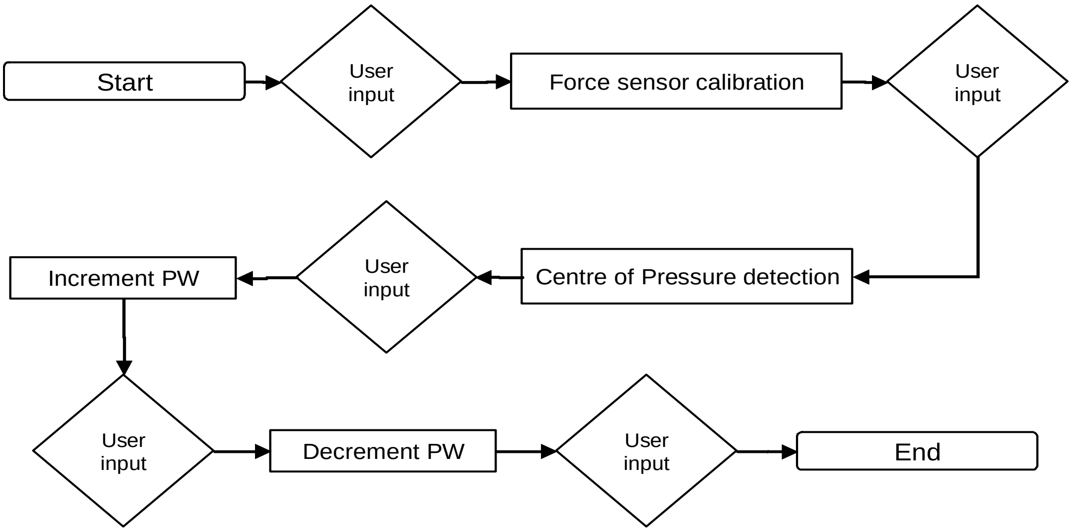

Fig. 5: Flow chart of the training routine Force senor values, centre of pressure and individual electrical stimulation pulse width thresholds are detected.

The device software consists of two main building blocks: the training routine and the Simple Reflex Agent (Fig. 4). The user can stop the Simple Reflex Agent by pressing a button installed on the device. During the training routine (Fig. 5) the user can control each step by pressing a button to go to the next sub-routine. The force sensor calibration involves the detection of minimum and maximum force sensor values (f_{max} and f_{min}) during swaying in medial, lateral, anterior and posterior direction. The centre of pressure (f_{COP}) is then detected by averaging the forces sensor values during quiet stand over a period of 5 seconds. Finally the maximum and minimum threshold of stimulation are detected by increasing the pulse width at first for the detection of the upper threshold and then lowering the threshold until the user presses a button. All values of the training routine are saved in a knowledge base. The program then uses the SRA for creating feedback according to the centre of pressure movement.

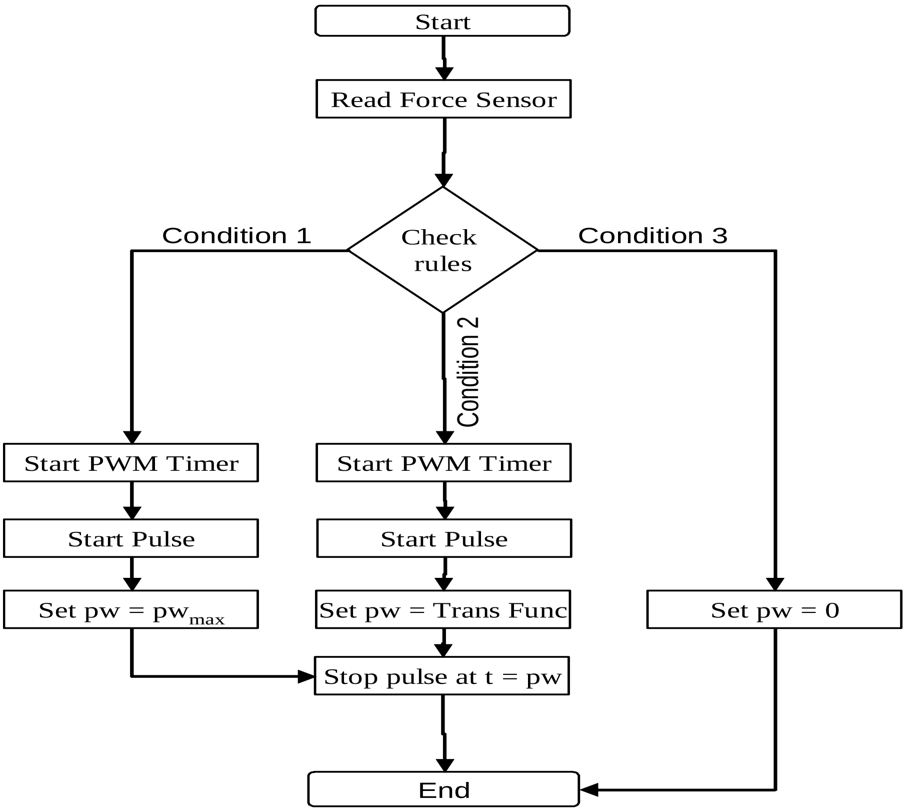

Fig. 6: Flow chart of simple reflex agent. The intelligent agent checks the rule base before the feedback stimulation is triggered

The SRA (Fig. 6) checks the conditions of the rule base (section 4.2.). If condition 1 of the rule base is detected the pulse width is set to pw_{max}, condition 2 results in the calculation of the pulse width using the transfer function (section 4.2.) and condition 3 triggers the end of a pulse by setting the pulse width to 0.

4.2 Rule Base for Intelligent Agent

The rule base used by the intelligent agent prevents pulses which are higher than pw_{max} but also assures that feedback on a certain electrode is only given when a force sensor value is within the force sensor value interval $[f_{COP} \; f_{max}]$. Three conditions for the current sensor value value, $f_{(t)}$, are tested before any pulse command is sent:

Condition 1) If $f_{(t)}$ is greater than or equals f_{max} then $pw_{(t)}$ is set to pw_{max}
Condition 2) If $f_{(t)}$ is greater than f_{COP} then pulse is calculated according to the pulse transfer function *(1)*:

$$pw_{(t)} = k_1 \cdot f_{(t)} - k_2 \tag{1}$$

Where

$$k_1 = \frac{pw_{max} - pw_{min}}{f_{max} - f_{COP}} \tag{2}$$

And

$$k_2 = -pw_{min} + \frac{f_{COP}(pw_{max} - pw_{min})}{f_{max} - f_{COP}} \tag{3}$$

Condition 3) If $f_{(t)}$ is smaller than f_{COP} then $pw_{(t)}$ is set to 0

Condition number 2 indicates that all values are in the estimated range and the pulse width can be calculated by the transfer function. The rule base assures that no uncomfortable sensation is given to the wearer.

5. DISCUSSION

5.1 Limitations

The developed software does incorporate the sensory threshold of the user, but it does not incorporate the change of those thresholds during the usage of the device. The human skin can adapt to electrical stimulation over time [21]. A possible solution for this is to study the adaptation of each individual and use the adaptation curve to counter measure against the adaptation when calculating the pulse width. Nevertheless this might not necessarily be useful as the adaptation to stimulation is a natural behaviour which also occurs for normal touch. Force sensors can change their behaviour over time, through change of temperature and natural erosion. A dynamic algorithm could be investigated in further research to solve this problem by detecting and countermeasuring the sensor drift. The proposed system can be easily extended by adding additional rules to the rule base.

5.2 Future Work

Further investigations should be considered for improving the detection of sensory thresholds in the training routine. A possible improvement is slowing down the increase or decrease of the pulse width when it reaches the area where it is more likely to have a threshold and accelerate the increase and decrease for pulse widths that are expected to be in between the two thresholds. This would allow finding the thresholds faster and is more practical.

Further work could be done in extending the knowledge base. A look up table which stores the equivalent pulse width pattern for each COP value could be useful for future design concepts that require a less time consuming approach for determining the pulse width. Additionally a more complex intelligent agent could be considered in future design concepts. The system could use artificial neural networks to learn the balance behaviour of the wearer of the device during its usage. Another possibility is the use of fuzzy logic to correctly detect and classify sensor or device errors and warn the user of a failure of the device.

Another considerable psychophysical fact for future studies is that each person has an individual psychophysical power function for magnitude estimation with electrotactile stimulation. The individual preference and the placement of the electrodes play an important role on how this function looks like for each individual. The information about the psychophysical power function could be integrated in the transfer function between COP information and pulse width.

6. CONCLUSIONS AND IMPLICATIONS

6.1 Implications

The software that has been developed in this study uses an intelligent agent, a simple reflex agent, to take decisions based on a predefined rule base. The rule base is obtained by using a novel training routine that detects the COP information, the minimum and maximum sensor values, and the sensory thresholds of the user for electrocutaneous stimulation. The developed calibration method in this study is based on the method of limits [17], however it also incorporates a tested fast routine allowing a quick calibration of the sensory thresholds. The calibration method and the novel learning algorithm that has been developed can support future designs of biofeedback systems. Additionally the psychophysical mapping function, combining centre of pressure information and individualised thresholds, is valuable for embedded software design considerations since the developed algorithm was computationally fast. It does not use any division but calculates all constants after the sensory and force sensor parameters are determined and stored in a knowledge base. The process is resource saving and can be implemented in every commercially available microcontroller. The embedded software solution presented in this work is a major contribution to the development of a portable EFS. Existing EFS or new concepts can make use of the software and integrate it into their solution.

6.2 Conclusions

This study presents the software architecture for a wearable EFS. The main requirements on the software for an EFS were summarized and justified the need for an AI based approach by using an intelligent agent to communicate between the perceptive sensor unit and the active stimulation unit.

A simple reflex agent was implemented. A rule base was defined which uses the information obtained in a training routine. The rule base is created in three steps. Firstly the system is trained to detect the sensor characteristics by saving the minimum and maximum force values in a knowledge base. Then the COP information is detected by analysing the stable stance of the user. Finally the method of limits was implemented using an accelerated time saving approach to detect sensory thresholds of electrocutaneous stimulation. A psychophysical mapping function involving the parameters in the knowledge base was derived and implemented. The rule base prevents harmful feedback in case of a sensor or data transmission error and automatically limits the pulse width to a comfortable range.

This AI approach allows the calculation of the ideal pulse width for electrotactile feedback and assures through a transfer function that the magnitude of the feedback is according to the placement of the COP information. The calculation of the pulse width is fast and was optimized for the implementation on a microcontroller. The presented software can be integrated into new concepts of electrotactile feedback devices and improve the quality and usability of EFS. Since the software can be used for embedded programming on a microcontroller, because of its size, it is suitable for portable systems, which can easily be carried around by people with sensory impairment. This portable system has been developed to improve the ability to judge the magnitude of COP displacement which can help to control balance and reduce the risk of falling.

ACKNOWLEDGEMENTS

The authors would like to thank the Faculty of Science & Technology at Bournemouth University for providing the electrical engineering facilities and for their support in the design and the manufacturing of the device.

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