Biosystems & Biorobotics

Volume 22

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**Aims & Scope**

Biosystems & Biorobotics publishes the latest research developments in three main areas: 1) understanding biological systems from a bioengineering point of view, i.e. the study of biosystems by exploiting engineering methods and tools to unveil their functioning principles and unrivalled performance; 2) design and development of biologically inspired machines and systems to be used for different purposes and in a variety of application contexts. The series welcomes contributions on novel design approaches, methods and tools as well as case studies on specific bioinspired systems; 3) design and developments of nano-, micro-, macrodevices and systems for biomedical applications, i.e. technologies that can improve modern healthcare and welfare by enabling novel solutions for prevention, diagnosis, surgery, prosthetics, rehabilitation and independent living.

On one side, the series focuses on recent methods and technologies which allow multiscale, multi-physics, high-resolution analysis and modeling of biological systems. A special emphasis on this side is given to the use of mechatronic and robotic systems as a tool for basic research in biology. On the other side, the series authoritatively reports on current theoretical and experimental challenges and developments related to the “biomechatronic” design of novel biorobotic machines. A special emphasis on this side is given to human-machine interaction and interfacing, and also to the ethical and social implications of this emerging research area, as key challenges for the acceptability and sustainability of biorobotics technology.

The main target of the series are engineers interested in biology and medicine, and specifically bioengineers and bioroboticists. Volume published in the series comprise monographs, edited volumes, lecture notes, as well as selected conference proceedings and PhD theses. The series also publishes books purposely devoted to support education in bioengineering, biomedical engineering, biomechatronics and biorobotics at graduate and post-graduate levels.

**About the Cover**

The cover of the book series Biosystems & Biorobotics features a robotic hand prosthesis. This looks like a natural hand and is ready to be implanted on a human amputee to help them recover their physical capabilities. This picture was chosen to represent a variety of concepts and disciplines: from the understanding of biological systems to biomechatronics, bioinspiration and biomimetics; and from the concept of human-robot and human-machine interaction to the use of robots and, more generally, of engineering techniques for biological research and in healthcare. The picture also points to the social impact of bioengineering research and to its potential for improving human health and the quality of life of all individuals, including those with special needs. The picture was taken during the LIFEHAND experimental trials run at Università Campus Bio-Medico of Rome (Italy) in 2008. The LIFEHAND project tested the ability of an amputee patient to control the Cyberhand, a robotic prosthesis developed at Scuola Superiore Sant’Anna in Pisa (Italy), using the tf-LIFE electrodes developed at the Fraunhofer Institute for Biomedical Engineering (IBMT, Germany), which were implanted in the patient’s arm. The implanted tf-LIFE electrodes were shown to enable bidirectional communication (from brain to hand and vice versa) between the brain and the Cyberhand. As a result, the patient was able to control complex movements of the prosthesis, while receiving sensory feedback in the form of direct neurostimulation. For more information please visit http://www.biorobotics.it or contact the Series Editor.

More information about this series at http://www.springer.com/series/10421
Wearable Robotics: Challenges and Trends

Proceedings of the 4th International Symposium on Wearable Robotics, WeRob2018, October 16–20, 2018, Pisa, Italy
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Wearable Sensors for Robotic Exoskeletons
Position Sensing and Control with FMG Sensors for Exoskeleton Physical Assistance

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Abstract. Human intention decoding is a primary requirement to control an exoskeleton. In this work, a new method of decoding human intention by Forcemyography (FMG) is explored to estimate elbow joint angle during arm motion. The method utilizes an FSR-based sensor band to read muscle contraction and relaxation. The readings of the sensor band are mapped to the desired joint angle by using coarse Gaussian support vector machine (SVM) regression algorithm. The estimated joint angle is further used to control an elbow joint exoskeleton. Results show that the new method is able to estimate reliably the joint angle for controlling the exoskeleton.

1 Introduction

Robotic exoskeletons have strong potential of use as assistive devices to assist the elderly and workers [1] and therefore effective methods of estimating human intention are needed for the assistance control. In the context of cognitive human robot interaction several solutions have been proposed using EEG [2], EMG [3] and FMG [4]. Among these methods, FMG has gained more interest due to its non-invasive nature and simple mechanical and electronic interface, and a good performance as well [5].

Intention detection by FMG is mostly implemented by FSR sensors. The sensors can be embedded inside a strap to detect muscle contraction and relaxation and interpret different movements. In the reported works, FMG has been used to classify forearm [4, 6] and ankle muscle activities [7], but not the upper arm muscle activities.

In this work, FMG is used to estimate the elbow joint rotation angle, which is achieved by detecting muscle activity of upper arm muscles and using SVM regression algorithm to interpret the readings. The developed method is able to detect small changes in joint angle, hence, increasing the reachable space. Moreover, the FMG sensor can also measure simultaneously the muscle strength/effort, which is not possible in other sensors like accelerometers and rotational sensors. In our previous work, the determination of motion type has been reported in [6]. In this paper, we have focused on the joint angle estimation and its application in the control of the exoskeleton motion.


2 FMG Sensor

It is known that the elbow joint motion is primarily governed by biceps and triceps. The contraction and relaxation of muscles cause the muscle shape and hardness to change. It is observed through experiments that due to muscle shape change, the perimeter of upper arm at the middle point increases during flexion and decreases during extension. Moreover, the change is associated to joint angle.

The change in muscle volume can be detected through an FSR based sensor band (S-Band). The S-Band is designed and constructed using an array of three FSRs placed inside a flexible strap and worn on the upper arm as shown in Fig. 1a. As the muscle contracts, the shape and hardness change of muscle will cause an outward normal force on S-Band. This change in normal force can be registered in relation to the arm bending angle. Therefore, with further post-processing, the force read by S-Band can be inferred in terms of joint angle.

![Fig. 1. (a) S-Band design and placement (b) placement of E-EXO on human arm](image)

3 Elbow Exoskeleton Design

An elbow joint exoskeleton (E-EXO) is developed as shown in Fig. 1b. The E-EXO has a range of motion of $0^\circ$–$130^\circ$. The motor has its built-in Hall sensors and an incremental encoder. An absolute encoder is integrated separately to get the actual joint angle of E-EXO.

4 SVM Implementation

The forces read by S-Band are interpreted as joint angle using SVM regression algorithm with 5-fold cross-validation framework. The details on hardware setup to collect data for training session, protocol followed for collecting data and testing are given in forthcoming sections.

4.1 Hardware Setup

The hardware is comprised of S-Band and an accelerometer ADXL-335. This accelerometer is able to measure accelerations ($\pm 3g$) in three axes. By wearing the accelerometer on the wrist, it is calibrated to provide the elbow joint angle.
All the data including FSR’s force readings and acceleration read through Arduino Due is transmitted to the MATLAB based GUI through serial port.

During experiments, subjects were instructed to keep shoulder and wrist in neutral position. Training data was collected by keeping static pose of forearm at five different joint angles for once and each position was maintained for 5s. Subject started from a joint angle near 0° and ended up near 110°, while the actual value of joint angle was computed through the accelerometer.

4.2 Real-Time Estimation

In the real-time joint angle estimation, subject performed two tasks i.e. keeping static pose at two random elbow joint angles and flexion of arm from neutral position.

5 Experiments and Results

5.1 Joint Angle Estimation

Four subjects were recruited for the experiments of real-time estimation of joint angle with the developed method. The results are provided in Table 1.

<table>
<thead>
<tr>
<th>Participants/Tasks</th>
<th>Holding position</th>
<th>Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position 1</td>
<td>Position 2</td>
</tr>
<tr>
<td>Subject 1</td>
<td>9.8°</td>
<td>7.12°</td>
</tr>
<tr>
<td>Subject 2</td>
<td>2.59°</td>
<td>6.52°</td>
</tr>
<tr>
<td>Subject 3</td>
<td>4.32°</td>
<td>6.81°</td>
</tr>
<tr>
<td>Subject 4</td>
<td>7.23°</td>
<td>6.76°</td>
</tr>
</tbody>
</table>

A maximum of 9.8° mean error was recorded for holding position, which is not too significant, as the absolute precision is not required. In the task of flexion, it can be seen that measurements on three out of four subjects have shown error within 10°. The measurement with one subject showed a high error of 19.8°. This can be resulted because the model was trained for constant positions, not for dynamic movements. In addition, the muscle contraction profiles are different for static pose and dynamic movements. Figure 2 shows the results for the joint angle estimation tasks performed by Subject 4.

5.2 E-EXO Control

A bilateral rehabilitation exercise was performed to control the E-EXO in real-time. S-Band was worn on right arm and E-EXO was worn by the other person on same arm. The desired joint angle estimated in MATLAB was transmitted back to Arduino Due control unit, where the control system generates the corresponding desired joint
velocity signal, which is controlled through ESCON’s (motor driver) built-in PI velocity controller. The control loop, shown in Fig. 3, is run on 50 Hz frequency. The position tracking result is shown in Fig. 4. It can be seen in Fig. 4 that the exoskeleton is able to track the desired trajectory and is also not sensitive to chattering/noise, which can cause discomfort to the subject.

**Fig. 2.** Joint angle estimation

**Fig. 3.** E-EXO control structure

**Fig. 4.** E-EXO position control results using estimated joint angle

6 Conclusion

This work presents FMG based position sensing and control method. The developed sensor, S-Band, is able to read the muscle volume change with acceptable performance and therefore has proven to be effective to estimate the elbow joint angle. The proposed
method finds it application in classifying and estimating forearm, wrist and lower limb motions for rehabilitation and assistance purposes. In future, the work will be focused on improving the design and integrating the sensor within the exoskeleton, to use the same control strategy for assistance in daily routine tasks.

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References

Force Localization Estimation
Using a Designed Soft Tactile Sensor

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Abstract. Wearable tactile sensors are significant in biomedical robotic applications where force feedback is important. In this work, a soft tactile sensor is proposed for force localization. The tactile sensor was manufactured by using layer-by-layer technique that enables flexibility. The sensor has 9 lead zirconate titanate (PZT) elements placed in 3×3 matrix form which are 4×4 mm² and the spatial resolution is 3 mm. The voltage values gathered from the sensor were conditioned by a charge amplifier circuit. A human inspired machine learning procedure called Neural Networks was used for force localization. The success rates with respect to different network structures were presented and the maximum success was realized as 80.71%.

1 Introduction

Nowadays the robotic research focuses on building systems that can interact with the environment effectively and safely. In the future, the robotic systems will not only be tasked in the known, safe spaces but also collaborate with humans and even worn by the humans to perform more complicated tasks in unknown spaces. However, the physical and functional properties of the robots are limited by their actuator, sensor components and by their physical architecture. We need to find new methodologies for building soft, embeddable/wearable sensors that enable more functions. Besides, we also need to find algorithms to use the developed sensors effectively and make the system smarter.

Tactile sense is an important and developed sense which can provide more information about the unstructured environment than vision especially in terms of force feedback [1]. If tactile sensors can be developed as smart sensitive skins with the requirements of biomedical applications [1, 2] then the technology will also be developed and provide new solutions. This paper presents a wearable, soft 3×3 PZT based tactile sensor with a sensitivity of 0.578–0.821 V/N for force localization using Neural Networks (Fig. 1). The sensor description and data acquisition, the test setup, and the neural network structures for the force localization from the provided signals has been explained and finally the results have been investigated.

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2 Sensor Description and Test Setup

The tactile sensor is composed of 9 PZT (PSI-5H4E) elements positioned as a $3 \times 3$ matrix form and 5 layers as shown in Fig. 2. The gap between PZT taxels is 3 mm and each PZT ceramic has an area of $4 \times 4$ mm$^2$. Two copper-kapton (Pyralux) electrodes which were cut using laser cutter have been used for the top and bottom electrodes of the PZT elements. In an attempt to have a human skin-like tissue on the sensor and to protect the PZT elements from the force impacts, upper and lower parts of the sensor were covered with a thin silicone (Ecoflex30). The detailed manufacturing process for $3 \times 1$ sensor array were presented in [3].

Fig. 2. (a) Layer by layer illustration of $3 \times 3$ matrix formed PZT based tactile sensor. (b) The manufactured tactile sensor.

High input impedance characteristic of piezoelectric material requires an operational amplifier based signal conditioning unit. A charge amplifier circuit [4] has been selected as the signal conditioner for our system due to the fact that the effect of cable impedance can significantly be reduced in measurements. The resistance and the capacitance values were selected with regard to the level of gain and the cut-off frequency of the amplifier. The force inputs to the tactile sensor were provided by a
direct drive linear actuator mounted on the linear stage of z axis (Fig. 3a). National Instruments 9264 DAQ was used for signal generation of the actuation which is a 10 Hz sine wave and the PZT taxels voltage output values were collected. The peaks of the voltage values were measured via a peak detector block in LabVIEW. These voltage peak values were then used for the training and validation processes of machine learning algorithm. The applied forces on the sensor were also measured by HBM U9C 50N load cell.

3 Force Localization Estimation

3.1 Data Gathering

The force localization is possible continuously on the sensor although we have discrete elements (Fig. 3c). For the 1st row of the sensor, starting from the PZT 1 to PZT 3, 1N of force was applied on every 1 mm and the peak-to-peak output voltages from the PZT elements are collected. Data acquisition process has been done for 14 x 14 mm² with 1 mm sensitivity starting from (0, 0) to (14, 14) and therefore there are totally 225 data points on the sensor used for training (Fig. 3b). Moreover, the validation data includes 196 data points which are shifted from training points by 0.5 mm starting from (0, 0.5) till (13, 13.5) with again 1 mm distance between each points are set as validation points.

3.2 Learning Algorithm

The position estimation was made from 0 to 14 mm for two dimensions. Since the position is a continuous data for this range, regression based machine learning algorithms should be used for the predictions. Multi-layer perceptron algorithm was used
for learning procedure. The network comprises several neurons that were connected with each other by weights and it was basically divided into three groups: the input neurons having 9 neurons because of 9 PZT taxels voltage outputs, the output neurons having 2 neurons for the estimation in 2D space and the hidden neurons. The number of the hidden neurons determines the smoothness of the decision boundary. Values of the weights were set by a calculation method called back propagation [5, 6]. There are a number of activation functions that can be used in network architecture [7]. In this study, 3 of these activation functions were implemented to hidden layers one by one without affecting input and output layers to observe the effects of the activation functions on the learning process.

3.3 Estimation Results

In training process, different network combinations were used in order to find the optimal network architecture and the estimations were made using two different group of test data. All the network structures had 2 hidden layers. Moreover, the average accuracy value was composed by the average value of two different test data accuracy values. The network parameters and the estimation results have been presented in Table 1.

<table>
<thead>
<tr>
<th>Hidden neuron number per layer</th>
<th>Used activation functions</th>
<th>Average accuracy [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Log-Sigmoid</td>
<td>78.94</td>
</tr>
<tr>
<td>10</td>
<td>Log-Sigmoid</td>
<td>75.71</td>
</tr>
<tr>
<td>20</td>
<td>Log-Sigmoid</td>
<td>72.73</td>
</tr>
<tr>
<td>3</td>
<td>Tan-Sigmoid</td>
<td>76.29</td>
</tr>
<tr>
<td>10</td>
<td>Tan-Sigmoid</td>
<td>67.20</td>
</tr>
<tr>
<td>20</td>
<td>Tan-Sigmoid</td>
<td>54.12</td>
</tr>
<tr>
<td>3</td>
<td>Rectified linear unit</td>
<td>44.01</td>
</tr>
<tr>
<td>10</td>
<td>Rectified linear unit</td>
<td>80.71</td>
</tr>
<tr>
<td>20</td>
<td>Rectified linear unit</td>
<td>77.36</td>
</tr>
</tbody>
</table>

4 Conclusion

In this paper, an application of force localization estimation using a designed soft PZT based tactile sensor have been illustrated. Force localization estimation was made for 14 × 14 mm² area on the tactile sensor using Artificial Neural Networks with 3 different activation functions. The best accuracy was obtained by using rectified linear unit activation function with 10 neurons for each hidden layer and the average estimation accuracy is 80.71%.
References

EIT-Based Tactile Sensing Patches for Rehabilitation and Human Machine Interaction

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Abstract. We present the development of an innovative stretchable tactile sensor based on electrical impedance tomography (EIT) for applications in wearable robotics and rehabilitation. To extract the tactile information we exploit the electrical impedance tomography technique to reconstruct the local conductivity changes of a piezoresistive fabric. The EIT method poses several new challenges in the reconstruction, counterbalanced by the overcoming of many of the drawbacks of the current tactile sensors. Results obtained are preliminary but encouraging and we believe that the combination of the EIT method with advanced machine learning techniques will enable reliable wearable tactile sensing.

1 Introduction

In the fields of neuro- and physical- rehabilitation and human machine interaction (HMI), there is a strong need for unobtrusive and conformable sensing devices that do not interfere with the subject’s body and/or the robot’s mechanics. Flexibility and stretchability of the sensing elements are the key factors to achieve effective and reliable wearable human-robot interfaces able to detect user movements, recognise movement intention and sense tactile interaction. We have previously developed flexible and stretchable sensing interfaces able to detect human posture and movement based on textile strain sensors and goniometers. Textile goniometers are double layer piezoresistive device that can reliably sense the joint angle of rotational joints [1]. They have been combined and fused with inertial microsensors to reconstruct the movement of upper [2] and lower limbs [3] with applications in neuro- [4] and physical- [5] rehabilitation and HMI [6]. To obtain fully functional wearable robotic interfaces, the capability to detect kinematic information has to be augmented with the tactile sensing modality (i.e. detection of normal/shear force and stimulus location), again in a flexible,
stretchable and conformable fashion. To detect the force interaction in multiple points between the subject and the robotic interface has many applications, spanning from prosthesis control [7], movement intention recognition in exoskeletons [8], to assessment of rehabilitation recovery [9].

In the present work we present the preliminary development of an innovative tactile sensor based on electrical impedance tomography (EIT). Our sensor is simply made of a piezoresistive fabric, where the local conductivity changes due to the applied mechanical stimuli. The change in conductivity is reconstructed thanks to the solution of the EIT inverse problem where current injection and voltage reading electrodes are placed only at the boundary of the sensing area. This approach overcomes several drawbacks intrinsically linked to distributed tactile sensing (no wires on the sensing area, conformability, possibility to adapt to irregular surfaces), even if it poses several new challenges in the reconstruction of the tactile stimuli.

2 Materials and Methods

The presence of different materials or wires embedded in a tactile sensor is usually one of the main cause in the reduction of their flexibility and/or stretchability. An approach that has been recently used to compensate for this drawback, which is the main topic of this work, is EIT [10]. This technique allows to place the electrodes only on the boundary of the active sensing area of a tactile sensor. As a consequence, no wiring is present inside the sensor. Therefore, EIT-based sensors can be placed over different surfaces even with irregular shapes as typically occur in the human robot interaction scenarios we are considering. EIT techniques are ill-posed non linear inverse problems, where the aim is to reconstruct the conductivity distribution of the body under study from measurements taken at electrodes placed the boundary. The reconstructed conductivity is then showed in an image by applying an inverse reconstruction algorithm [11].

A typical EIT system consists of a current source, a switching mechanism for generating current injection patterns between the boundary electrodes and a data acquisition unit for potential measurements [12]. In order to address some of the necessary requirements for rehabilitation and human robot interaction applications, we have developed an EIT system which presents low power consumption, precision in the measurements and high temporal resolution. A block diagram of our EIT platform is shown in Fig. 1 and consists of 3 main elements which are described below.

The transducer element is represented by block 3. We have used a thin, stretchable, piezoresistive fabric material provided by Eeonyx. The material has a surface resistance of 30 KΩ, it is low-cost, light weight, very flexible, bendable and conformable to different surfaces. For validation purposes we have used a 3D-printed circular frame made out of two disc layers to house the conductive sheet. The frame presents 16 extrusions where conductive copper stripes are placed to create the electrodes. A custom printed circuit board (PCB) illustrated by block 2 along with its simple schematic in Fig. 1, is used for performing a DC constant