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| **Intelligent Systems** |
| Project |
|  |
| Developing of a neural system, a Mamdani-type fuzzy inference system and a Sugeno-type fuzzy inference system for the identification of a volunteer position/activity |
|  |
| **Francesco Paolo Culcasi** |
| **30/05/2016** |
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**Summary**

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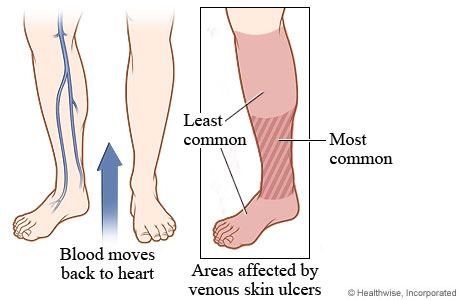
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# **1 – Project specifications**

The project requires the analysis of a set of medical data. The application context is dermatology and, in particular, the compression therapy by means of bandages in the treatment of venous ulcers of the leg.

In dermatology, venous ulcers are very frequent lesion of the skin of the legs, due to a compromised functioning of the blood circulation. To repair these ulcers, the blood circulation must be enhanced by exploiting the calf muscle pump which allows the blood to be moved back to the heart. The basic way to re-establish the blood circulation is the compression therapy.

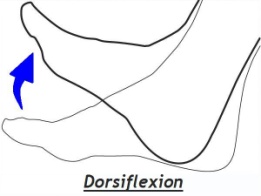
***Figure 1*** *Compression therapy*

In the compression therapy, the doctor applies a compression bandage on the leg of the patient providing a given pressure of the ulcer area. The pressure applied by the bandage allows to repair the ulcer, typically, in a few months.

The pressure applied by the bandage, and thus the efficiency of the therapy, depends on several factors:

* The type of bandage (depending, e.g., on the elasticity);
* The correct application of the bandage: an appropriate pressure should be applied in several parts of the leg according to the position of the ulcer, and the pressure should remain constant as much as possible between bandage applications;
* The activities performed by the patient during the therapy (e.g., walking, standing, etc.).

## 1.1 – Data description

The data refer to 10 volunteers. A compression bandage was applied to their calf. Three sensors were applied in three different position to measure sub-bandage pressure. Each volunteer wears the bandage for 12 minutes. During this time, the volunteer perform different activities or maintains their positions. Each activity/position is performed/maintained for about 3 minutes. The sensors measure the pressure with the sampling time of about 82 ms. The positions/activities taken into account are the following:

1. Supine position
2. Dorsiflexion standing

***Figure 2*** *Dorsiflexion activity*

1. Walking
2. Stair climbing

The data are organized as follows. One folder for each volunteer is provided. In each folder there are 4 files, one for each position/activity performed. Each file contains the measurements of the three sensors (in the first three columns), and the corresponding sampling time (in the last column). Please, note that the sensor measurements are electrical resistance and are measured in Ohms.

## 1.2 – Objective

The objective of the project is twofold: on the one hand, we want to identify the position/activity of the volunteer by analyzing the pressure of the bandage, i.e., to distinguish among supine position, dorsiflexion standing, walking and stair climbing; on the other hand, we want to find out the least temporal interval that is necessary and sufficient to recognize the position/activity.

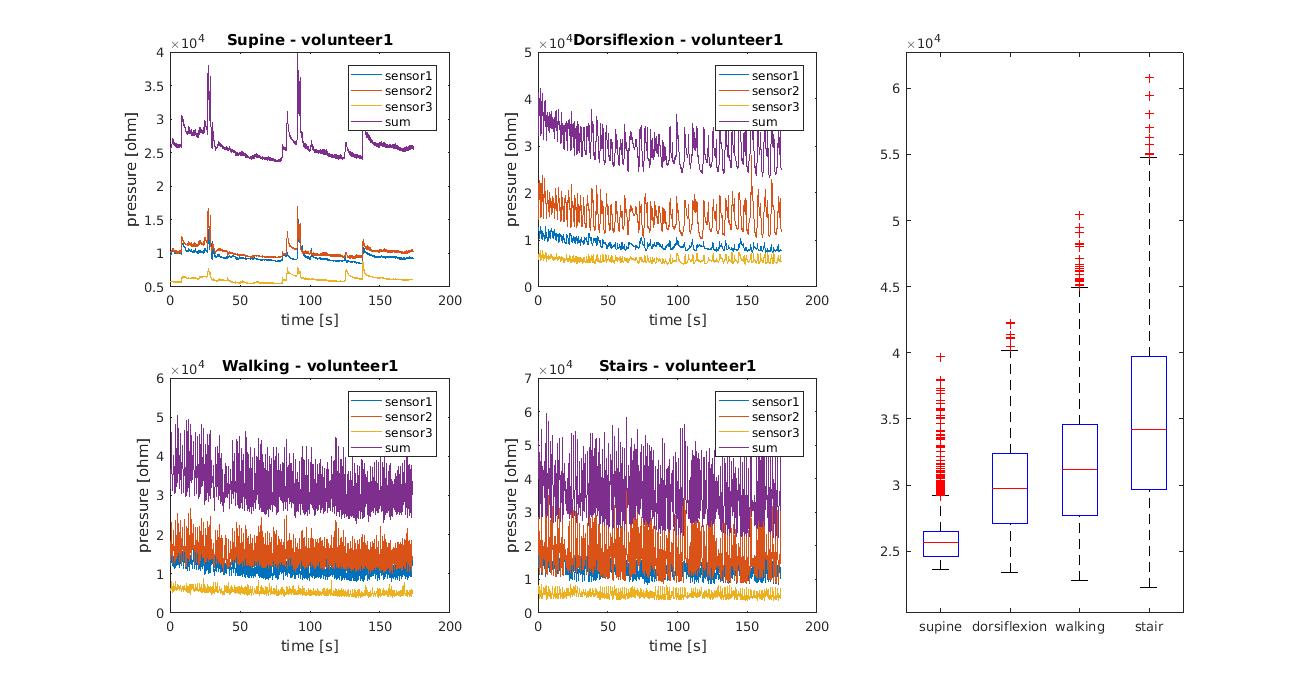
# **2 – Data analysis**

Given the data organization described in the previous chapter, each signal coming from a sensor is a set of approximately 2000 samples. Rather than give all these data as input of our system, we prefer to appropriately represent the signal in terms of a reduced number of features that can summarize the information of the original signals.

For this reason in the following paragraphs we are going to evaluate the signal after a preliminar feature extraction phase.

## 2.1 – Data initialization

At the starting point we have to deal with raw signals that are quite difficult to analyze. This implies a pre-processing phase with the purpose to get some structures in order to ease the computations on data ([*Appendix A.1*](#_A.1_init.m)). From the calf pressure measurements of different activities we observe that the three different sensors may show different shapes and shifts due to their position under the calf sub-bandage. For this reason we also introduced a fourth “virtual” sensor, obtained as the sum of the former three, to summarize the overall measurement.

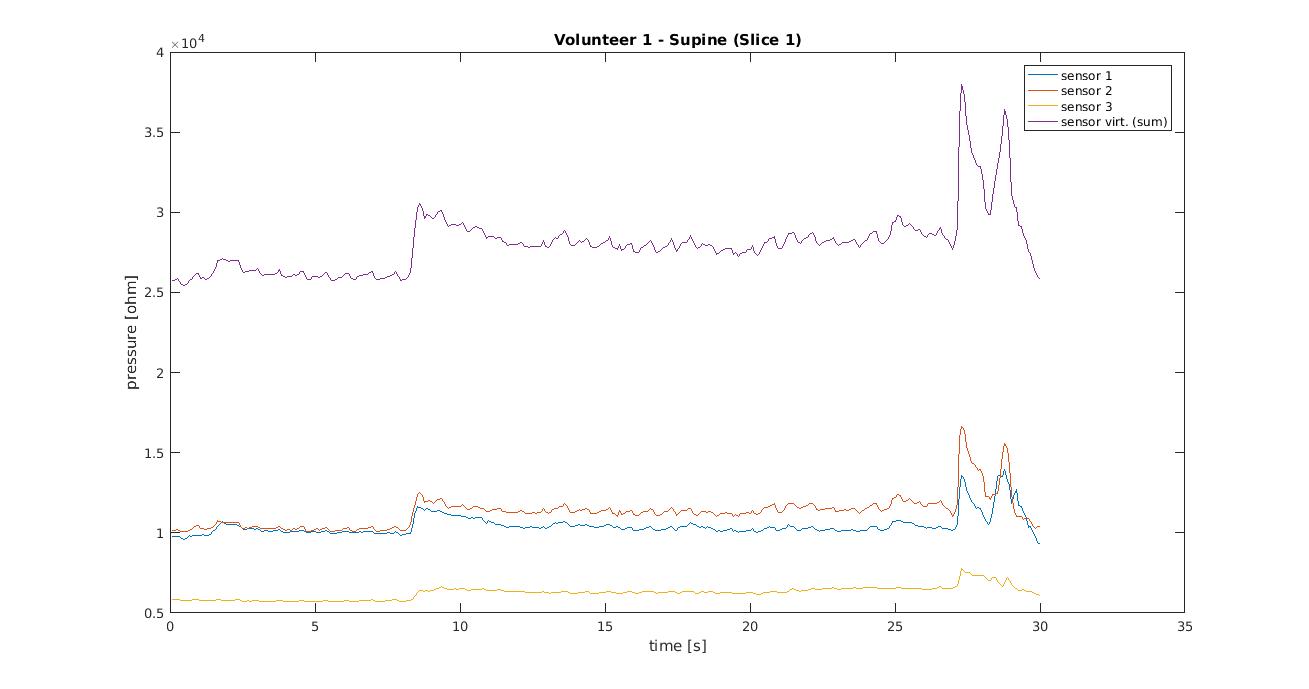


***Figure 1*** *Signals and boxplots of position/activities measured on volunteer 1*

Moreover our data should be sliced to obtain several pieces of the signal with duration smaller than the 3 minute signal for each activity. This has a twofold profit: we split every signal to find out the least temporal interval that is necessary and sufficient to recognize the position/activity and even more we have much more signals that we can use to train/test/valuate our neural network ([*Appendix A.2*](#_A.2_split.m)).

We notice from the signals that it has been sampled with a sampling period of ~82ms (or with a 12.2Hz sampling rate). Therefore we can compute the number N of samples needed to form a M-seconds-long piece of the signal with the following formula:

A vector with several of these values has been defined to switch quickly among different temporal intervals in our project. The values are computed for the following intervals: 3sec, 5sec, 10sec, 12sec, 15sec, 20sec, 30sec, 1min, 2min.



***Figure 2*** *First 30-seconds-long Slice of the supine signals from volunteer*

## 2.2 – Data cleaning

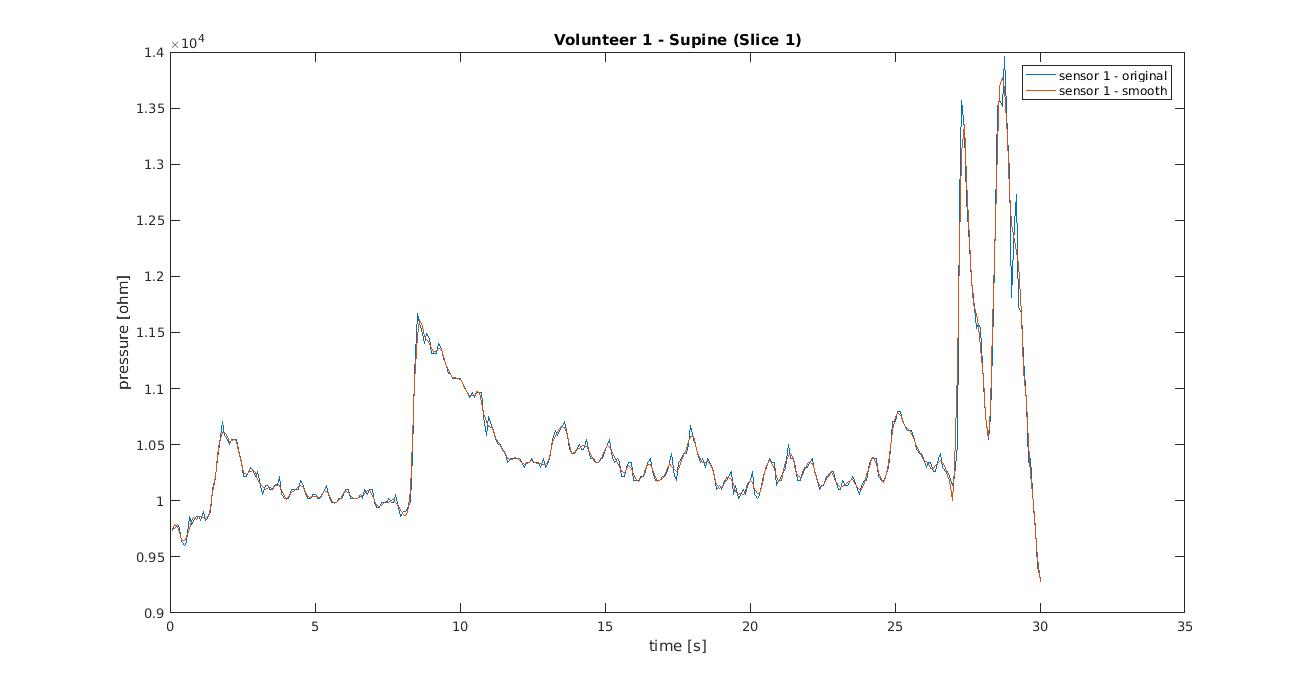
The signals we are going to process are obtained from pressure sensors. As like as every real world signal they are affected from noise that deteriorates the signal.

For this reason it is the norm to apply some cleaning techniques before any feature extraction.

### 2.2.1 – Signal smoothing

One of the most common smoothing technique is the use of Savitzky-Golay filter. Savitzky–Golay filter is a digital filter that can be applied to a set of digital data points for the purpose of smoothing the data, with a consequent increase of the signal-to-noise ratio without excessive distortions of the signal. This is achieved, in a process known as convolution, by fitting successive sub-sets of adjacent data points with a low-degree polynomial by the method of linear least squares.

For our project we used a third-order polynomial and a frame length of 7 ([*Appendix A.3*](#_A.3_cleaning.m)).



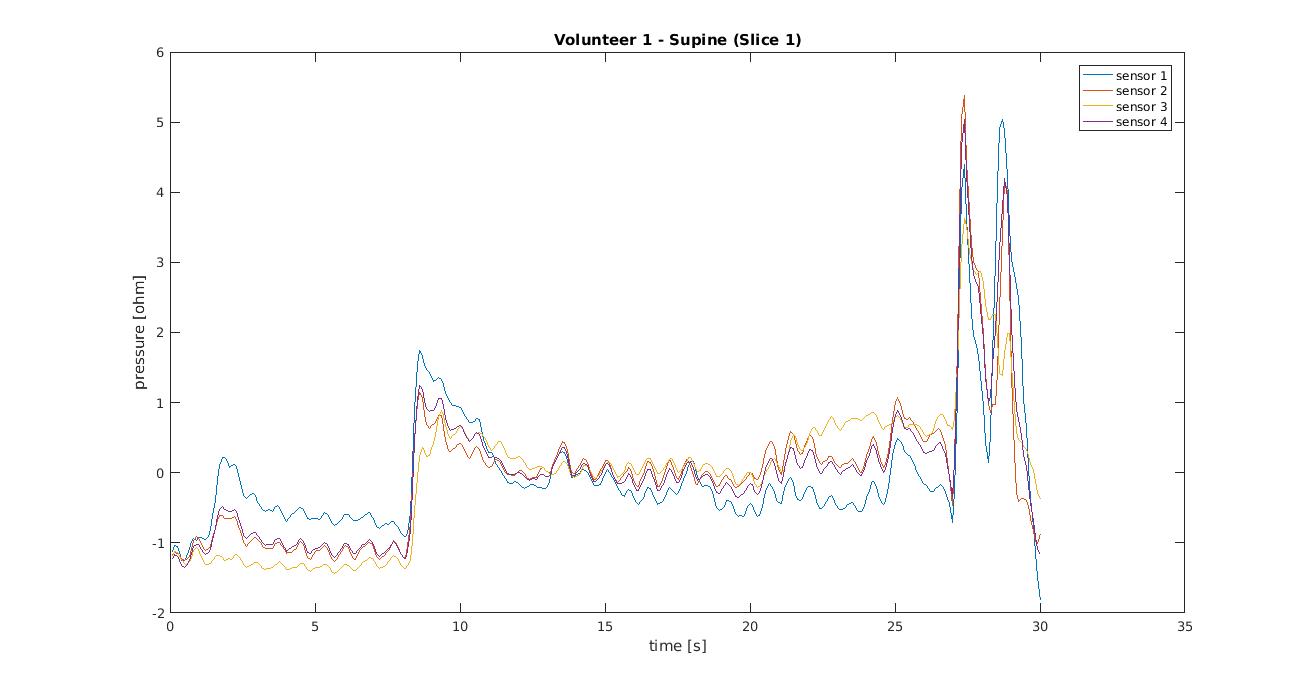
***Figure 3*** *Savitzky-Golay filter applied to a signal slice*

### 2.2.2 – Normalization

Another important point to deal with is the following: signals may have different scale and shift (see ***Figure 2***). This is a huge problem since we would like to compare them. To solve this problem we rely on the normalization process.

Since our dataset may contain some outliers we use Z-score normalization of the signal X (Z-score is not affected from outliers). It can be described with the formula belove:

where we define with μ and σ the signal mean and standard deviation respectively.



***Figure 4*** *Normalized signals*

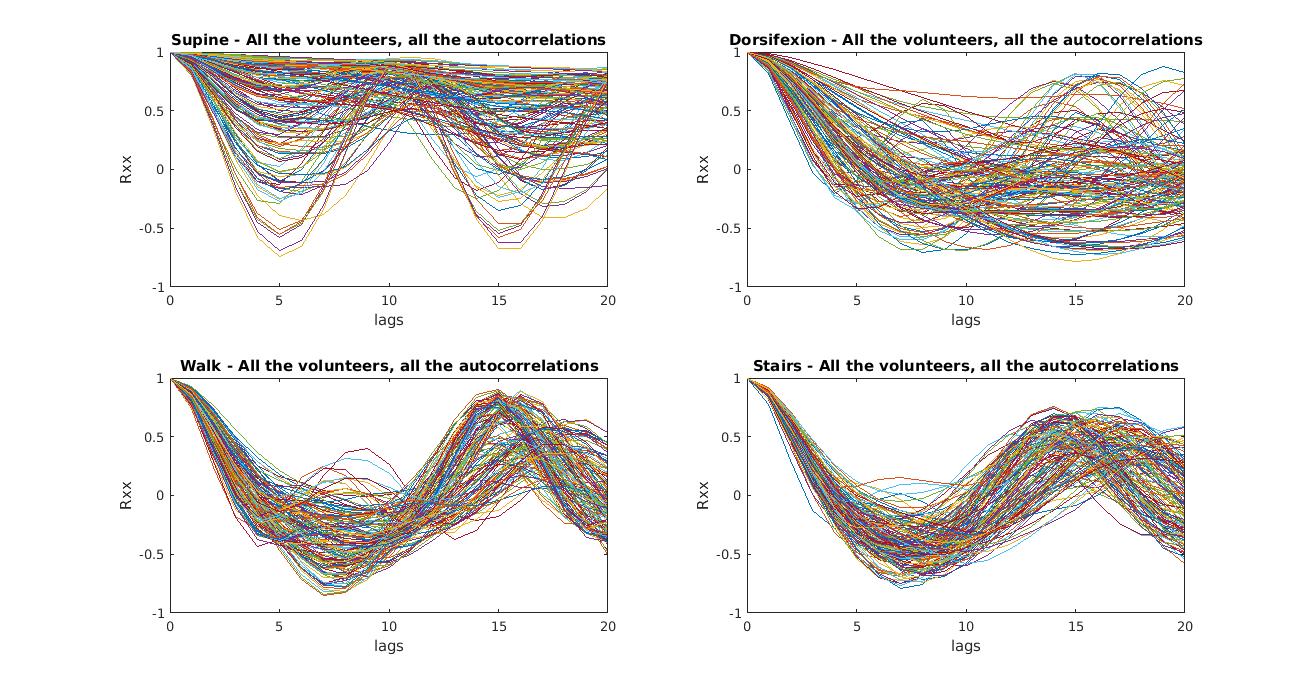
## 2.3 – Feature extraction

The signals, as whole, are quite difficult to analyze, than our goal is to represent them in terms of a reduced set of features. In order to do that we start analyzing signals’ shape.

From , representing the 4 activities of the volunteer 1, it become immediately evident that signals belonging on different activities can be discriminated by the following temporal characteristics:

* **Max/Min**: the maximum and minimum values of each signals may be significatively important;
* **First/Third Quartile**: as like as max/min, with the benefict to elide outliers;
* **Standardized moments**:
  + **1st std. moment (mean)**: after the normalization phase the mean value has been nullified;
  + **2nd std. moment (variance)**: the same as for mean value.
  + **3rd std. moment (skewness)**: is a measure of the asymmetry, computed as
  + **4th std. moment (kurtosis)**: is a measure of the "tailedness", measured as:
* **Autocorrelation**: is the correlation of a signal with a delayed copy of itself as a function of delay, and can be obtained with

For this project we take in consideration the first 20 lags (Δ=1,2,…,20).



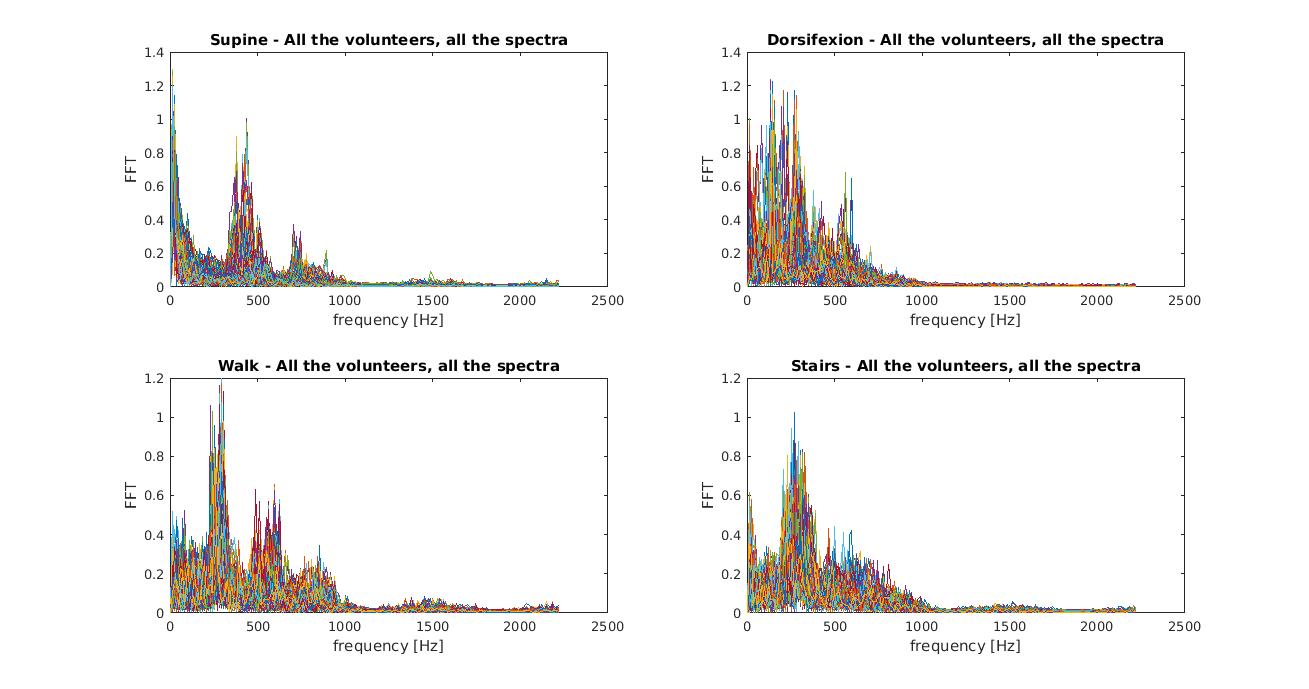
***Figure 5*** *Autocorrelations for all the activities of every volunteer*

In addition, performing some spectral analysis, we can infeer common frequential features for spectra for the same positions/actvities (see ). We can introduce some frequency features that look appropiated:

* **Fundamental frequency** (f0): achieved by detecting the maximum peak abscissa of the signals’ spectrum, obtained by Fast Fourier Transform (FFT) formula,

To faster compute f0 we can approximate it with the maximum value of the FFT;

* **Amplitude of the f0 peak** (amp);
* **Power Spectral Density** (PSD): obtained from the spectrum through the formula,



***Figure 6*** *Fast fourier transforms for every volunteer separated on activity/position*

The feature extraction phase is showed in the [*Appendix A.4*](#_A.4_featureEx.m).

## 2.4 – Feature selection

So far we have obtained 29 features: max, min, first and third quartile, skewness, kurtosis, autocorrelations (20), f0, amp and PSD. But we have to compute these for each of the 4 sensors (3 real + 1 virtual). Then we have a total of 116 features.

They are still a lot of inputs for the system, thus we have to select only the more significant for the activity classification.

### 2.4.1 – Sequential feature selection

To obtain the most important features to discriminate among positions/activities we can take advantage of the tools MATLAB makes available.

One of this is “sequentialfs”, that selects a subset of features from the input data matrix basing on the the result of the criterion function ([*Appendix A.8*](#_A.8_featureSel.m)). Every detail can be found in the MATLAB documentation.

# **3 – Neural Network**

Neural networks are good at recognizing patterns. MATLAB provides two ways to solve this kind of problems:

* Use the nprtool GUI;
* Use a command-line solution.

It is generally best to start with the GUI, and then to use the GUI to automatically generate command-line scripts. All the reasoning in the sections below take form in the script showed in [Appendix B.1](#_B.1_nn.m).

Before using either one of the two methods listed above, the first step is to define the problem by selecting a data set.

## 3.1 – Defining the problem

To define a pattern recognition problem, we arrange a set of input features vectors (the ones selected in paragraph ) as columns in a matrix. Then we arrange another set of vectors so that they indicate the classes to which the input vectors are assigned. Target vector have 4 elements (we have 4 activities to classify), where for each target vector, one element is 1 and the others are 0.

## 3.2 – Train the Neural Network

To train the neural network we have to ask a preliminary question:

*“What's the best number of hidden neurons?”*

In order to answer, we write down some script code to perform the following computations:

* For more values for the number n, number of hidden neurons:
  + Train the network 10 times;
  + Compute the average performance (Mean Square Error);
* Choice as final number of hidden neurons the one that produces the best performance value (least MSE).

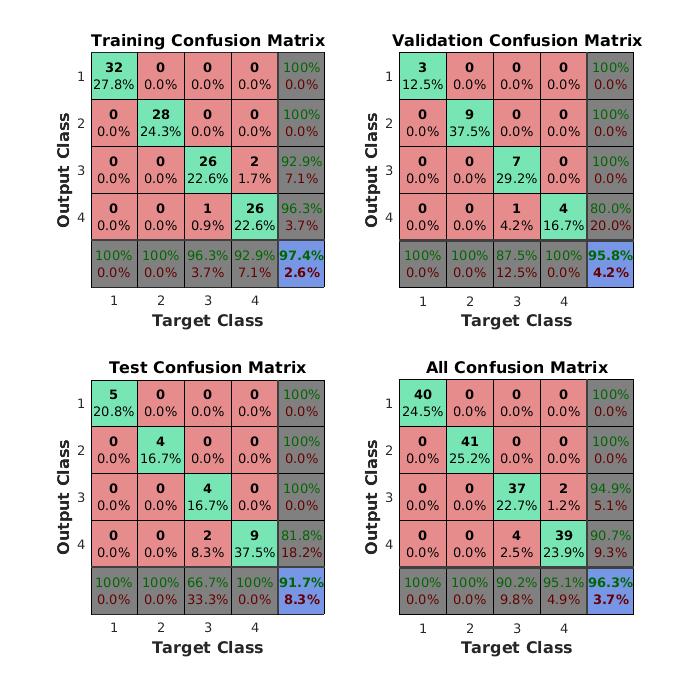
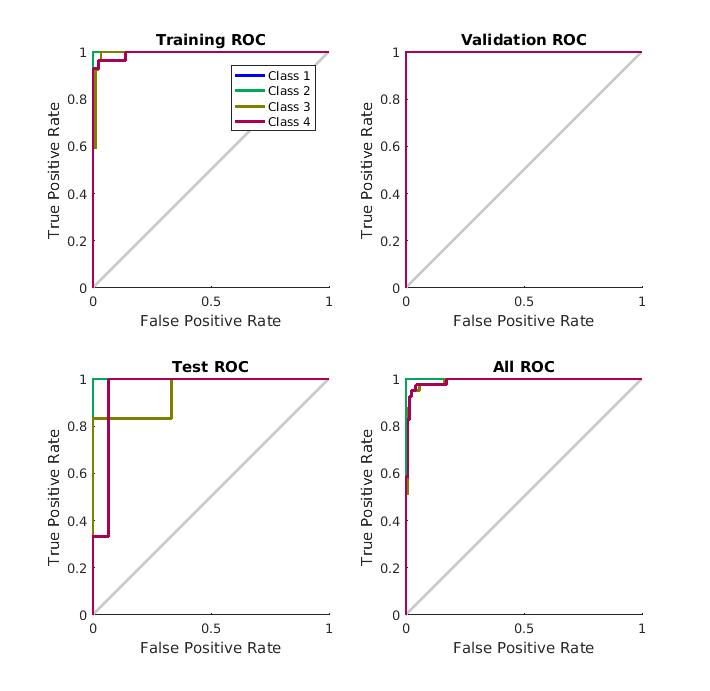
Then we automatically generate the command-line script from the graphical tool “nprtool” for the Neural Network with chosen number of hidden neurons. The settings used for the division of data is the following: 70% training, 15% validation and 15% testing.

## 3.3 – Network outputs evaluation

Once we have got our network trained, we can use it to compute some network outputs. These can be used to evaluate its “goodness”. These information can be showed in diagrams such as **Confusion Matrix** and **ROC plots** (respectively  ***Figure 7*** and ***Figure 8***).

Some of the information we can scavenge from these diagrams are:

* **Accuracy (ACC)**: Overall, how often is the classifier correct?
* **Precision (PPV)**: How many times the classifier is correct in predicting a class over its overall predictions of that class?
* **Sensitivity** or Recall **(TPR)**: How many times the classifier predicts the correct class among all the overall actual occurrences of that class?
* **Miss rate (FNR)**: How many times the classifier does not predict a class?
* **Specificity (TNR)**: When the classifier is correct at not classify an input as a class over the whole not-members of that class?
* **Fall-out** (false alarm): When the classifier predicts a class, wrongly?
  + .

***Figure 7*** *Confusion matrices* ***Figure 8*** *ROC plots*

### 3.2.1 – Smaller necessary time interval

Now that we have described the procedure to produce the neural network, we can apply it for different time intervals, in order to find the least necessary time interval. There is not a “*best*” time interval because, obviously, it is relative to the performance we are asking to the neural network.

We run a script ([*Appendix B.1*](#_B.1_nn.m)) that is able to choice the best number of hidden neurons for the neural network, by running 10 times the training with a number “*n*” of hidden neurons, and computing the mean error as measure of performance. Then we choose the best, and use it to run 10 times the training. Among the last networks we choice the one with best performance.

The following ***Table 1*** shows, with percentage, the results obtained for every class and for each interval.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Intervals** | **Performances** | **Classes** | | | |
| **Supine** | **Dorsiflexion** | **Walking** | **Stair climbing** |
| 3sec | Accuracy (ACC) | 96,25 | 90,51 | 87,76 | 85,00 |
| Precision (PPV) | 93,42 | 79,73 | 73,75 | 72,41 |
| Sensitivity (TPR) | 91,19 | 83,72 | 79,71 | 64,56 |
| Specificity (TNR) | 97,90 | 92,81 | 90,46 | 91,81 |
| Miss rate (FNR) | 8,81 | 16,28 | 20,29 | 35,44 |
| Fall-out (FPR) | 2,10 | 7,19 | 9,54 | 8,19 |
| **Model Accuracy** | 79,77 | | | |
| 5sec | Accuracy (ACC) | 97,27 | 93,79 | 89,17 | 86,29 |
| Precision (PPV) | 94,50 | 88,34 | 77,17 | 73,21 |
| Sensitivity (TPR) | 94,50 | 86,75 | 80,66 | 71,21 |
| Specificity (TNR) | 98,19 | 96,15 | 92,01 | 91,31 |
| Miss rate (FNR) | 5,50 | 13,25 | 19,34 | 28,79 |
| Fall-out (FPR) | 1,81 | 3,85 | 7,99 | 8,69 |
| **Model Accuracy** | 83,26 | | | |
| 10sec | Accuracy (ACC) | 99,53 | 95,75 | 91,34 | 89,13 |
| Precision (PPV) | 98,73 | 92,36 | 83,02 | 77,78 |
| Sensitivity (TPR) | 99,36 | 90,62 | 82,50 | 79,25 |
| Specificity (TNR) | 99,58 | 97,47 | 94,32 | 92,44 |
| Miss rate (FNR) | 0,64 | 9,38 | 17,50 | 20,75 |
| Fall-out (FPR) | 0,42 | 2,53 | 5,68 | 7,56 |
| **Model Accuracy** | 87,87 | | | |
| 12sec | Accuracy (ACC) | 98,46 | 95,97 | 93,09 | 91,36 |
| Precision (PPV) | 96,15 | 92,31 | 88,00 | 81,62 |
| Sensitivity (TPR) | 97,66 | 91,60 | 83,97 | 84,73 |
| Specificity (TNR) | 98,73 | 97,44 | 96,15 | 93,59 |
| Miss rate (FNR) | 2,34 | 8,40 | 16,03 | 15,27 |
| Fall-out (FPR) | 1,27 | 2,56 | 3,85 | 6,41 |
| **Model Accuracy** | 89,44 | | | |
| 15sec | Accuracy (ACC) | 99,25 | 98,26 | 96,27 | 95,77 |
| Precision (PPV) | 98,98 | 97,00 | 93,00 | 90,38 |
| Sensitivity (TPR) | 97,98 | 96,04 | 92,08 | 93,07 |
| Specificity (TNR) | 99,67 | 99,00 | 97,67 | 96,68 |
| Miss rate (FNR) | 2,02 | 3,96 | 7,92 | 6,93 |
| Fall-out (FPR) | 0,33 | 1,00 | 2,33 | 3,32 |
| **Model Accuracy** | 94,78 | | | |
| 20sec | Accuracy (ACC) | 99,65 | 98,94 | 96,47 | 96,47 |
| Precision (PPV) | 100,00 | 97,22 | 94,20 | 91,78 |
| Sensitivity (TPR) | 98,57 | 98,59 | 91,55 | 94,37 |
| Specificity (TNR) | 100,00 | 99,06 | 98,11 | 97,17 |
| Miss rate (FNR) | 1,43 | 1,41 | 8,45 | 5,63 |
| Fall-out (FPR) | 0,00 | 0,94 | 1,89 | 2,83 |
| **Model Accuracy** | 95,76 | | | |
| 30sec | Accuracy (ACC) | 100,00 | 100,00 | 99,39 | 99,39 |
| Precision (PPV) | 100,00 | 100,00 | 100,00 | 97,62 |
| Sensitivity (TPR) | 100,00 | 100,00 | 97,56 | 100,00 |
| Specificity (TNR) | 100,00 | 100,00 | 100,00 | 99,18 |
| Miss rate (FNR) | 0,00 | 0,00 | 2,44 | 0,00 |
| Fall-out (FPR) | 0,00 | 0,00 | 0,00 | 0,82 |
| **Model Accuracy** | 99,39 | | | |
| 1min | Accuracy (ACC) | 100,00 | 97,73 | 95,45 | 97,73 |
| Precision (PPV) | 100,00 | 91,67 | 100,00 | 91,67 |
| Sensitivity (TPR) | 100,00 | 100,00 | 81,82 | 100,00 |
| Specificity (TNR) | 100,00 | 96,97 | 100,00 | 96,97 |
| Miss rate (FNR) | 0,00 | 0,00 | 18,18 | 0,00 |
| Fall-out (FPR) | 0,00 | 3,03 | 0,00 | 3,03 |
| **Model Accuracy** | 95,45 | | | |

***Table 1*** *Performance of neural networks versus varing time intervals*

It is noteworthy that with an interval 20 seconds long it is possible to reach an accuracy of about 95%. With a 30 seconds interval the accuracy rise to 99%, and the first 2 classes are classified without errors.

It is also important to notice how with the 1 minute long intervals the accuracy decrease. This can be attributed to the lower number of signal pieces available to train the network.

# **4 – Fuzzy Inference System**

In this chapter we develop a Mamdani-type Fuzzy Inference System (FIS) with the help of the MATLAB *Fuzzy Logic Toolbox Graphical User Interface Tools*.

For this system we fix the time interval to the best we have found with neural network, i.e. 30 seconds long time intervals.

## 4.1 – Fuzzy Inference System

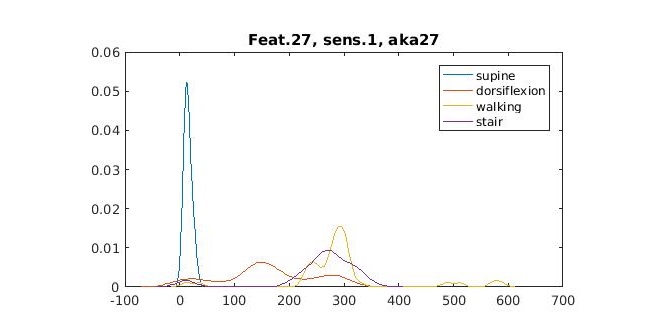
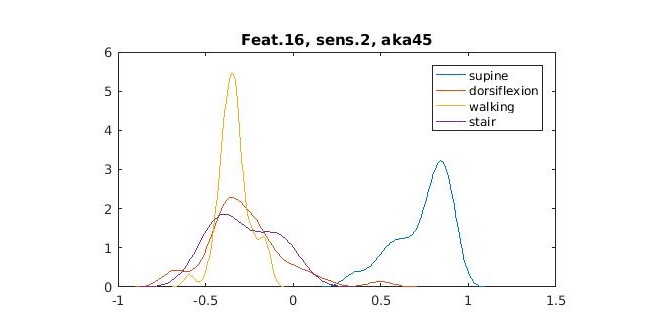
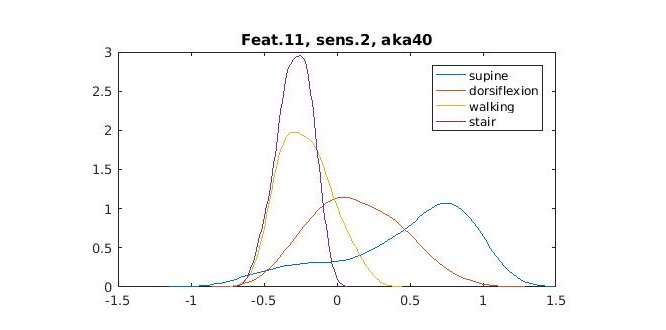
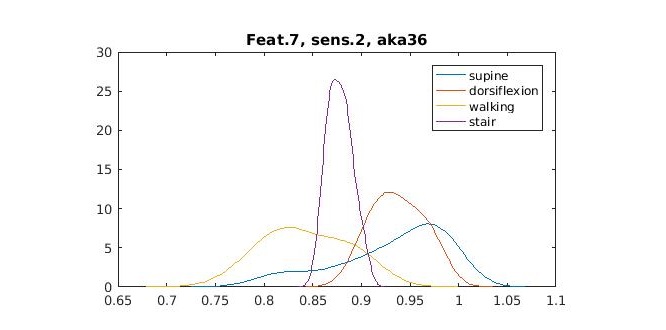
For the definition of the problem, we first run the command “fuzzy“ on MATLAB, in order to start the *FIS editor*.

From the showing GUI we introduce inputs and outputs of the FIS.

### 4.1.1 – Feature selection

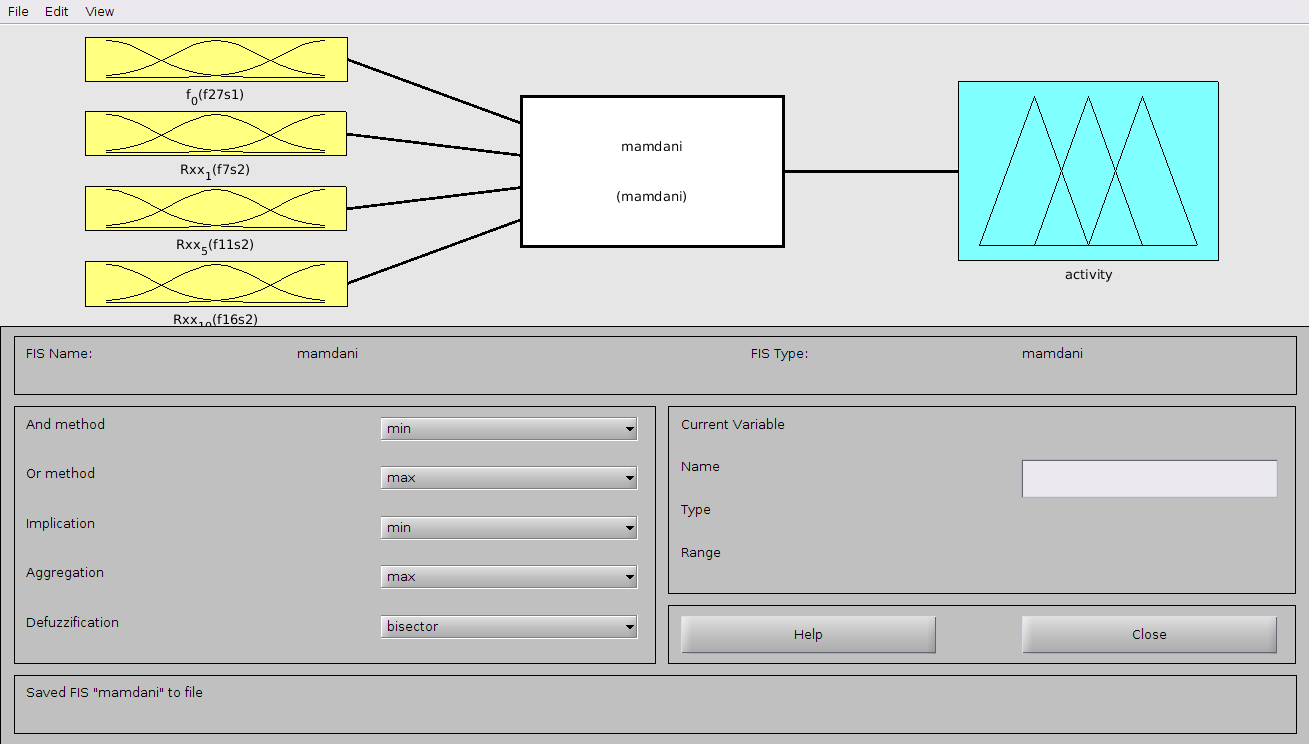
Since, this time, the choice of the features lies on our ability to write down the membership functions, we prefer to plot the Probability Mass Function (PMF) of each feature, so that it’s easier for us to take the features in which activities differ the most ([Appendix C.1](#_C.1_–_fuzzy_sys.m)).

From the plots we have chosen the following features:

****

The resulting system is a 4inputs-1output.

Its structure is showed in the figure below.

****

***Figure 9*** *FIS structure*

## 4.2 – Membership Functions

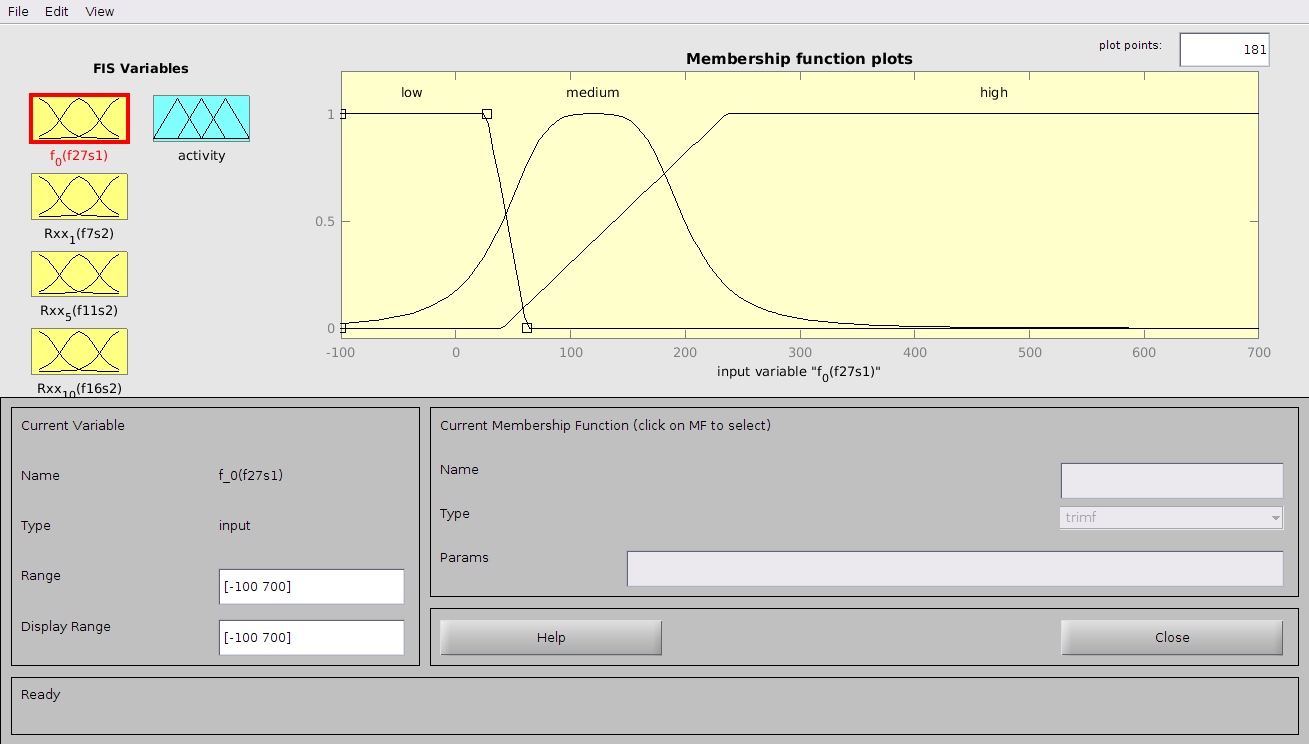
From the PMFs chosen in the previous paragraph, we use the *Membership Function Editor* to write the following membership functions.

### 4.2.1 – Feature #27 (Foundamental frequency, feature 27, sensor 1)

This input variable has been named f0(f27s1). The range of the values for this feature is [-100 700].

#### Linguistic variables

|  |  |  |
| --- | --- | --- |
| **Linguistic variable** | **Type of membership function** | **Parameters** |
| low | trampmf | [-100 -100 27.08 61.99] |
| medium | gbellmf | [79.4 1.87 120.1] |
| high | trampmf | [40.5 235.9 700 700] |



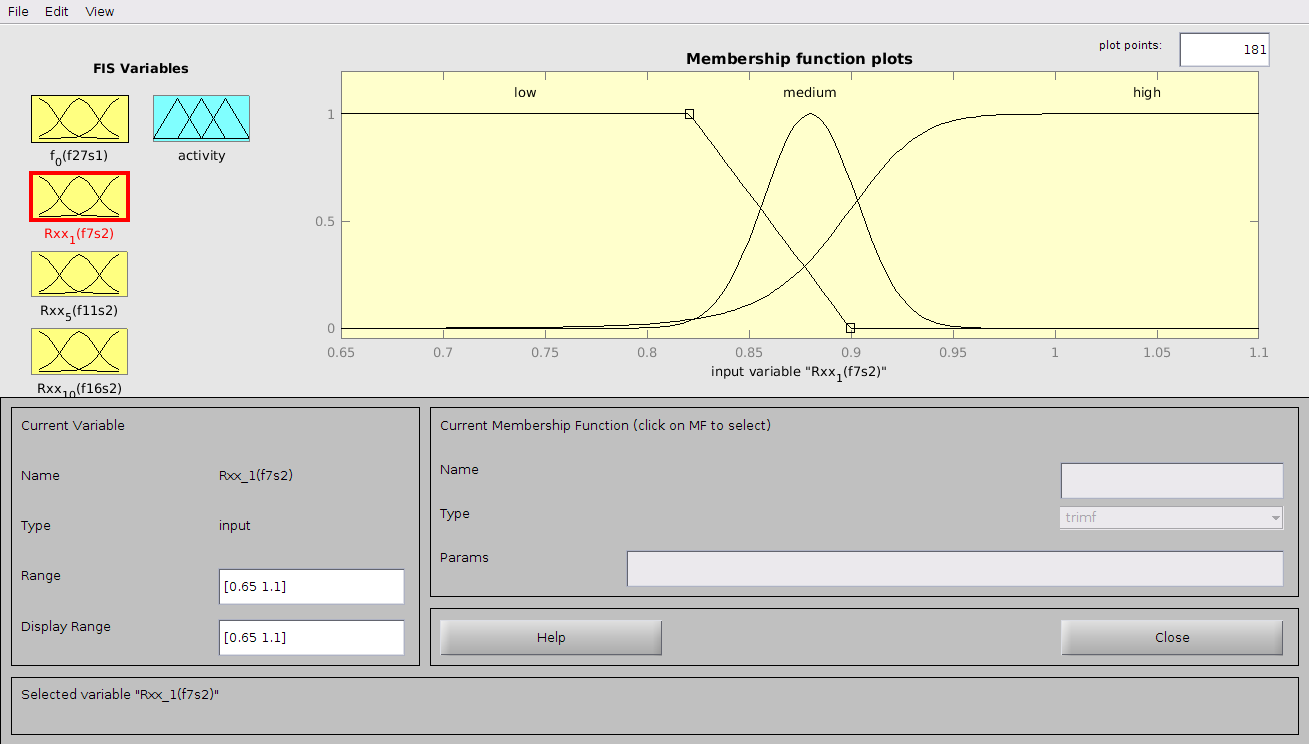
***Figure 10*** *MF for the feature #27*

### 4.2.2 – Feature #36 (Autocorrelation, delta=1, feature 7, sensor 2)

This input variable has been named *Rxx1(f7s2)* and the range of the values for this feature is [0.65 1.1].

#### Linguistic variables

|  |  |  |
| --- | --- | --- |
| **Linguistic variable** | **Type of membership function** | **Parameters** |
| low | trampmf | [0.6187 0.6187 0.8207 0.8997] |
| medium | gaussmf | [0.02266 0.88] |
| high | gbellmf | [0.167 4.3 1.063] |



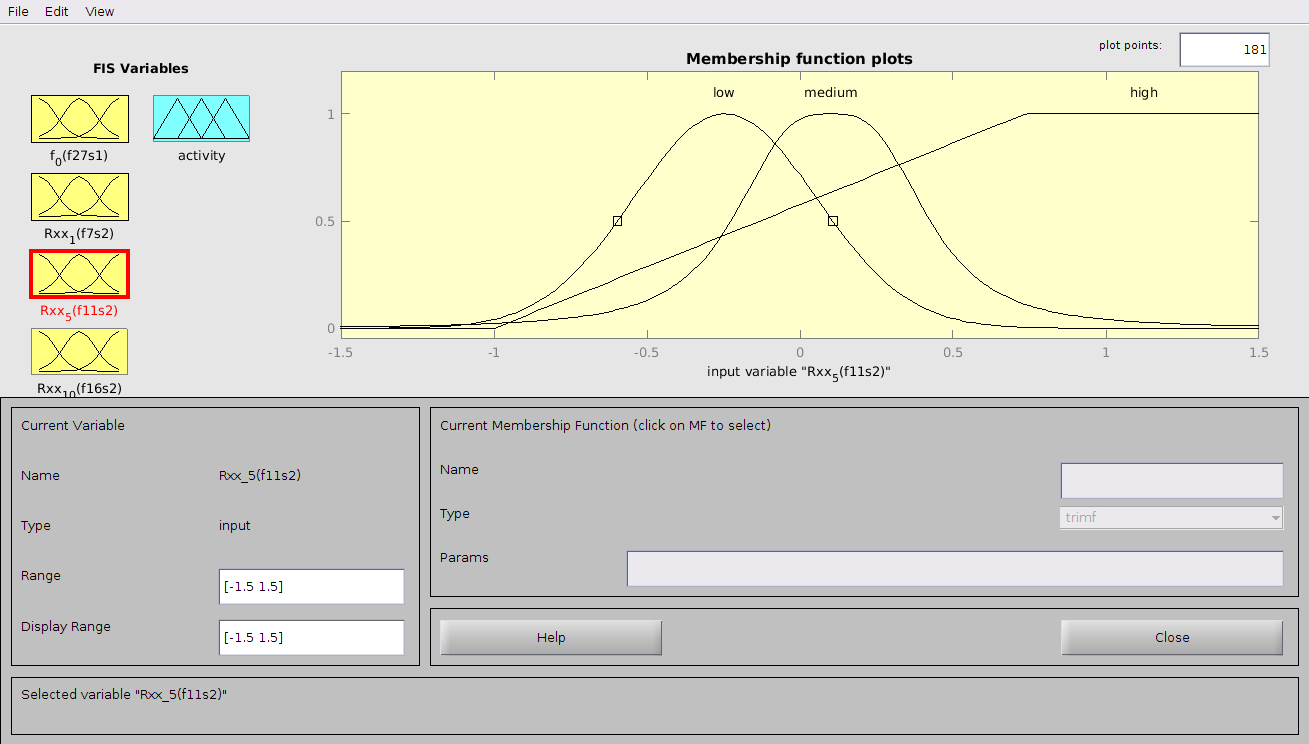
***Figure 11*** *MF for the feature #36*

### 4.2.3 – Feature #40 (Autocorrelation, delta=5, feature 11, sensor 2)

This input variable name is *Rxx5(f11s2)* and the range of the values for this feature is [-1.5 1.5].

#### Linguistic variables

|  |  |  |
| --- | --- | --- |
| **Linguistic variable** | **Type of membership function** | **Parameters** |
| low | gaussmf | [0.299 -0.2449] |
| medium | gbellmf | [0.3259 1.55 0.1] |
| high | trampmf | [-0.9986 0.7353 1.5 1.5] |



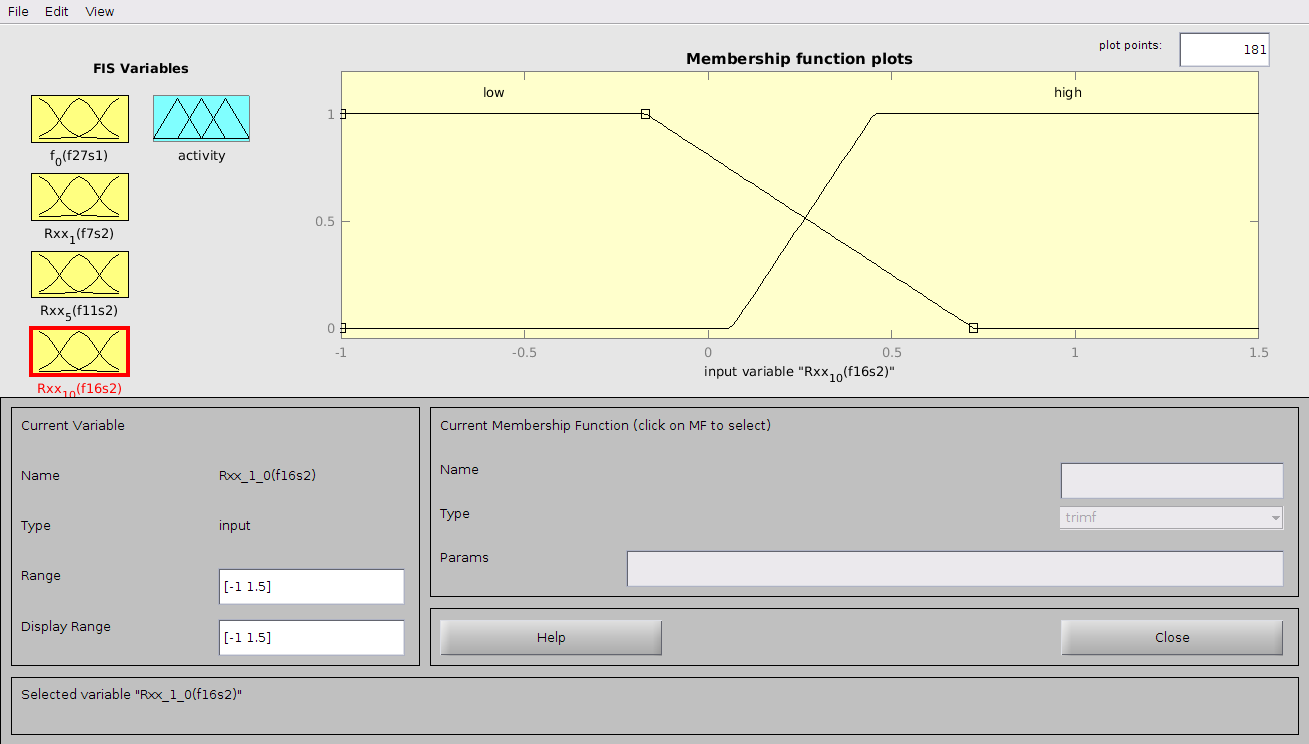
***Figure 12*** *MF for the feature #40*

### 4.2.3 – Feature #45 (Autocorrelation, delta=11, feature 16, sensor 2)

The last input variable name is *Rxx10(f16s2).* The range of values for this feature is [-1.5 1.5].

#### Linguistic variables

|  |  |  |
| --- | --- | --- |
| **Linguistic variable** | **Type of membership function** | **Parameters** |
| low | trampmf | [-1 -1 -0.1709 0.722] |
| high | trampmf | [0.0635 0.4515 1.5 1.5] |



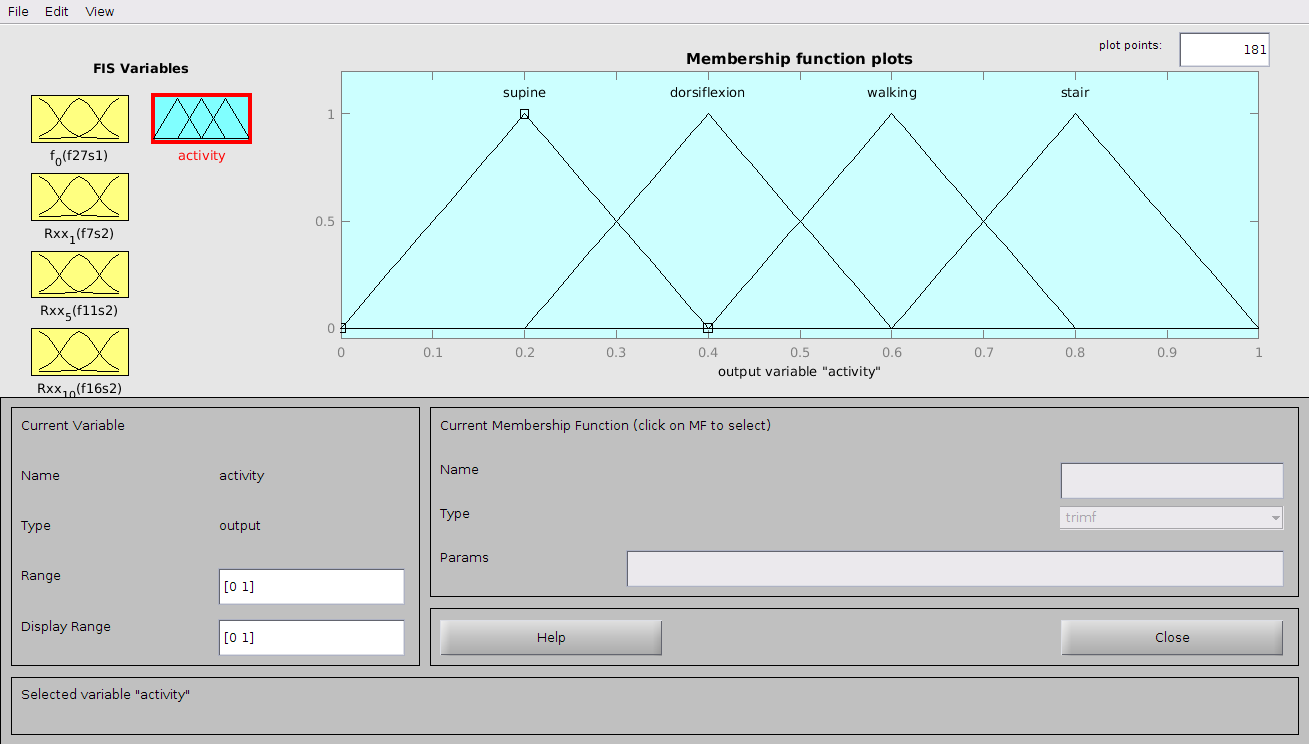
***Figure 13*** *MF for the feature #45*

### 4.2.4 – Activity

The only output variable name is *activity* and the range of the values for this feature is [0 1].

#### Linguistic variables

|  |  |  |
| --- | --- | --- |
| **Linguistic variable** | **Type of membership function** | **Parameters** |
| supine | trimf | [0 0.2 0.4] |
| dorsiflexion | trimf | [0.2 0.4 0.6] |
| walking | trimf | [0.4 0.6 0.8] |
| stair | trimf | [0.6 0.8 1] |



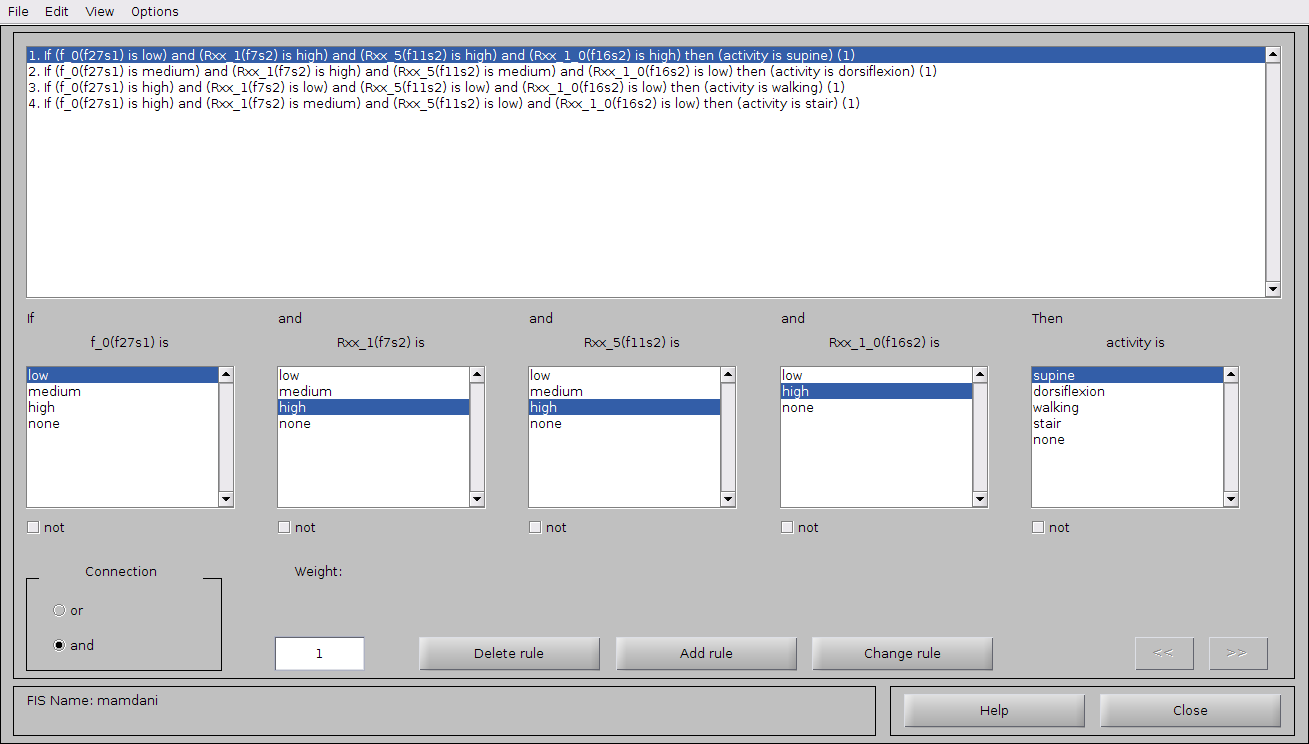
***Figure 14*** *MF for the output*

## 4.3 – Rules

Now we can write the rules that our FIS have to use in order to infer the output. In this regard the *Rule Editor* helps us.

The rules we are going to use are the following:

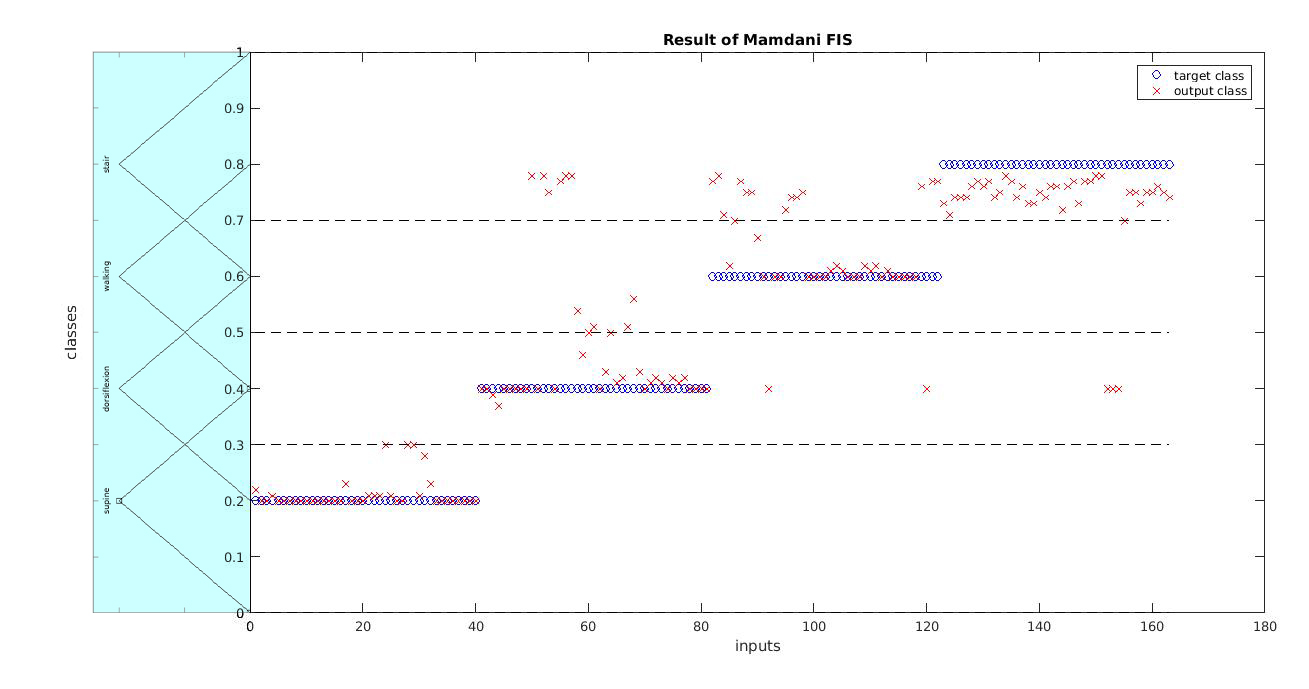
1. *If (f0(f27s1) is low) and (Rxx1(f7s2) is high) and (Rxx5(f11s2) is high) and (Rxx10(f16s2) is high) then (activity is supine) (1)*
2. *If (f0(f27s1) is medium) and (Rxx1(f7s2) is high) and (Rxx5(f11s2) is medium) and (Rxx10(f16s2) is low) then (activity is dorsiflexion) (1)*
3. *If (f0(f27s1) is high) and (Rxx1(f7s2) is low) and (Rxx5(f11s2) is low) and (Rxx10(f16s2) is low) then (activity is walking) (1)*
4. *If (f0(f27s1) is high) and (Rxx1(f7s2) is medium) and (Rxx5(f11s2) is low) and (Rxx10(f16s2) is low) then (activity is stair) (1)*



***Figure 15*** *Rules for Mamdani FIS*

## 4.4 – Performance evaluation

We plot the results of our FIS in ***Figure 16***.



***Figure 16*** *Results of Mamdani FIS*

For the evaluation of FIS performance we can still use the same script used for neural networks ([Appendix B.2](#_B.2_cfmatrix2.m)).

The results are displayed in the following tables.

|  |  |  |  |
| --- | --- | --- | --- |
| **Target class** | | | |
| Supine | Dorsiflexion | Walking | Stair climbing |
| **Output class** | Supine | 37 | 0 | 0 | 0 |
| Dorsiflexion | 3 | 29 | 2 | 3 |
| Walking | 0 | 6 | 25 | 0 |
| Stair climbing | 0 | 6 | 14 | 38 |

***Table 2*** *Confusion matrix of Mamdani FIS*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Intervals** | **Performances** | **Classes** | | | |
| **Supine** | **Dorsiflexion** | **Walking** | **Stair climbing** |
| 30 sec | Accuracy (ACC) | 98,16 | 87,73 | 86,50 | 85,89 |
| Precision (PPV) | 100,00 | 78,38 | 80,65 | 65,52 |
| Sensitivity (TPR) | 92,50 | 70,73 | 60,98 | 92,68 |
| Specificity (TNR) | 100,00 | 93,44 | 95,08 | 83,61 |
| Miss rate (FNR) | 7,50 | 29,27 | 39,02 | 7,32 |
| Fall-out (FPR) | 0,00 | 6,56 | 4,92 | 16,39 |
| **Model Accuracy** | **79,14** | | | |

***Table 3*** *Performance of Mamdani FIS*

From tables above (***Table 2*** and ***Table 3***) we can deduce that the main problem is the misclassification of walking activities that are evaluated as stair climbing.

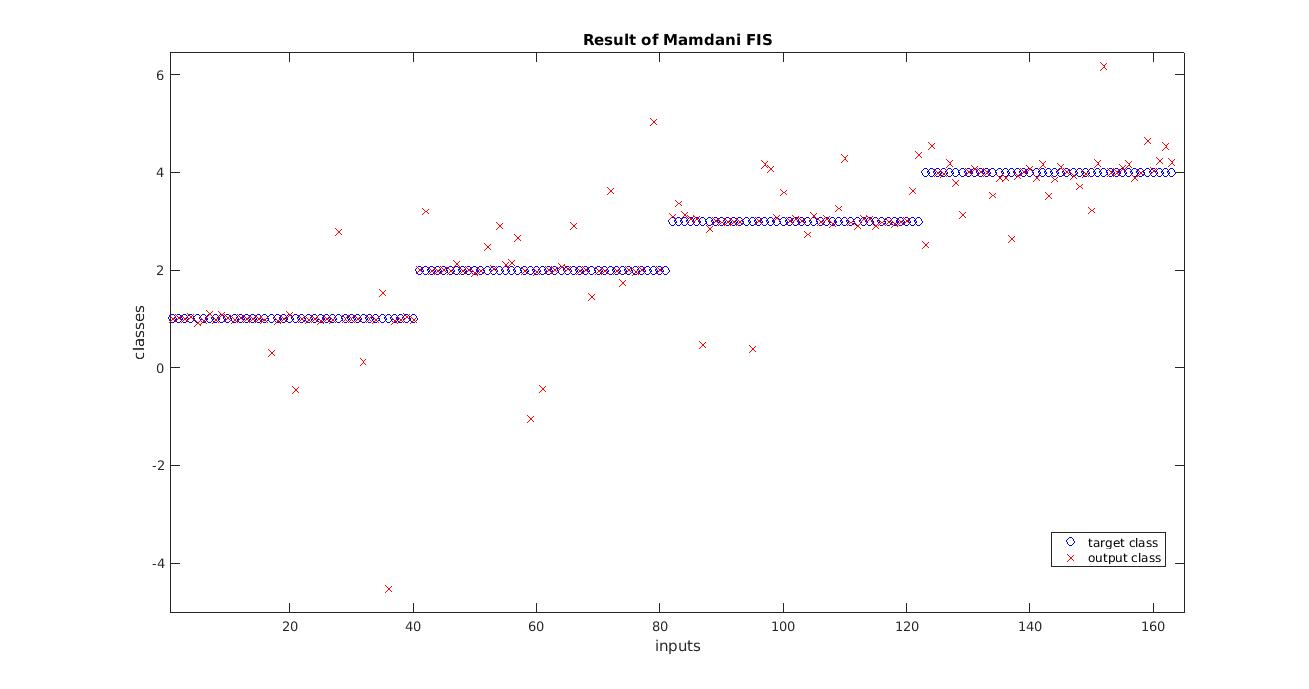
# **5 – Adaptive Network-based FIS**

For the FIS system we prefered a Mamdani-type, taking advantade of the higher interpretability to the detriment of accuracy. Whereas for the ANFIS system we prefer to start with a Sugeno-type FIS, to obtain a greater accuracy.

It is not always easy to build linear (sometime second order) membership functions, but MATLAB provides the command "mam2sug" that Transforms Mamdani fuzzy inference system into Sugeno fuzzy inference system. We wrote a script ([Appendix D.1](#_D.1_–_adaptiveNeuroFIS.m)) that, in addition to this convertion, randomly separate the input data set in three parts for training, testing and validating with a proportion of 70%, 15% and 15% respectively.

With the help of MATLAB ANFIS Editor, started typing the command “andfisedit”, we loaded each dataset, the Sugeno-type FIS and started the training it with an hybrid optimization method and 3 epocs. The hybrid optimization method is a combination of least-squares and backpropagation gradient descent method.

Then we validated the system and the performance obtained are the following.



***Figure 17*** *Result of Sugeno ANFIS*

The performance are calculated and are showed in the next tables.

|  |  |  |  |
| --- | --- | --- | --- |
| **Target class** | | | |
| Supine | Dorsiflexion | Walking | Stair climbing |
| **Output class** | Supine | 37 | 0 | 0 | 0 |
| Dorsiflexion | 3 | 29 | 2 | 3 |
| Walking | 0 | 6 | 25 | 0 |
| Stair climbing | 0 | 6 | 14 | 38 |

***Table 4*** *Confusion matrix of Sugeno ANFIS*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Intervals** | **Performances** | **Classes** | | | |
| **Supine** | **Dorsiflexion** | **Walking** | **Stair climbing** |
| 30 sec | Accuracy (ACC) | 98,16 | 87,73 | 86,50 | 85,89 |
| Precision (PPV) | 100,00 | 78,38 | 80,65 | 65,52 |
| Sensitivity (TPR) | 92,50 | 70,73 | 60,98 | 92,68 |
| Specificity (TNR) | 100,00 | 93,44 | 95,08 | 83,61 |
| Miss rate (FNR) | 7,50 | 29,27 | 39,02 | 7,32 |
| Fall-out (FPR) | 0,00 | 6,56 | 4,92 | 16,39 |
| **Model Accuracy** | **79,14** | | | |

***Table 5*** *Performance of Sugeno ANFIS*

From tables above we can deduce that the main problem is the misclassification of walking activities that are evaluated as stair climbing.

# **6 – Conclusions**

Starting from the sensor signals we have computed some features both from temporal and frequency domains, able to represent the main characteristics of each activity/position.

We have developed a neural network, a Mamdani-type fuzzy inference system and a Sugeno-type adaptive neuro-fuzzy inference system.

The results for the neural network showed that the accuracy of our system can reach 99% for signals long enough (30 seconds time interval), but even with littler interval the accuracy is still acceptable.

The Mamdani-type FIS, as expected, was not so accurate (less than 80%), mainly due to the easier form of its membership rules.

With the Sugeno-type ANFIS, generate starting from the Mamdani-type FIS, we increased the performance surpass the 80% of accuracy.

# **Appendix A – Data pre-processing**

## A.1 init.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80  81  82  83  84  85  86  87  88  89  90  91  92  93  94  95  96  97  98  99  100  101  102  103  104  105  106 | %% 01 Data initialization - init.m  % - Data are grouped by activity/position and collected in a structure.  addpath**(**'gitProjects/intelligent-system/'**);**  load**(**'ProjectWS.mat'**);**  % This variable disable plots, so to fast computations.  showPlots **=** false**;**  % Neglect first row, it's just a row of zeros for every activity.  supine **=** **{**V01A**(**2**:end,:),** V02A**(**2**:end,:),** V03A**(**2**:end,:),** V04A**(**2**:end,:),**...  V05A**(**2**:end,:),** V06A**(**2**:end,:),** V07A**(**2**:end,:),** V08A**(**2**:end,:),** ...  V09A**(**2**:end,:),** V10A**(**2**:end,:)};**  dorsiflexion **=** **{**V01B**(**2**:end,:),** V02B**(**2**:end,:),** V03B**(**2**:end,:),** ...  V04B**(**2**:end,:),** V05B**(**2**:end,:),** V06B**(**2**:end,:),** V07B**(**2**:end,:),** ...  V08B**(**2**:end,:),** V09B**(**2**:end,:),** V10B**(**2**:end,:)};**  walking **=** **{**V01C**(**2**:end,:),** V02C**(**2**:end,:),** V03C**(**2**:end,:),** V04C**(**2**:end,:),**...  V05C**(**2**:end,:),** V06C**(**2**:end,:),** V07C**(**2**:end,:),** V08C**(**2**:end,:),** ...  V09C**(**2**:end,:),** V10C**(**2**:end,:)};**  stair **=** **{**V01D**(**2**:end,:),** V02D**(**2**:end,:),** V03D**(**2**:end,:),** V04D**(**2**:end,:),**...  V05D**(**2**:end,:),** V06D**(**2**:end,:),** V07D**(**2**:end,:),** V08D**(**2**:end,:),** ...  V09D**(**2**:end,:),** V10D**(**2**:end,:)};**  % Build the structure.  Struct **=** struct**(**'supine'**,**supine**,**'dorsiflexion'**,**dorsiflexion**,**'walking'**,**...  walking**,**'stair'**,**stair**);**  **for** i**=**1**:**10  % - Create a new signal as the sum of the three existing components  % and append at the other components.  Struct**(**i**).**supine **=** ...  **[**Struct**(**i**).**supine**(:,**4**),** Struct**(**i**).**supine**(:,**1**:**3**),** ...  sum**(**Struct**(**i**).**supine**(:,**1**:**3**),**2**)];**  Struct**(**i**).**dorsiflexion **=** ...  **[**Struct**(**i**).**dorsiflexion**(:,**4**),** Struct**(**i**).**dorsiflexion**(:,**1**:**3**),** ...  sum**(**Struct**(**i**).**dorsiflexion**(:,**1**:**3**),**2**)];**  Struct**(**i**).**walking **=** ...  **[**Struct**(**i**).**walking**(:,**4**),** Struct**(**i**).**walking**(:,**1**:**3**),** ...  sum**(**Struct**(**i**).**walking**(:,**1**:**3**),**2**)];**  Struct**(**i**).**stair **=** ...  **[**Struct**(**i**).**stair**(:,**4**),** Struct**(**i**).**stair**(:,**1**:**3**),** ...  sum**(**Struct**(**i**).**stair**(:,**1**:**3**),**2**)];**    % - Plot of each volunteer's activity/position signal and boxplot  % to better show patterns, time features, probability distribution.  **if** showPlots  % full screen figure  figure**(**'units'**,**'normalized'**,**'outerposition'**,[**0 0 1 1**]);**    subplot**(**2**,**3**,**1**);**  plot**(**Struct**(**i**).**supine**(:,**1**),**Struct**(**i**).**supine**(:,**2**:**5**));**  title**(**strcat**(**'Supine - volunteer '**,**num2str**(**i**)));**  legend**(**'sensor1'**,**'sensor2'**,**'sensor3'**,**'sum'**);**  xlabel**(**'time [s]'**);**  ylabel**(**'pressure [ohm]'**);**  subplot**(**2**,**3**,**2**);**  plot**(**Struct**(**i**).**dorsiflexion**(:,**1**),**Struct**(**i**).**dorsiflexion**(:,**2**:**5**));**  title**(**strcat**(**'Dorsiflexion - volunteer '**,**num2str**(**i**)));**  legend**(**'sensor1'**,**'sensor2'**,**'sensor3'**,**'sum'**);**  xlabel**(**'time [s]'**);**  ylabel**(**'pressure [ohm]'**);**  subplot**(**2**,**3**,**4**);**  plot**(**Struct**(**i**).**walking**(:,**1**),**Struct**(**i**).**walking**(:,**2**:**5**));**  title**(**strcat**(**'Walking - volunteer '**,**num2str**(**i**)));**  legend**(**'sensor1'**,**'sensor2'**,**'sensor3'**,**'sum'**);**  xlabel**(**'time [s]'**);**  ylabel**(**'pressure [ohm]'**);**  subplot**(**2**,**3**,**5**);**  plot**(**Struct**(**i**).**stair**(:,**1**),**Struct**(**i**).**stair**(:,**2**:**5**));**  title**(**strcat**(**'Stairs - volunteer '**,**num2str**(**i**)));**  legend**(**'sensor1'**,**'sensor2'**,**'sensor3'**,**'sum'**);**  xlabel**(**'time [s]'**);**  ylabel**(**'pressure [ohm]'**);**  subplot**(**2**,**3**,[**3 6**]);**  var **=** **[**Struct**(**i**).**supine**(:,**5**)'** Struct**(**i**).**dorsiflexion**(:,**5**)'**...  Struct**(**i**).**walking**(:,**5**)'** Struct**(**i**).**stair**(:,**5**)'];**  var **=** var**./**3**;**  grp **=** **[**zeros**(**1**,**length**(**Struct**(**i**).**supine**)),** ...  ones**(**1**,**length**(**Struct**(**i**).**dorsiflexion**)),** ...  2.**\***ones**(**1**,**length**(**Struct**(**i**).**walking**)),** ...  3.**\***ones**(**1**,**length**(**Struct**(**i**).**stair**))];**  boxplot**(**var**,**grp**,**'Labels'**,{**'supine'**,**'dorsiflexion'**,**'walking'**,**...  'stair'**});**  **end**  **end**  clear supine dorsiflexion walking stair i**;**  % clean origen structures  clear V01A V01B V01C V01D ...  V02A V02B V02C V02D ...  V03A V03B V03C V03D ...  V04A V04B V04C V04D ...  V05A V05B V05C V05D ...  V06A V06B V06C V06D ...  V07A V07B V07C V07D ...  V08A V08B V08C V08D ...  V09A V09B V09C V09D ...  V10A V10B V10C V10D**;** |

## A.2 split.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56 | %% 02 Data splitting - split.m  % - We need to split every signal to find out the least temporal interval  % that is necessary and sufficient to recognize the position/activity.  % N.B. We are using a sampling period of ~82ms (12.2Hz).  % Number of samples based on the interval size:  % N1 = 12.2Hz \* 3sec = 36.6; %3sec  % N2 = 61; %5sec  % N3 = 122; %10sec  % N4 = 144.4; %12sec  % N5 = 183; %15sec  % N6 = 244; %20sec  % N7 = 366; %30sec  % N8 = 732; %1min  % N9 = 1464; %2min - not enough signals to train NN  % N = 2196; %3min - NO SIGNAL HAS A 3min LONG TRACE  N **=** **[**37 61 122 145 183 244 366 732**];**  % The index only need to use one choice among the upper showed.  index **=** 7**;**  clear A B C D**;**  A **=** Struct**(**1**).**supine**(**1**:**N**(**index**),** 2**:**5**);**  B **=** Struct**(**1**).**dorsiflexion**(**1**:**N**(**index**),** 2**:**5**);**  C **=** Struct**(**1**).**walking**(**1**:**N**(**index**),** 2**:**5**);**  D **=** Struct**(**1**).**stair**(**1**:**N**(**index**),** 2**:**5**);**  % If the piece of signal cannot fill entirely the number of samples  % needed, it wont be used:  % "length(Struct(i).<activity>)/N(j)" is used just for its integer part so  % to truncate incomplete pieces of signal.  **for** i**=**1**:**10  **for** k**=**2**:**length**(**Struct**(**i**).**supine**)/**N**(**index**)**  A **=** **[**A Struct**(**i**).**supine**(**1**+**N**(**index**)\*(**k**-**1**):**k**\***N**(**index**),** 2**:**5**)];**  **end**  **for** k**=**2**:**length**(**Struct**(**i**).**dorsiflexion**)/**N**(**index**)**  B **=** **[**B Struct**(**i**).**dorsiflexion**(**1**+**N**(**index**)\*(**k**-**1**):**k**\***N**(**index**),** 2**:**5**)];**  **end**  **for** k**=**2**:**length**(**Struct**(**i**).**walking**)/**N**(**index**)**  C **=** **[**C Struct**(**i**).**walking**(**1**+**N**(**index**)\*(**k**-**1**):**k**\***N**(**index**),** 2**:**5**)];**  **end**  **for** k**=**2**:**length**(**Struct**(**i**).**stair**)/**N**(**index**)**  D **=** **[**D Struct**(**i**).**stair**(**1**+**N**(**index**)\*(**k**-**1**):**k**\***N**(**index**),** 2**:**5**)];**  **end**  **end**  clear i k**;**  clear Struct**;**  **if** showPlots  figure**,** plot**(**0.082**\*(**1**:**size**(**A**,**1**)),**A**(:,**1**:**4**))**  title**(**'Volunteer 1 - Supine (Slice 1)'**)**  xlabel**(**'time [s]'**)**  ylabel**(**'pressure [ohm]'**)**  legend**(**'sensor 1'**,** 'sensor 2'**,** 'sensor 3'**,** 'sensor virt. (sum)'**)**  **end** |

## A.3 cleaning.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42 | %% 03 Data cleaning - cleaning.m  % Clean the signal from noise by mean of a smoothing filter  % (Savitzky-Golay Filter), sgolayfilt(X,K,F):  % - K=3, third-order polynomial;  % - F=7, just an odd value greater than the piece of signal;  clear smoothA**;**  smoothA **=** sgolayfilt**(**A**,**3**,**7**);**  **if** showPlots  figure**,** plot**(**0.082**\*(**1**:**size**(**smoothA**,**1**)),[**A**(:,**1**)** smoothA**(:,**1**)])**  title**(**'Volunteer 1 - Supine (Slice 1)'**);**  xlabel**(**'time [s]'**);**  ylabel**(**'pressure [ohm]'**);**  legend**(**'sensor 1 - original'**,** 'sensor 1 - smooth'**);**  **end**  clear smoothB**;**  smoothB **=** sgolayfilt**(**B**,**3**,**7**);**  clear smoothC**;**  smoothC **=** sgolayfilt**(**C**,**3**,**7**);**  clear smoothD**;**  smoothD **=** sgolayfilt**(**D**,**3**,**7**);**  clear A B C D**;**  % Use Z-score normalization for each signal, in order to be able to compare  % signals.  smoothA **=** zscore**(**smoothA**);**  smoothB **=** zscore**(**smoothB**);**  smoothC **=** zscore**(**smoothC**);**  smoothD **=** zscore**(**smoothD**);**  **if** showPlots  figure**,** plot**(**0.082**\*(**1**:**size**(**smoothA**)),**smoothA**(:,**1**:**4**))**  title**(**'Volunteer 1 - Supine (Slice 1)'**);**  xlabel**(**'time [s]'**);**  ylabel**(**'pressure [ohm]'**);**  legend**(**'sensor 1'**,** 'sensor 2'**,** 'sensor 3'**,** 'sensor 4'**);**  **end** |

## A.4 featureEx.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80  81  82  83  84  85  86  87  88  89  90  91  92  93  94  95  96  97  98  99  100  101  102  103  104  105  106  107  108  109  110  111  112  113  114  115  116  117  118  119  120  121  122  123  124  125  126  127  128  129 | %% 04 Feature extraction - featureEx.m  % Obtain a set of temporal feature starting from the N(j) samples of the  % signal.  featuresA **=** **[**max**(**smoothA**);** min**(**smoothA**);** quantile**(**smoothA**,[**.25 .5**]);** ...  skewness**(**smoothA**);** kurtosis**(**smoothA**)];**  featuresB **=** **[**max**(**smoothB**);** min**(**smoothB**);** quantile**(**smoothB**,[**.25 .5**]);** ...  skewness**(**smoothB**);** kurtosis**(**smoothB**)];**  featuresC **=** **[**max**(**smoothC**);** min**(**smoothC**);** quantile**(**smoothC**,[**.25 .5**]);** ...  skewness**(**smoothC**);** kurtosis**(**smoothC**)];**  featuresD **=** **[**max**(**smoothD**);** min**(**smoothD**);** quantile**(**smoothD**,[**.25 .5**]);** ...  skewness**(**smoothD**);** kurtosis**(**smoothD**)];**  % Autocorrelation: computed at lags 0,1,2, ... T= min[20,length(y)-1]  RxxA **=** my\_autocorr**(**smoothA**);** % See my\_autocorr.m  RxxB **=** my\_autocorr**(**smoothB**);**  RxxC **=** my\_autocorr**(**smoothC**);**  RxxD **=** my\_autocorr**(**smoothD**);**  **if** showPlots  figure**(**'units'**,**'normalized'**,**'outerposition'**,[**0 0 1 1**]);**    subplot**(**2**,**2**,**1**);**  plot**(**0**:**20**,**RxxA**);**  title**(**'Supine - All the volunteers, all the autocorrelations'**);**  xlabel**(**'lags'**);**  ylabel**(**'Rxx'**);**    subplot**(**2**,**2**,**2**);**  plot**(**0**:**20**,**RxxB**);**  title**(**'Dorsifexion - All the volunteers, all the autocorrelations'**);**  xlabel**(**'lags'**);**  ylabel**(**'Rxx'**);**    subplot**(**2**,**2**,**3**);**  plot**(**0**:**20**,**RxxC**);**  title**(**'Walk - All the volunteers, all the autocorrelations'**);**  xlabel**(**'lags'**);**  ylabel**(**'Rxx'**);**    subplot**(**2**,**2**,**4**);**  plot**(**0**:**20**,**RxxD**);**  title**(**'Stairs - All the volunteers, all the autocorrelations'**);**  xlabel**(**'lags'**);**  ylabel**(**'Rxx'**);**  **end**  % first value, autocorr with lags=0 is always equal to 1  % (it's irrelevant)  featuresA **=** **[**featuresA**;** RxxA**(**2**:end,:)];**  featuresB **=** **[**featuresB**;** RxxB**(**2**:end,:)];**  featuresC **=** **[**featuresC**;** RxxC**(**2**:end,:)];**  featuresD **=** **[**featuresD**;** RxxD**(**2**:end,:)];**  clear RxxA RxxB RxxC RxxD**;**  % Frequential features:  % - Fundamental frequency f0  % - Power Spectral Density PSD  % Define the frequency domain  f **=** 12.2**\*(**0**:**N**(**index**)/**2**-**1**);**  % Compute the single-sided spectrum  fftA **=** my\_fft**(**smoothA**,**N**(**index**));** % See my\_fft.m  fftB **=** my\_fft**(**smoothB**,**N**(**index**));**  fftC **=** my\_fft**(**smoothC**,**N**(**index**));**  fftD **=** my\_fft**(**smoothD**,**N**(**index**));**  **if(**showPlots**)**  figure**(**'units'**,**'normalized'**,**'outerposition'**,[**0 0 1 1**]);**    subplot**(**2**,**2**,**1**);**  plot**(**f**,**fftA**);**  title**(**'Supine - All the volunteers, all the spectra'**);**  xlabel**(**'frequency [Hz]'**);**  ylabel**(**'FFT'**);**    subplot**(**2**,**2**,**2**);**  plot**(**f**,**fftB**);**  title**(**'Dorsifexion - All the volunteers, all the spectra'**);**  xlabel**(**'frequency [Hz]'**);**  ylabel**(**'FFT'**);**    subplot**(**2**,**2**,**3**);**  plot**(**f**,**fftC**);**  title**(**'Walk - All the volunteers, all the spectra'**);**  xlabel**(**'frequency [Hz]'**);**  ylabel**(**'FFT'**);**    subplot**(**2**,**2**,**4**);**  plot**(**f**,**fftD**);**  title**(**'Stairs - All the volunteers, all the spectra'**);**  xlabel**(**'frequency [Hz]'**);**  ylabel**(**'FFT'**);**  **end**  % The max amplitude should be a good approximation for the fundamental  % frequency  **[**amp**,** x**]** **=** max**(**fftA**);**  % [~, x2] = findpeaks(fftA, 'MinPeakProminence', 0.7\*max(fftA));  % PSD  PSD **=** sum**(**fftA**.^**2**);**  % figure  % plot(f,fftA(:,[1 11 111]));  % hold on;  % plot(f(x([1 11 111])),y([1 11 111]),'rv');  featuresA **=** **[**featuresA**;** f**(**x**);** amp**;** PSD**];**  **[**amp**,** x**]** **=** max**(**fftB**);**  featuresB **=** **[**featuresB**;** f**(**x**);** amp**;** sum**(**fftB**.^**2**)];**  **[**amp**,** x**]** **=** max**(**fftC**);**  featuresC **=** **[**featuresC**;** f**(**x**);** amp**;** sum**(**fftC**.^**2**)];**  **[**amp**,** x**]** **=** max**(**fftD**);**  featuresD **=** **[**featuresD**;** f**(**x**);** amp**;** sum**(**fftD**.^**2**)];**  clear smoothA smoothB smoothC smoothD f i fftA fftB fftC fftD amp x PSD**;**  %% Rotate matrix  % Since we use 4 columns to represent 3 sensor signals + 1 "virtual"  % sensor (the sum), we move all the features of the same piece of signal  % on the same column.  newFeaturesA **=** rotate\_features**(**featuresA**);**  newFeaturesB **=** rotate\_features**(**featuresB**);**  newFeaturesC **=** rotate\_features**(**featuresC**);**  newFeaturesD **=** rotate\_features**(**featuresD**);**  clear featuresA featuresB featuresC featuresD**;** |

## A.5 rotate\_features.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9 | **function** f **=** rotate\_features **(**features**)**  f **=** **[**features**(:,**1**);** features**(:,**2**);** features**(:,**3**);** ...  features**(:,**4**)];**  **for** k**=**1**:**size**(**features**,**2**)/**4**-**1**;**  f **=** **[**f **[**features**(:,**4**\***k**+**1**);** features**(:,**4**\***k**+**2**);** features**(:,**4**\***k**+**3**);** ...  features**(:,**4**\***k**+**4**)]];**  **end**  **end** |

## A.6 my\_autocorr.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10 | % My extension of autocorr(), in order to compute autocorr on a matrix of  % more than 1 signal, where each column is a different signal  **function** Rxx **=** my\_autocorr **(**matrix**)**  % If "matrix" has only a column, I only need to compute correlation once  Rxx **=** autocorr**(**matrix**(:,**1**));**    **for** k**=**2**:**size**(**matrix**,**2**)**  Rxx **=** **[**Rxx autocorr**(**matrix**(:,**k**))];**  **end**  **end** |

## A.7 my\_fft.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7 | **function** f **=** my\_fft **(**matrix**,** ind**)**  **if(**mod**(**ind**,**2**)~=**0**),** ind **=** ind**-**1**;** **end**  f **=** fft**(**matrix**);**  f **=** abs**(**f**./**ind**);**  f**(**ind**/**2**+**1**:end,** **:)** **=** **[];**  f**=** f**.\***2**;**  **end** |

## A.8 featureSel.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30 | %% 05 Feature Selection  % Sequential feature selection  % Fix the number of features on which we would like to reduce each signal  num\_features **=** 4**;**  % Classify each activity with a different class:  % Y = 0 => supine  % Y = 1 => dorsiflexion  % Y = 2 => walking  % Y = 3 => stairs  sizeA **=** size**(**newFeaturesA**,**2**);**  sizeB **=** size**(**newFeaturesB**,**2**);**  sizeC **=** size**(**newFeaturesC**,**2**);**  sizeD **=** size**(**newFeaturesD**,**2**);**  X **=** **[**newFeaturesA newFeaturesB newFeaturesC newFeaturesD**]';**  Y **=** **[**zeros**(**sizeA**,**1**);** ones**(**sizeB**,**1**);** 2**\***ones**(**sizeC**,**1**);** 3**\***ones**(**sizeD**,**1**)];**  f **=** **@(**xtrain**,** ytrain**,** xtest**,** ytest**)** ...  sum**(**ytest **~=** classify**(**xtest**,** xtrain**,** ytrain**));**  **if** showPlots  opts **=** statset**(**'display'**,**'iter'**);**  **[**fs**,** **~]** **=** sequentialfs**(**f**,**X**,**Y**,**'nfeatures'**,**num\_features**,**...  'options'**,**opts**);**  **else**  **[**fs**,** **~]** **=** sequentialfs**(**f**,**X**,**Y**,**'nfeatures'**,**num\_features**);**  **end**  clear f**;** |

# **Appendix B –Neural network**

## B.1 neur\_netw.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80  81  82  83  84  85  86  87  88  89  90  91  92  93  94  95  96  97  98  99  100  101  102 | %% 06 Neural network  % "What's the best number of hidden neurons?"  inputs **=** X**(:,**fs**)';**  targets **=** zeros**(**4**,**size**(**X**,**1**));**  targets**(**1**,**1**:**sizeA**)** **=** 1**;**  targets**(**2**,**sizeA**+**1**:**sizeA**+**sizeB**)** **=** 1**;**  targets**(**3**,**sizeA**+**sizeB**+**1**:**sizeA**+**sizeB**+**sizeC**)** **=** 1**;**  targets**(**4**,**sizeA**+**sizeB**+**sizeC**+**1**:end)** **=** 1**;**  n1 **=** num\_features**;** % lowest number of hidden neurons  n2 **=** 10**;** % highest number of hidden neurons  % preallocate followings' for speed  performances **=** zeros**(**10**,**1**);**  meanPerformance **=** zeros**(**n2**-**n1**+**1**,**1**);**  **for** n **=** n1**:**1**:**n2**,**  % Create a Pattern Recognition Network  hiddenLayerSize **=** n**;**  **for** k**=**1**:**10**,**  net **=** patternnet**(**hiddenLayerSize**);**    % Setup Division of Data for Training, Validation, Testing  net**.**divideParam**.**trainRatio **=** 70**/**100**;**  net**.**divideParam**.**valRatio **=** 15**/**100**;**  net**.**divideParam**.**testRatio **=** 15**/**100**;**    % hide window: speed up computations  net**.**trainParam**.**showWindow **=** false**;**  % Train the Network  **[**net**,~]** **=** train**(**net**,**inputs**,**targets**);**    % Test the Network  outputs **=** net**(**inputs**);**  performances**(**k**)** **=** perform**(**net**,**targets**,**outputs**);**  **end**  meanPerformance**(**n**-**n1**+**1**)** **=** mean**(**performances**);**  **end**  **if** showPlots  figure**,** plot**(**n1**:**n2**,** meanPerformance**,** 'r-o'**);**  title**(**'MSE: less is better'**);**  ylabel**(**'mean square error'**);**  xlabel**(**'# of hidden neurons'**);**  legend**(**'mean performance'**);**  **end**  %% Train the neural network  % Best among the networks with chosen number of hidden neurons  **[~,**hiddenLayerSize**]** **=** min**(**meanPerformance**);**  hiddenLayerSize **=** hiddenLayerSize **+** n1 **-** 1**;**  perf **=** inf**;**  **for** k**=**1**:**10**,**  net\_temp **=** patternnet**(**hiddenLayerSize**);**  % Setup Division of Data for Training, Validation, Testing  net\_temp**.**divideParam**.**trainRatio **=** 70**/**100**;**  net\_temp**.**divideParam**.**valRatio **=** 15**/**100**;**  net\_temp**.**divideParam**.**testRatio **=** 15**/**100**;**  % hide window: speed up computations  net\_temp**.**trainParam**.**showWindow **=** showPlots**;**  % Train the Network  **[**net\_temp**,~]** **=** train**(**net\_temp**,**inputs**,**targets**);**  % Test the Network  outputs **=** net\_temp**(**inputs**);**  perf\_temp **=** perform**(**net\_temp**,**targets**,**outputs**);**  **if(**perf\_temp **<** perf**),**  best\_net **=** net\_temp**;**  perf **=** perf\_temp**;**  **end**  **end**  clear n1 n2 n performances meanPerformance**;**  clear k perf perf\_temp net net\_temp outputs hiddenLayerSize**;**  %% Print evaluations  outputs **=** best\_net**(**inputs**);**  % errors = gsubtract(targets,outputs);  % performance = perform(best\_net,targets,outputs);  % % View the Network  % view(best\_net)  %  % % Plots  % figure, plotperform(tr)  % figure, plottrainstate(tr)  % figure, plotconfusion(targets,outputs)  % figure, ploterrhist(errors)  clear best\_net**;**  **[**actual**,~,~]** **=** find**(**targets**);**  **[~,**predict**]** **=** max**(**outputs**);**  cfmatrix2**(**actual**',**predict**,[**1 2 3 4**],** 1**,** 1**);**  clear predict outputs**;** |

## B.2 cfmatrix2.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  …  72  73  74  75  76  77  78  79  80  81  82  83  84  85  86  87  88  89  90  91  92  93  94  95  96  97  98  99  100  101  102  103  104  105  106  107  108  109  110  111  112  113  114  115  116  117  118  119  120  121  122  123  124  125  126  127  128  129  130  131  132  133  134  135  136  137  138  139  140  141  142  143  144  145  146  147  148  149  150  151  152  153  154  155  156  157  158  159  160  161  162  163  164  165  166  167  168  169  170  171  172  173  174  175  176  177  178  179  180  181  182  183  184  185  186  187  188  189  190  191  192  193  194  195  196  197  198  199  200  201  202  203  204  205  206  207  208  209  210  211  212  213  214  215 | %% https://it.mathworks.com/matlabcentral/fileexchange/21212-confusion-matrix---matching-matrix-along-with-precision--sensitivity--specificity-and-model-accuracy  **function** **[**confmatrix**]** **=** cfmatrix2 ...  **(**actual**,** predict**,** classlist**,** per**,** printout**)**  % CFMATRIX2 calculates the confusion matrix for any prediction  % algorithm ( prediction algorithm generates a list of classes to which  % each test feature vector is assigned );  %  % Outputs: confusion matrix  %  % Actual Classes  % p n  % \_\_\_|\_\_\_\_\_|\_\_\_\_\_\_|  % Predicted p'| | |  % Classes n'| | |  %  % Also the TP, FP, FN and TN are output for each class based  % on http://en.wikipedia.org/wiki/Confusion\_matrix  % The Precision, Sensitivity and Specificity for each class  % have also been added in this update along with the overall  % accuracy of the model ( ModelAccuracy ).  % If classlist not entered: make classlist equal to all  % unique elements of actual  **if** **(**nargin **<** 2**)**  error**(**'Not enough input arguments. Need atleast two vectors as input'**);**  **elseif** **(**nargin **==** 2**)**  classlist **=** unique**(**actual**);** % default values from actual  per **=** 0**;**  printout **=** 1**;**  **elseif** **(**nargin **==** 3**)**  per **=** 0**;** % default is numbers and input 1 or higher for percentage  printout **=** 1**;**  **elseif** **(**nargin **==** 4**)**  printout **=** 1**;** % default is silent output ( 0 ); one or higher printsout  **elseif** **(**nargin **>** 5**)**  error**(**'Too many input arguments.'**);**  **end**  **if** **(**length**(**actual**)** **~=** length**(**predict**))**  error**(**'First two inputs need to be vectors with equal size.'**);**  **elseif** **((**size**(**actual**,**1**)** **~=** 1**)** **&&** **(**size**(**actual**,**2**)** **~=** 1**))**  error**(**'First input needs to be a vector and not a matrix'**);**  **elseif** **((**size**(**predict**,**1**)** **~=** 1**)** **&&** **(**size**(**predict**,**2**)** **~=** 1**))**  error**(**'Second input needs to be a vector and not a matrix'**);**  **end**  format short g**;**  n\_class **=** length**(**classlist**);**  confmatrix **=** zeros**(**n\_class**);**  line\_two **=** '----------'**;**  line\_three **=** '\_\_\_\_\_\_\_\_\_|'**;**  **for** i **=** 1**:**n\_class  **for** j **=** 1**:**n\_class  m **=** **(**predict **==** classlist**(**i**)** ...  **&** actual **==** classlist**(**j**));**  confmatrix**(**i**,**j**)** **=** sum**(**m**);**  **end**  line\_two **=** strcat**(**line\_two**,**'---'**,**num2str**(**classlist**(**i**)),**'-----'**);**  line\_three **=** strcat**(**line\_three**,**'\_\_\_\_\_\_\_\_\_\_'**);**  **end**  TPFPFNTN **=** zeros**(**4**,** n\_class**);**  Accuracy **=** zeros**(**1**,** n\_class**);**  Precision **=** zeros**(**1**,** n\_class**);**  Sensitivity **=** zeros**(**1**,** n\_class**);**  Specificity **=** zeros**(**1**,** n\_class**);**  MissRate **=** zeros**(**1**,** n\_class**);**  Fall\_Out **=** zeros**(**1**,** n\_class**);**  temps1 **=** sprintf**(**' TP '**);**  temps2 **=** sprintf**(**' FP '**);**  temps3 **=** sprintf**(**' FN '**);**  temps4 **=** sprintf**(**' TN '**);**  temps5 **=** sprintf**(**'Accur. '**);**  temps6 **=** sprintf**(**'Preci. '**);**  temps7 **=** sprintf**(**'Sensi. '**);**  temps8 **=** sprintf**(**'Speci. '**);**  temps9 **=** sprintf**(**'MissR. '**);**  temps10**=** sprintf**(**'FallO. '**);**  **for** i **=** 1**:**n\_class  % TP  TPFPFNTN**(**1**,** i**)** **=** confmatrix**(**i**,**i**);**  temps1 **=** strcat**(**temps1**,**sprintf**(**' | %3d \t'**,**TPFPFNTN**(**1**,** i**)));**    % FP  TPFPFNTN**(**2**,** i**)** **=** sum**(**confmatrix**(**i**,:))-**confmatrix**(**i**,**i**);**  temps2 **=** strcat**(**temps2**,**sprintf**(**' | %3d \t'**,**TPFPFNTN**(**2**,** i**)** **));**    % FN  TPFPFNTN**(**3**,** i**)** **=** sum**(**confmatrix**(:,**i**))-**confmatrix**(**i**,**i**);**  temps3 **=** strcat**(**temps3**,**sprintf**(**' | %3d \t'**,**TPFPFNTN**(**3**,** i**)** **));**    % TN  TPFPFNTN**(**4**,** i**)** **=** sum**(**confmatrix**(:))** **-** sum**(**confmatrix**(**i**,:))** **-**...  sum**(**confmatrix**(:,**i**))** **+** confmatrix**(**i**,**i**);**  temps4 **=** strcat**(**temps4**,**sprintf**(**' | %3d \t'**,**TPFPFNTN**(**4**,** i**)** **));**    % Accuracy(class) = (TP(class)+TN(class))/all  Accuracy**(**i**)** **=** **(**TPFPFNTN**(**1**,** i**)+**TPFPFNTN**(**4**,** i**))/**sum**(**confmatrix**(:))\***100**;**  temps5 **=** strcat**(**temps5**,**sprintf**(**' | %3.2f \t'**,**Accuracy**(**i**)** **));**    % Precision(class) = TP(class) / ( TP(class) + FP(class) )  Precision**(**i**)** **=** TPFPFNTN**(**1**,** i**)** **/** sum**(**confmatrix**(**i**,:))\***100**;**  temps6 **=** strcat**(**temps6**,**sprintf**(**' | %3.2f \t'**,**Precision**(**i**)** **));**    % Sensitivity(class) = Recall(class) = TruePositiveRate(class)  % = TP(class) / ( TP(class) + FN(class) )  Sensitivity**(**i**)** **=** TPFPFNTN**(**1**,** i**)** **/** sum**(**confmatrix**(:,**i**))\***100**;**  temps7 **=** strcat**(**temps7**,**sprintf**(**' | %3.2f \t'**,**Sensitivity**(**i**)** **));**    % Specificity ( mostly used in 2 class problems )=  % TrueNegativeRate(class)  % = TN(class) / ( TN(class) + FP(class) )  Specificity**(**i**)** **=** TPFPFNTN**(**4**,** i**)** **/** **(** TPFPFNTN**(**4**,** i**)** **+** TPFPFNTN**(**2**,** i**)** **)\***100**;**  temps8 **=** strcat**(**temps8**,**sprintf**(**' | %3.2f \t'**,**Specificity**(**i**)** **));**    % Miss rate = FN(class) / ( TP(class) + FN(class) )  MissRate**(**i**)** **=** TPFPFNTN**(**3**,** i**)/**sum**(**confmatrix**(:,**i**))\***100**;**  temps9 **=** strcat**(**temps9**,**sprintf**(**' | %3.2f \t'**,**MissRate**(**i**)** **));**  % Fall-out = FP(class) / ( TN(class) + FP(class) )  Fall\_Out**(**i**)** **=** TPFPFNTN**(**2**,** i**)/(** TPFPFNTN**(**4**,** i**)** **+** TPFPFNTN**(**2**,** i**)** **)\***100**;**  temps10 **=** strcat**(**temps10**,**sprintf**(**' | %3.2f \t'**,**Fall\_Out**(**i**)** **));**    **end**  ModelAccuracy **=** sum**(**diag**(**confmatrix**))/**sum**(**confmatrix**(:))\***100**;**  temps11 **=** sprintf**(**'Model Accuracy is %1.2f '**,**ModelAccuracy**);**  **if** **(**per **>** 0**)** % ( if > 0 implies true; < 0 implies false )  confmatrix **=** **(**confmatrix **./** length**(**actual**)).\***100**;**  **end**  **if** **(** printout **>** 0 **)** % ( if > 0 printout; < 0 no printout )  disp**(**'------------------------------------------'**);**  disp**(**' Actual Classes'**);**  disp**(**line\_two**);**  disp**(**'Predicted| '**);**  disp**(**' Classes| '**);**  disp**(**line\_three**);**    **for** i **=** 1**:**n\_class  temps **=** sprintf**(**' %d '**,**i**);**  **for** j **=** 1**:**n\_class  temps **=** strcat**(**temps**,**sprintf**(**' | %3.1f '**,**confmatrix**(**i**,**j**)));**  **end**  disp**(**temps**);**  clear temps  **end**  disp**(**'------------------------------------------'**);**  disp**(**'------------------------------------------'**);**  disp**(**' Actual Classes'**);**  disp**(**line\_two**);**  disp**(**temps1**);** disp**(**temps2**);** disp**(**temps3**);** disp**(**temps4**);**  disp**(**temps5**);** disp**(**temps6**);** disp**(**temps7**);** disp**(**temps8**);**  disp**(**temps9**);** disp**(**temps10**);**  disp**(**'------------------------------------------'**);**  disp**(**temps11**);**  disp**(**'------------------------------------------'**);**  **end**  clear temps1 temps2 temps3 temps4 temps5 temps6 temps7 temps8 temps9 temps10 temps11 |

# **Appendix C –Fuzzy Inference System**

## C.1 – fuzzy\_sys.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80  81  82  83  84  85  86  87  88  89  90  91  92  93  94  95  96  97  98  99  100  101  102  103  104  105  106  107  108  109  110  111  112  113  114  115  116  117  118  119  120  121  122  123  124  125  126  127  128  129  130  131  132  133  134 | %% 07 Fuzzy inference system  % How to define good membership functions?  % try to plot the distributions of values for every feature and choice the  % most separated, i.e. choice the features that better help to distinguish  % among classes of position/activities  % Plot boxplots to better distinguish among mean, quartiles, max and min of  % every feature distribution  **if(**showPlots**),**  **for** k**=**mod**(**find**(**fs**),**29**),**  figure**,**  **for** w**=**0**:**3  subplot**(**2**,**2**,**w**+**1**);**  var **=** **[**newFeaturesA**(**w**\***29 **+** k**,:)';** ...  newFeaturesB**(**w**\***29 **+** k**,:)';** ...  newFeaturesC**(**w**\***29 **+** k**,:)';** ...  newFeaturesD**(**w**\***29 **+** k**,:)'];**  grp **=** **[**zeros**(**1**,**size**(**newFeaturesA**,**2**)),** ...  ones**(**1**,**size**(**newFeaturesB**,**2**)),** ...  2.**\***ones**(**1**,**size**(**newFeaturesC**,**2**)),** ...  3.**\***ones**(**1**,**size**(**newFeaturesD**,**2**))];**  boxplot**(**var**,**grp**,**'Labels'**,{**'A'**,**'B'**,**'C'**,**'D'**});**  tmp\_title **=** 'Feature '**;**  tmp\_title **=** strcat**(**tmp\_title**,**num2str**(**k**));**  tmp\_title **=** strcat**(**tmp\_title**,**', sensor '**);**  tmp\_title **=** strcat**(**tmp\_title**,**num2str**(**w**+**1**));**  tmp\_title **=** strcat**(**tmp\_title**,**': alias '**);**  tmp\_title **=** strcat**(**tmp\_title**,**num2str**(**w**\***29 **+** k**));**  title**(**tmp\_title**);**  clear tmp\_title**;**  **end**  **end**  **end**  %% Plot PDF of every feature to ease the definition of membership functions  **if(**showPlots**),**  **for** k**=**mod**(**find**(**fs**),**29**),** % features  figure**,**  **for** w**=**0**:**3**,** % sensors  subplot**(**2**,**2**,**w**+**1**);**  **[**f**,**xi**]** **=** ksdensity**(**newFeaturesA**(**w**\***29**+**k**,:));**  plot**(**xi**,**f**);**  hold on**;**  **[**f**,**xi**]** **=** ksdensity**(**newFeaturesB**(**w**\***29**+**k**,:));**  plot**(**xi**,**f**);**  **[**f**,**xi**]** **=** ksdensity**(**newFeaturesC**(**w**\***29**+**k**,:));**  plot**(**xi**,**f**);**  **[**f**,**xi**]** **=** ksdensity**(**newFeaturesD**(**w**\***29**+**k**,:));**  plot**(**xi**,**f**);**  title\_str **=** strcat**(**'Feat.'**,**num2str**(**k**));**  title\_str **=** strcat**(**title\_str**,**', sens.'**);**  title\_str **=** strcat**(**title\_str**,**num2str**(**w**+**1**));**  title\_str **=** strcat**(**title\_str**,**', aka '**);**  title\_str **=** strcat**(**title\_str**,**num2str**(**w**\***29**+**k**));**  title**(**title\_str**);**  clear title\_str**;**  legend**(**'supine'**,**'dorsiflexion'**,**'walking'**,**'stair'**);**  **end**  **end**  clear f xi**;**  **end**  %%  fs**(:)=**0**;**  fs**([**27 36 40 45**])** **=** 1**;**  % mamdani = readfis('mamdani.fis');  mamdani **=** readfis**(**'mamdani.fis'**);**  inputs **=** X**(:,**fs**);**  size1 **=** sizeA**;**  size2 **=** size1**+**sizeB**;**  size3 **=** size2**+**sizeC**;**  size4 **=** size3**+**sizeD**;**  targets **=** zeros**(**size**(**Y**,**1**),**1**);**  targets**(**1**:**size1**)** **=** 0.2**;**  targets**(**size1**+**1**:**size2**)** **=** 0.4**;**  targets**(**size2**+**1**:**size3**)** **=** 0.6**;**  targets**(**size3**+**1**:end)** **=** 0.8**;**  outputs **=** evalfis**(**inputs**,**mamdani**);**  % errors = gsubtract(targets,outputs);  % pre\_error = sqrt(mean(errors.^2))  **if(**showPlots**),**  figure**,**  plot**(**1**:**size**(**outputs**,**1**),**targets**,**'bo'**,**1**:**size**(**outputs**,**1**),**outputs**,**'rx'**);**  hold on**;**  plot**(**1**:**size**(**outputs**,**1**),**zeros**(**1**,**size**(**outputs**,**1**)),**'k--'**);**  plot**(**1**:**size**(**outputs**,**1**),**0.3**\***ones**(**1**,**size**(**outputs**,**1**)),**'k--'**);**  plot**(**1**:**size**(**outputs**,**1**),**0.5**\***ones**(**1**,**size**(**outputs**,**1**)),**'k--'**);**  plot**(**1**:**size**(**outputs**,**1**),**0.7**\***ones**(**1**,**size**(**outputs**,**1**)),**'k--'**);**  plot**(**1**:**size**(**outputs**,**1**),**ones**(**1**,**size**(**outputs**,**1**)),**'k--'**);**  title**(**'Result of Mamdani FIS'**);**  xlabel**(**'inputs'**);**  ylabel**(**'classes'**);**  legend**(**'target class'**,**'output class'**);**  **end**  % just to better understand plot  **for** k**=**1**:**size**(**outputs**,**1**)**  **if** outputs**(**k**)<**0.3  outputs**(**k**)** **=** 0.2**;**  **elseif** outputs**(**k**)<**0.5  outputs**(**k**)** **=** 0.4**;**  **elseif** outputs**(**k**)<**0.7  outputs**(**k**)** **=** 0.6**;**  **else**  outputs**(**k**)** **=** 0.8**;**  **end**  **end**  % figure,  % plot(1:size(outputs,1),targets,'bo',1:size(outputs,1),outputs,'rx');  % title('Result of Mamdani FIS');  % xlabel('inputs');  % ylabel('classes');  % legend('target class','output class');  % figure, plot(outputs(1:size1),1:size1,'bo');  % hold on;  % plot(outputs(size1+1:size2),size1+1:size2,'go');  % plot(outputs(size2+1:size3),size2+1:size3,'ro');  % plot(outputs(size3+1:end),size3+1:size4,'ko');  cfmatrix2**(**actual**',(**outputs**.\***5**)',[**1 2 3 4**],** 0**,** 1**);**  clear k**;** |

# **Appendix D –Adaptive Neuro FIS**

## D.1 – adaptiveNeuroFIS.m

|  |  |
| --- | --- |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43 | %% 08 ANFIS  inputs2 **=** **[**inputs actual**];**  index **=** randperm**(**size**(**inputs2**,**1**));**  indTrain **=** floor**(**size**(**inputs2**,**1**)\***70**/**100**);**  indTest **=** floor**(**size**(**inputs2**,**1**)\***15**/**100**);**  % indVal = floor(size(inputs2,1)\*15/100);  inTrain **=** inputs2**(**index**(**1**:**indTrain**),:);**  inTest **=** inputs2**(**index**(**indTrain**+**1**:**indTrain**+**indTest**),:);**  inVal **=** inputs2**(**index**(end-**indTest**:end),:);**  sugeno **=** mam2sug**(**mamdani**);**  anfisedit**;**  %%  outputs **=** evalfis**(**inputs**,**sugeno0**);**  **if(**showPlots**),**  figure**,**  plot**(**1**:**size**(**outputs**,**1**),**targets**.\***5**,**'bo'**,**1**:**size**(**outputs**,**1**),**outputs**,**'rx'**);**  title**(**'Result of Mamdani FIS'**);**  xlabel**(**'inputs'**);**  ylabel**(**'classes'**);**  legend**(**'target class'**,**'output class'**);**  **end**  % just to better understand plot  **for** k**=**1**:**size**(**outputs**,**1**)**  **if** outputs**(**k**)<**1.5  outputs**(**k**)** **=** 1**;**  **elseif** outputs**(**k**)<**2.5  outputs**(**k**)** **=** 2**;**  **elseif** outputs**(**k**)<**3.5  outputs**(**k**)** **=** 3**;**  **else**  outputs**(**k**)** **=** 4**;**  **end**  **end**  cfmatrix2**(**actual**',**outputs**',[**1 2 3 4**],** 0**,** 1**);** |