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Evaluation of Commercial Analog Front Ends for Pattern Recognition Based Control of Robotic Prostheses

Master's thesis in Biomedical Engineering

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Abstract

Even though myoelectric prostheses have been under development for several decades, some drawbacks of the common prostheses such as the discomfort of socket prostheses and the long-term stability of the myoelectric signal have hindered the development. Integrum is a company that works with osseointegration and has a solution that replaces the socket with a titanium bone implant. They have also started the development of an Osseointegrated Human-Machine Gateway (OHMG) for the Natural Control of Artificial Limbs (NCAL). This improves the long-term stability of the myoelectric signals by making it possible to use implanted electrodes instead of surface electrodes.

The Analog Front Ends (AFEs) used at Integrum have been designed using discrete components. The advent of new AFE Integrated Circuits (ICs) for biopotential recordings in 2010, the Texas Instruments ADS1298 and the Intan Technologies RHA2216, has opened the possibility of replacing the former prototype with an IC. With several front ends in one single IC, size, power consumption and complexity could be reduced and make it more suitable for a portable device.

A system for evaluation of these two leading AFE ICs on the market suitable for recording of electromyogram (EMG) signals has been made. The evaluation was based on Pattern Recognition of EMG signals and was compared with a former AFE prototype used in studies at Integrum. The result showed that the three AFEs achieved pattern recognition accuracy of 93.5%. The most promising device for low frequency signal content is the Texas Instruments ADS1298 while for higher frequencies the Intan Technologies RHA2216 might be a more suitable choice even though the CMRR for RHA2216 is substantially lower which might still make it less suitable for some situations.

Drivers have also been written for the Stand-Alone Hardware Platform under development at Integrum to ease integration of a suitable AFE in the next clinical trial prosthesis.

Acknowledgement

We would like to thank Max J. Ortiz C., our supervisor at Integrum for his guidance and support during this Masters Thesis Project.

We would also like to thank Professor Bo Håkansson, our examiner at the department of Signals and Systems at Chalmers University of Technology (CTH) for guidance and for accepting and reviewing this thesis project.

Finally we would like to thank everyone at Integrum that volunteered for recording sessions.

Contents

1 Introduction

One of the aids that can be used for upper limb amputees is hand prostheses. There are mainly three different categories, cosmetic, body powered and myoelectric prosthesis [1]. This report is focused on myoelectric controlled robotic prostheses and the Analog Front End (AFE) for recording of the myoelectric signals.

1.1 Background

There are several problems with today's most common prostheses, which leads to them being rejected and not used by the patients [1]. One of the problems is that the socket prostheses causes skin problems and cannot be worn for a longer period of time [2, 3]. Another issue is the lack of natural ways of controlling the prosthesis and sense feedback from the prosthesis, which are important criteria of robotic prostheses as stated by users [1, 4]. Long-term stability of the control signals is also critical and is difficult to achieve since skin surface electrodes are affected by movement and moisture. Implanted electrodes on the other hand need some way to extract the signal through the skin [5].

Integrum AB, Gothenburg, Sweden, is a company focused at developing bone anchored prosthesis fixtures and fixation methods. The company is leaded by Dr Richard Brånemark who is the son of Professor emeritus Per-Ingvar Brånemark who discovered osseointegration and made it accepted as a new method for fixation of dental implants [6]. Osseointegration means that the bone grows tight to the implant without significant scar tissue in between [7, 8]. Since 1990 osseointegration has been used for treatment of amputees and fixation of prostheses. With the fixation technique using bone anchored titanium implants, the socket can be replaced with a fixture that has no skin contact which therefore increases comfort and the time the prosthesis can be worn [3, 9].

To increase the long-term stability of robotic prostheses control, Max J. Ortiz C. at Chalmers University of Technology (CTH), in collaboration with Integrum, have started the development of a robotic prostheses interface that combines the bone-anchored fixture with implantable electrodes and an Osseointegrated Human Machine Gateway (OHMG). With the OHMG, the problem with percutaneous electrode connections can be avoided [5].

Natural control of the prosthesis is accomplished by recordings of Electromyogram (EMG) or Electroneurogram (ENG) signals that would have normally been used for controlling the same motion in an intact limb. To interpret these signals and thus the users intentions, Pattern Recognition has successfully been used [5].

So far the devices used at Integrum for recording EMG signals has been done using discrete instrumental and operational amplifiers. Since these devices are built using several integrated circuits (ICs) for each channel, size and power consumption performance could be increased by replacing them with a single IC including several amplifier channels in one single chip. The design of a Stand-Alone Hardware Platform has already started as part of making a portable prosthesis control system [10].

Texas Instruments (TI) released in 2010 a chip that is an AFE for biopotential recordings with sigma-delta ADCs. Mainly it is aimed towards electrocardiogram (ECG) and electroencephalogram (EEG) systems. Since this chip has several differential mode input channels and ADC converters included into one IC and supports the desired frequency range (see Chapter 2) it may be suitable for electromyogram (EMG) and electroneurogram (ENG) signals as well. Intan Technologies is another company that has developed a chip for biopotential recordings, released 2010, which is also an alternative for replacing the existing AFE.

If any of these two chips are suitable for replacing the currently used discrete component design, this could reduce the size and power consumption of the AFE and thus provide a solution better suitable for integration into a portable device.

1.2 Aim of Study

The goal is to implement a system for evaluation of the leading biopotential AFE ICs on the market suitable for recording of EMG and ENG signals. The evaluation should be based on Pattern Recognition of recordings from EMG signals for the control of Robot Prostheses and should be compared with former AFE prototypes used in studies at Integrum.

The system should be used to compare available solutions that are promising candidates for replacing the former amplifier prototypes. To ease integration and further testing of the devices, drivers should also be written for the Stand-Alone Hardware Platform being developed at Integrum.

2 Requirements of an Analog Front End for Robotic Prostheses Control

The different amplifiers characteristics that are prioritized when searching for suitable Analog Front Ends are the signal resolution after ADC conversion, Input Referred Noise (IRN), Common Mode Rejection Ratio (CMRR) and bandwidth. This chapter describes what demands that were used when looking for suitable AFEs. The EMG and ENG signals have low amplitude over a relatively wide bandwidth as shown in table 1.

Since this AFE is supposed to be used in a portable system, power consumption and size are also important aspects. Therefore only ICs including multiple channels and with relatively low power consumption in the order of miliwatts were selected to minimize size and complexity.

Table 1: Input signal characteristics [1, 5, 11]

Signal	**Bandwidth**	**Main Energy**	**Amplitude**
EMG	dc-500 Hz	70-300 Hz	0.25-5 mV
ENG	500-7k Hz	500-3k Hz	5-300 μV

2.1 Analog to Digital Conversion (ADC)

There are two main ways of achieving good resolution of the signal in the ADC. One way is to have high gain and lower resolution of the ADC and the other way is to have lower gain and high ADC resolution [12, 13]. Equation 1 shows how the input signal resolution is dependent on the reference voltage of the ADC (V_{ref}), if it , the gain G and the bit-resolution of the ADC (n). Given that the noise is not affected, low gain can be compensated for by increasing the number of bits in the ADC.

$$InputResolution = \frac{V_{ref}}{G * 2^n} \tag{1}$$

2.2 Noise and filtering

There are two noise source categories, intrinsic and extrinsic noise. Intrinsic noise is noise generated in the AFE and includes transistor flicker and ADC quantization noise. The most common extrinsic noise sources are power line harmonics (50 Hz or 60 Hz with overtones depending on location) and cable and skin contact artifacts caused during motion [14, 12, 15, 16].

Important noise qualities when determining the performance of an AFE are the Input Referred Noise (IRN) and the Common Mode Rejection Ratio (CMRR). An ideal differential amplifier would have no IRN and infinite CMRR. To get a good signal to noise ratio the noise produced by the amplifier must be low compared to the input signal. Many AFEs for biopotential recordings have typically an Input Referred Noise (IRN) level of 1-4 μV [17, 18, 19, 20, 21].

Rejection performance of the common mode signals, CMRR, should be at least 80 dB for high quality instrumentation amplifiers as suggested by Webster and Clark [22, Ch 3.4], even though some recommend higher, 100-120 dB [11, 12]. The bandwidths of EMG and ENG signals are wide and to lower the noise and filter out unwanted frequencies, low pass, high pass and notch filters may be used. These filters could either be implemented in hardware or software. Some filtering must however be implemented before the analog to digital conversion to avoid aliasing and large-slow-fluctuations saturating the amplifier [23, 12].

A low cutoff frequency of 20-30 Hz is recommended to reduce most of the movement artifacts from skin contact and cables. As an upper cutoff frequency, 400-450 Hz is recommended since the energy of the noise is higher than the energy of the EMG signal at higher frequencies than this. To reduce power line harmonic interference, notch filters may be used that filter out these specific frequencies. [14, 12]

3 Materials and Method

To determine if the AFE ICs that have been selected are suitable for recording of EMG signals a test setup has been made. The setup was used to evaluate the Texas Instruments (TI) ADS1298, Intan Technologies RHA2216 and Integrum AD2 in simultaneous recordings of EMG signals.

3.1 Materials

First the three AFEs that were compared are described with background, features and a short summary focused on their suitability and configuration for this project. Thereafter the surrounding components used are described in the order they appear in the signal chain, from electrodes to software for analysis.

3.1.1 Texas Instruments ADS1298

The ADS1298 IC is a low power AFE designed for biopotential measurements. It has 8 input channels with one 24 bit $\Delta\Sigma$ ADC for each channel, supporting simultaneous sampling of all channels, see figure 1. The chip is especially suited for portable ECG monitoring systems with many implemented ECG features (Goldberg and Wilson Center terminal, PACE detection and Right Leg Drive (RLD) support). The ADS1298 has been used as ECG recorder in portable monitoring systems for different physiological signals [24].

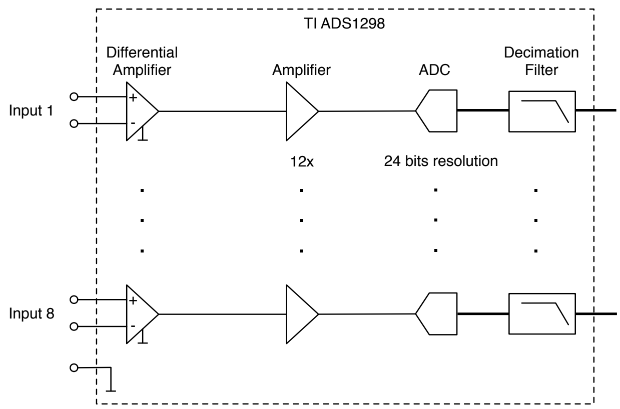

Figure 1: Texas Instruments ADS1298 AFE configuration .

Important features of the TI ADS1298 are listed below: [25]

- Input referred noise: 2.2-483 μV_{pp} and 0.4-44 μV_{rms} depending on sample rate
- CMRR: 115 dB
- Gain: 1-12x
- Lower cutoff frequency: <0.1 Hz
- Upper cutoff frequency: 65-8.4k Hz

- Power consumption: 0.75 mW/channel
- ADC resolution 17-24 bit
- ADC reference voltage: 2*2.4 V

Even though the TI ADS1298 is mainly marketed for ECG and EEG use, EMG signals should still be possible to record since the frequency range is adjustable. The gain of the device is adjustable up to 12 times. For this application the highest gain were used since the signal strength of the EMG signals are at millivolt level and higher gain gives lower IRN.

What is noteworthy for this device is that the ADC resolution decreases with sampling rate, which is a property of the sigma-delta decimation [23]. Since this device has such low gain, it is compensated for by a high-resolution sigma delta ADC. Table 2 shows the ADC resolution in relation to different sample rates. The ADC resolution decreases at 16 and 32 kSPS to 19 and 17 bits respectively, since the resolution is still well below the IRN it is the IRN that sets the limit for what signal change that can be detected.

Table 2: The relation between ADC resolution, IRN and Bandwidth (BW) for different programmed sample rates at 12 times gain of the TI ADS1298.

Sample Rate [SPS]	BW [Hz]	ADC resolution [bits | μV]	IRN [μV_{rms}]
500	131	24 | 0.024	0.5
1000	262	24 | 0.024	0.6
2000	542	24 | 0.024	0.9
4000	1048	24 | 0.024	1.2
8000	2096	24 | 0.024	1.8
16000	4193	19 | 0.76	5.2
32000	8398	17 | 3.1	28.6

One of the more interesting ECG features that this chip supports is the Right Leg Drive (RLD) circuit. Driven right leg circuits were originally developed for ECG recordings but has been used for other biopotentials as well and may improve the CMRR while pertaining good isolation to the power grid [12, 26].

For this project a demonstration kit for the ADS1298 was used to test the device, ADS1298ECGFE-PDK. It has its own Digital Signal Processor (DSP) but another data bridge device was used to allow real time capture, which is described in chapter 3.1.5. The motherboard was only used for power regulation of the battery power. Figure 2 shows the evaluation board for the ADS1298 connected to the motherboard included in the demonstration kit. The device was configured to run in high-resolution mode using internal reference for the ADC.

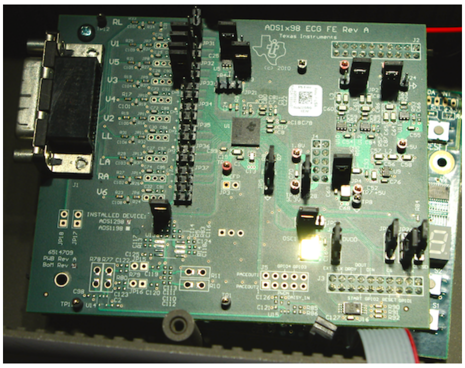

Figure 2: Evaluation Board 'ADS1298ECG-FE Kit' for the Texas Instruments ADS1298.

3.1.2 Intan Technologies RHA2216

The Intan Technologies RHA2000 series chips are integrated bioamplifiers that have been developed at the Department of Electrical & Computer Engineering at University of Utah. Professor Reid Harrison that developed the first generation of this chip started Intan Technologies Inc. that now sells this IC-series. Their former chip RHA1016 has been used in different bioamplifier applications [27, 28]. The RHA2216 has 16 built in differential amplifiers and a MUX output stage capable of switching between input channels at high speed, see figure 3. The input has series capacitors on each channel for high pass filtering. Both upper and lower cutoff frequencies of the band-pass filter are adjustable via external resistors, which makes it adaptable for both EMG and ENG signal bandwidths.

Important features of the Intan Tech RHA2216 are listed below: [29]

- Input referred noise: 2 µV typical, varies slightly with bandwidth
- CMRR: 82 dB
- Gain: 200x
- Lower cutoff frequency: 0.02-1k Hz
- Upper cutoff frequency: 10-20k Hz
- Power consumption @ 10 kHz, 3 V: 7.0 mW total; 0.44 mW/channel
- The MUX can switch at 1 MHz which means that the 16 channels may be sampled at 62.5 kSPS, or higher if less channels are used.

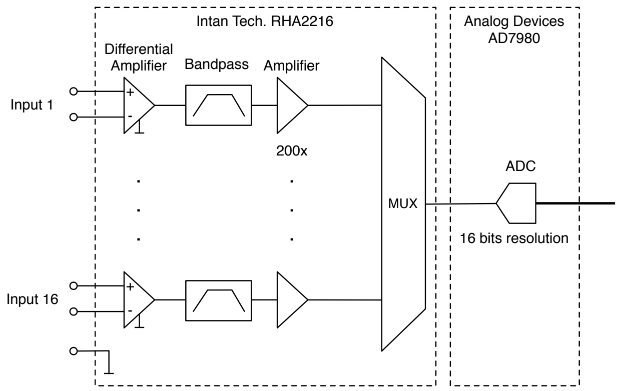

Figure 3: Intan Technologies RHA2216 AFE configuration.

The datasheet recommends using this chip together with an ADC from Analog Devices, AD7980, which can sample up to 1 MSPS and has a power dissipation of 10 mW [30]. This makes the total power dissipation for the chip plus ADC 17 mW, which is approximately 1mW/channel for 16 channels.

For the evaluation an amplifier board from Intan Technologies was used that had the RHA2216 and the suggested ADC AD7980 from Analog Devices mounted on a PCB with all the necessary peripheral components soldered to it, see figure 4 [31]. The lower and upper cutoff frequencies ware changed by replacing the external resistors to 20-750 Hz setting.

Only one output is used on this AFE and the input amplifier signals are sequentially multiplexed. Flank triggered pulses are used to control the multiplexer and the ADC. To get correct timing three different PWM signals, Convert, Step and Reset were set up in the Data Bridge Circuit. Convert instructed the ADC to start a conversion, Step instructed the MUX in the AFE to select the next input and Reset instructed it to select Channel 0 as input. Reset was toggled low after channel 3 was reached since only a total of four channels were used. The Step flank was also used to trigger an interrupt to fetch the data via Serial Peripheral Interface (SPI) from the ADC before next conversion.

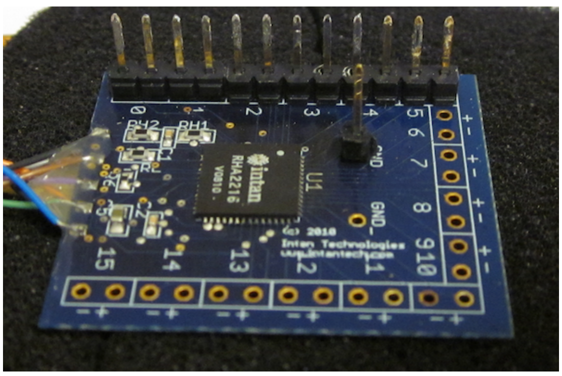

Figure 4: Amplifier Board for Intan Technologies RHA2216.

3.1.3 Integrum AD2 Amplifier

The AD2 amplifier board was developed by Max J. Ortiz C. at CTH/Integrum [5]. This device has been used for recording surface EMG signals before and was therefore used as a reference to compare the recording result with. This device uses an external ADC from National Instruments, the NI USB-6009. An overview of the AD2 AFE is shown in figure 5 and the PCB can be seen in figure 6.

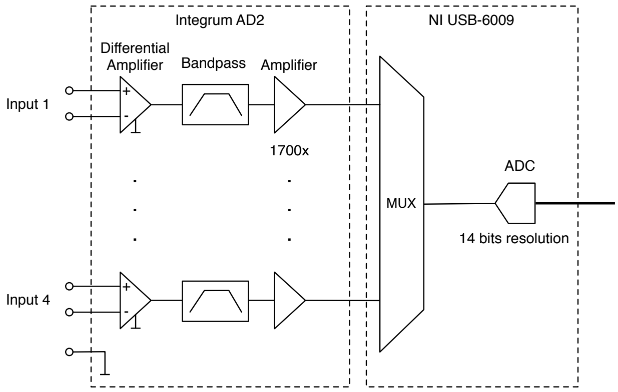

Figure 5: Integrum AD2 AFE configuration.

Important features of the Integrum AD2 are listed below:

- CMRR of the input differential amplifier: 100 dB
- Adjustable gain up to 10000x
- Lower cutoff frequency: 20 Hz
- Upper cutoff frequency: 3.5 kHz
- NI USB-6009 ADC resolution: 14 bits
- ADC reference voltage: 2*10 V
- On board isolation stage

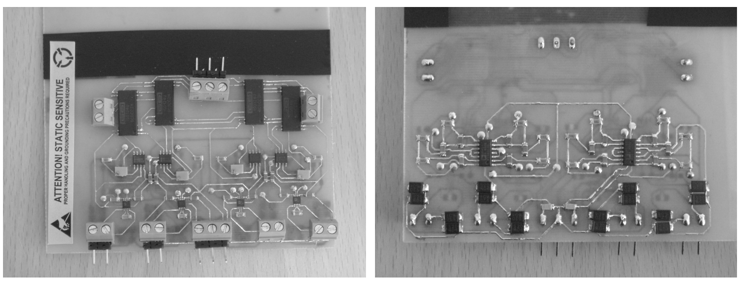

Figure 6: AD2 discrete amplifier solution from Integrum.

3.1.4 Electrodes

To measure the EMG signals, eight 1 cm diameter dry stainless steel surface electrodes were used. They were placed in four bipolar configurations with 2 cm inter-electrode distance along the muscle fibers in the most proximal third of the forearm. The electrodes position differed slightly between the subjects. However, these were always placed equidistant with two pairs covering the flexor muscles and the other two the extensor group.

The electrodes were connected using crocodile connectors to twisted pair cables. The cables were connected to a breadboard where the signals were split into separate twisted pair cables for the different amplifiers. For grounding, three self adhesive electrodes from MediHighTec was used and placed on the opposite arm to the EMG electrodes, one separate for each AFE ground.

3.1.5 Data Bridge Circuit

The Data Bridge Circuit was used to transfer the data between the AFE and the recording computer. For the AD2 a USB controlled ADC was used which is mentioned in the previous section Integrum AD2 Amplifier.

To configure and receive data from the TI ADS1298 and the Intan Technologies RHA2216, one Texas Instruments Piccolo board was used per device. The TI Piccolo is the microcontroller (MCU) chosen for the Stand Alone Hardware Platform [10]. This MCU runs at 80 MHz and has Serial Peripheral Interface (SPI) communication towards the AFE ADCs and has an FTDI-chip to create a USB Virtual COM Port (VCP).

The maximum SPI bit rate is 20 MHz for the Piccolo and the maximum speed for sending data via the Serial Communication Interface is 1.25 MBaud [32]. This is not a standard baud rate for RS-232 communication. To be able to set non-standard baud rates aliasing was used. Aliasing means that a standard baud rate divisor setting is replaced in the drivers by a non-standard setting. In this case, the standard rate 4800 Baud was set to 1.26 MBaud, since this was the closest to 1.25 MBaud possible to set. This is within the maximum 3% margin of baud rate error specified by FTDI [33].

One limitation when using a Virtual COM Port (VCP) is that the data is only polled by the PC operating system and buffer overrun can occur when having too high data rate [34]. Therefore the sample rate was limited to 2000 SPS. The theoretical max is higher since 4 channels, 24 bit resolution and 2000 SPS means only $4 * 24 * 2000 = 192000\, bit/s$. In the case of this evaluation the limit had no major consequence since the EMG signals has lower bandwidth and are filtered before the analog conversion.

3.1.6 USB Isolators and Power Supply

The USB Isolators (Ulink UH401) were used to isolate the user from the power grid for safety reasons and at the same time this separates the ground making sure that the three AFEs did not share the same ground to avoid any interference. The Integrum AD2 amplifier already had a built in isolation stage and therefore no extra USB isolator for AD2 was used.

The Isolators can only deliver 100 mA, therefore batteries was used to power the devices. Four R6 batteries were used to power the Piccolos and the TI ADS1298 evaluation kit. The Intan Technologies amplifier board gets 3.3 V power from the Piccolo boards. To limit the voltage to Piccolo boards, 5 V voltage regulators (National Semiconductor LM2940CT) were used since the Piccolo has some components sensitive to voltage above 5.3 V.

3.1.7 Pattern Recognition Software

The software used for acquisition of the EMG signals from the three devices was an extension of a MATLAB program developed by Max Ortiz at CTH/Integrum [5]. The program was further developed in order to support the TI Piccolo data bridge circuits described above. The software started the recording from all devices simultaneously and stored the data from the Piccolo devices in real time. The data from NI USB-6009 was sent to MATLAB after each recording set was finished.

The program trained a multi-layer perceptron network through backpropagation. Figure 7 shows the structure of the network. Five features (standard deviation, mean absolute value, wave length, number of slope changes, number of zero crossings) were calculated from each channel, which gave a total of 20 inputs to the network. There were six outputs, which referred to six different movements trained (open hand, close hand, wrist flexion, wrist extension, supination and pronation). The network was tested with a portion of the measured data, which were not used for the training or validation of the network. It was used to collect the mean, max, min and standard deviation for several repetitive calculations of different networks.

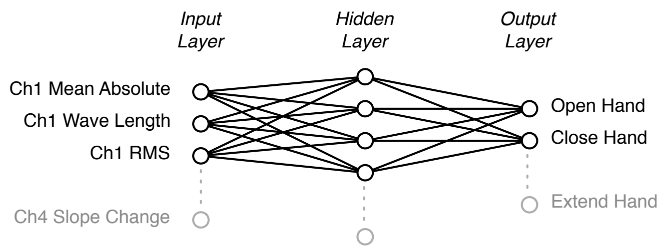

Figure 7: Artificial Neural Network (ANN) for robotic control.

3.2 Method

In order to compare the AFEs, a system for recording from all three devices simultaneously was implemented. This was made to make sure that all devices were receiving the same EMG signals. The position of the electrodes and the surrounding noise influence are parameters that change drastically between each recording session and are therefore impossible to repeat for successive sessions.

This chapter starts by describing the recording setup, followed by tests to ensure that the devices perform similar to what is specified in the devices datasheets are described. Then the filtering and pattern recognition evaluation procedures are presented.

3.2.1 Recording Setup

The EMG electrodes are placed on one arm of the subject and three different ground electrodes are placed on the opposite arm. Figure 8 shows an overview of the system. Twisted pair cables were used for connection to a breadboard where the signal was split into the three different AFEs. The dotted lines show where the safety isolators are positioned. Figure 9 shows a photo of the recording setup where the three brown boxes contains the different AFE evaluation boards.

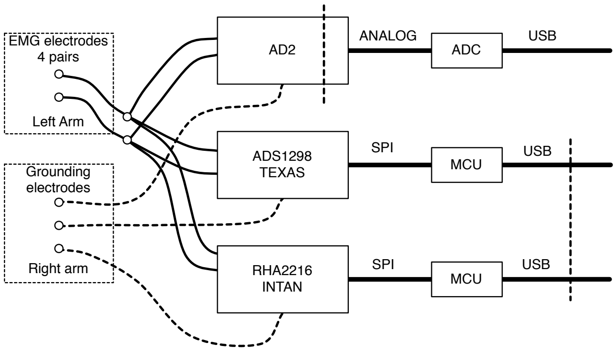

Figure 8: Recording setup overview.

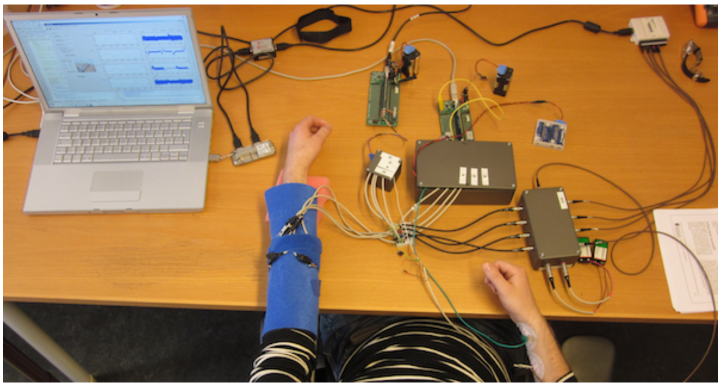

Figure 9: Recording setup. All three devices connected to the same 4 EMG electrode pairs.

3.2.2 Measurement of Amplifier Properties

To determine that the system was set up correctly, measurements of gain, bandwidth, IRN and CMRR was made.

Gain The total gain of the amplifier was measured using a sinus signal of $0.5\,\mu V_{\mathrm{rms}}$@125 Hz. The signal was generated using an Agilent 33210A function generator with an external $50\,\Omega$ 20 dB attenuator and a $50\,\Omega$ pass through terminator. The gain is calculated according to equation 2 where V_{ref} and n is the reference voltage and resolution of the ADC respectively and N_{adcRms} is the ADC result.

$$G = \frac{N_{adcRms} * V_{ref}/2^n}{V_{inRms}} \tag{2}$$

Bandwidth The bandwidth of the AFEs were determined by sweeping the frequency of a signal generator until the output was attenuated 3 dB.

Input Referred Noise (IRN) The test setup for measurement of the Input Referred Noise is shown in figure 10. By connecting both input terminals to ground and measuring the output noise the noise produced by the amplifiers and the quantization noise was determined. The IRN is calculated according to equation 3.

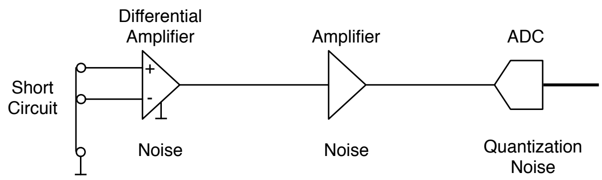

Figure 10: Input short setup to measure Input Referred Noise.

$$IRN_{rms} = \frac{OutputNoise_{rms}}{G} \tag{3}$$

Common Mode Rejection Ratio (CMRR) To measure the CMRR a common mode test signal was generated by a signal generator and was connected as shown in figure 11. The CMRR is calculated by dividing the common mode gain, which should be less than one, with the differential mode gain, equation 4. The frequency of the signal generator was set to 125 Hz. This frequency was chosen as an in-band frequency that shouldn't interfere with the 50 Hz and its overtones from power lines.

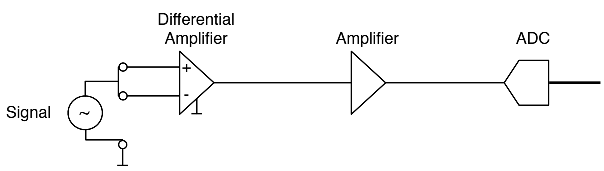

Figure 11: Common Mode input signal setup to measure Common Mode Rejection Ratio (CMRR).

$$CMRR = \frac{G_{DM}}{G_{CM}} \tag{4}$$

3.2.3 Signal Processing

Since the three different amplifiers that were compared have different possibilities in filtering, all signals were band-passed in software to make the comparison fair. This filtering could also be implemented in the microprocessor or DSP extracting the features and therefore the bandwidth of the hardware shouldn't affect the results. However, the upper cutoff frequency should be below Nyquist frequency to avoid aliasing.

3.2.4 Recodings from test subjects for Pattern Recognition Analysis

A total of ten recordings were performed on eight test subjects, eight left arms and two right arms. Figure 12 shows a picture from one recording session.

During the recordings the test subjects did 6 different movements with 3 repetitions of 6 second for each movement with 6 seconds of relaxation between each contraction. From the contraction part of the recordings, signal features were extracted and fed to an Artificial Neural Network (ANN). Statistics of the pattern recognition result were stored and compared between the different AFEs. Each pattern recognition session was run 10 times since the stochastics may affect the result. The mean, max, min and std of the test set accuracy were stored.

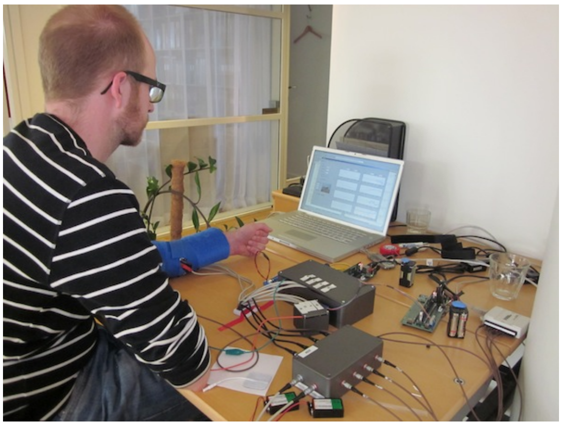

Figure 12: Recording exercises for Pattern Recognition.

4 Results and Discussion

First the results from the measurements of the amplifier properties are presented and then the performance of the pattern recognition follows. Finally some other observations that followed are presented such as mobile phone interference and correlation analysis.

4.1 Amplifier Properties

The measured gain for the different AFEs is shown in table 3. The gain is within 5% of what is stated in the datasheet according to these measurements.

Table 3: Gain measured at 125 Hz.

	TI ADS1298	Intan Tech. RHA2216	Integrum AD2
Gain measured	12x	190x	1700x
Gain datasheet	12x	200x	-

The bandwidth of the AFEs and the corresponding values from the respective datasheets are shown in table 4. For TI ADS1298 the lower cutoff frequency is very low. This may cause some problems with saturation of the amplifiers when motion artifacts are introduced.

Table 4: 3 dB bandwidth.

	TI ADS1298	Intan Tech. RHA2216	Integrum AD2
Lower measured	<0.1 Hz	0.6 Hz	20 Hz
Upper measured	510 Hz	620 Hz	3500 Hz
Lower datasheet	-	1 Hz	-
Upper datasheet	524 Hz	750 Hz	-

Despite that the gain is very different between the amplifiers they all meet similar input referred noise performance, summarized in table 5. The table shows the average noise between the different channels and standard deviation.

Table 5: Input Referred Noise (IRN) - Differential Mode (DM). Average and standard deviation between the four channels.

	TI ADS1298	Intan RHA2216	Integrum AD2
IRN measured (10 s)	0.94±0.04 μV_{rms}	2.4±0.2 μV_{rms}	6.3±0.3 μV_{rms}
Filtered 20-500 Hz	0.75±0.02 μV_{rms}	1.6±0.1 μV_{rms}	3.6±1.2 μV_{rms}
IRN datasheet	0.9 μV_{rms}	2 μV_{rms}[1]	-

The device with the lowest gain, TI ADS1298, has the highest signal resolution after the digital to analog conversion due to its high ADC resolution. Figure 13 shows the short circuit noise of the different amplifiers together with the resolution of the signal on the right hand side axis. The signal to noise ratio is mainly limited by the noise introduced in the amplifiers and less affected by the quantization noise, figure 13. An FFT of the noise signal was also made

[1] Excluding ADC quantization noise

which shows the 6th order Butterworth filtered signal at 20-500 Hz, see figure 14. The AD2 seems to have some self-resonant noise frequencies in the spectra, which increases the total noise.

For the ADS1298 the IRN is greatly dependent on the sample rate and, in turn, the bandwidth, as shown in table 2. At 2 kHz bandwidth, the noise is approximately the same for TI ADS1298 and Intan Technologies RHA2216. The TI ADS1298 approximately meets the Integrum AD2 noise value at 4 kHz bandwidth and at higher bandwidth, 8 kHz, the IRN is almost 30 μV_{rms}.

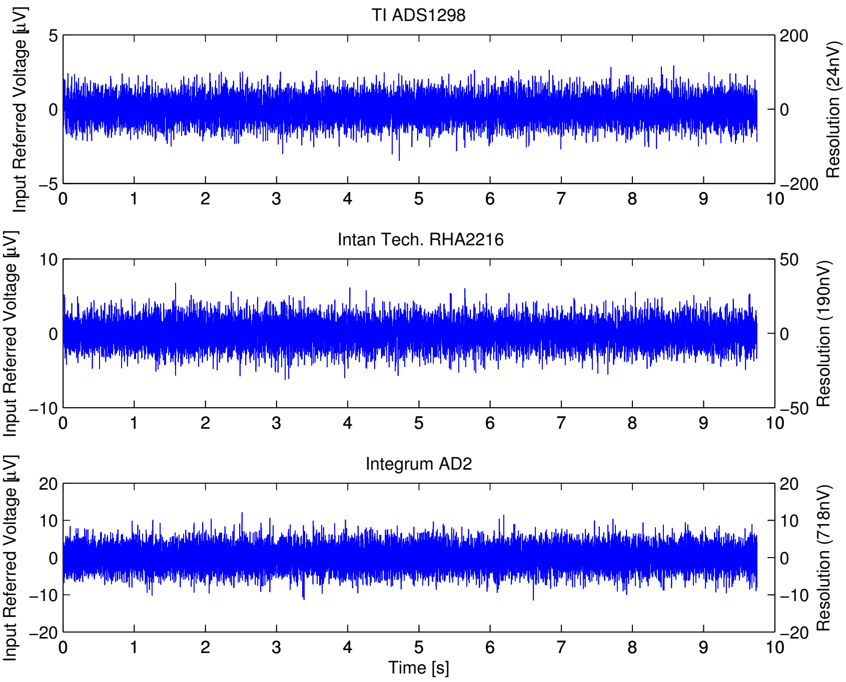

Figure 13: Input Referred Noise (IRN) - time domain, 10 seconds. The right hand scale shows the number of quantization levels and the minimum ADC precision.

The CMRR was measured to be similar to what was expected from the datasheet for the TI ADS1298 and the Intan Tech RHA2216. For the Integrum AD2 the measured CMRR is higher than what is stated for the input differential amplifier datasheet and hardly any trace of the 125 Hz signal was observed in the frequency spectra.

Table 6: CMRR - Common mode signal 125Hz.

	TI ADS1298	Intan Tech. RHA2216	Integrum AD2
CMRR measured	115 dB	81 dB	>115 dB
CMRR datasheet	115 dB	82 dB	100 dB

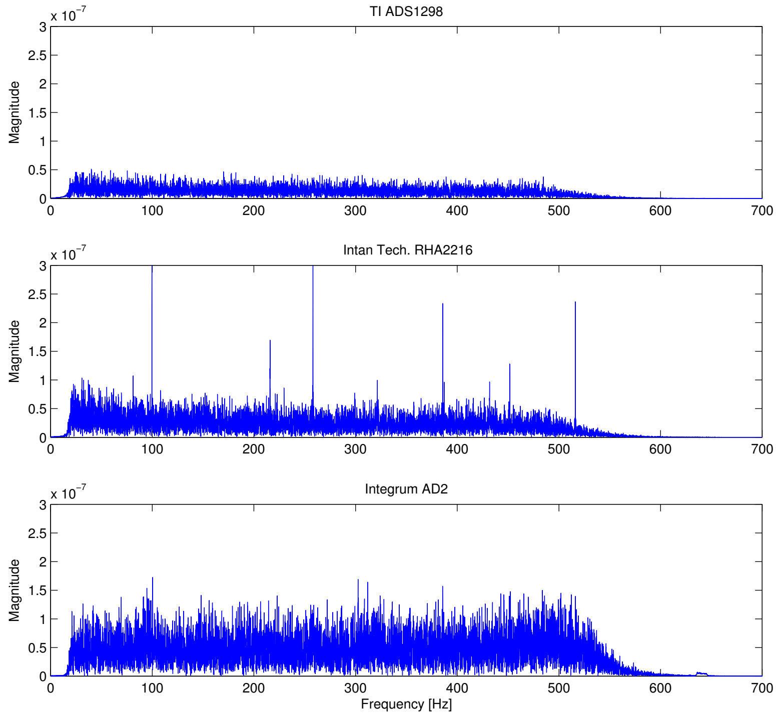

Figure 14: Input Referred Noise (IRN) - frequency domain, 10 seconds recording.

The Intan Tech RHA2216 has substantially lower CMRR than the other devices. This is clear when subjected to interference from a mobile phone. Figure 15 shows the susceptibility of the Intan Tech RHA2215 to mobile phone interference. The measurement was made with the mobile phone approximately 1 m from the cables during the initiation of a phone call. When closing the distance to 0.1-0.2 m, noise was introduced in the TI ADS1298 as well but no noise was observed in the AD2.

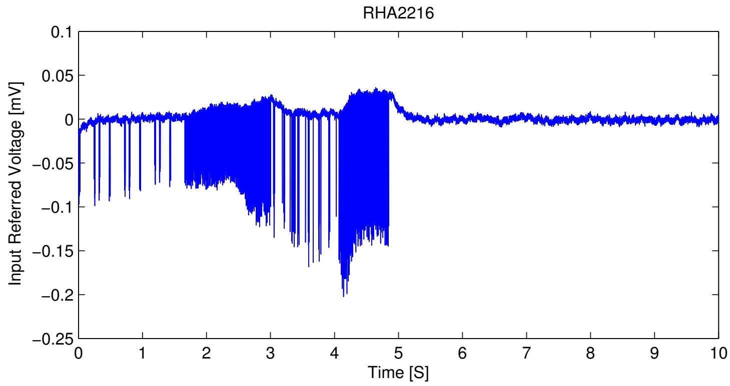

Figure 15: Recording from the RHA2216 with interferance from a mobile phone during the first half of the recording.

When comparing the intrinsic noise sources, the TI ADS1298 seems to be a proper choice for low bandwidths while for bandwidths above 2 kHz the Intan Technologies RHA2216 noise level is lower. However, the lower CMRR of the RHA2216 might be critical under some circumstances. As long as the signal to input referred noise ratio is sufficient for the TI ADS1298 and the amplifier does not saturate due to low frequency drift for the given application, the TI ADS1298 is suggested since the CMRR is a very important property in most applications.

4.2 Pattern Recognition Performance

The results from the training of the ANNs for pattern recognition shows that all three devices perform equally well at discriminating which movements were performed. The values in figure 16 are merged representations of statistics from 10 training runs in the pattern recognition software based on 10 different recoding sessions.

The reason why they perform equally well may be because the quality of the recordings performed were too good, meaning that few noise sources and other disturbances such as motion artifacts were present. Because of this, the difference in CMRR and rejection to low frequency noise had less impact on the result. If the signals would have been weaker, the input referred noise could probably also have made a difference to the result.

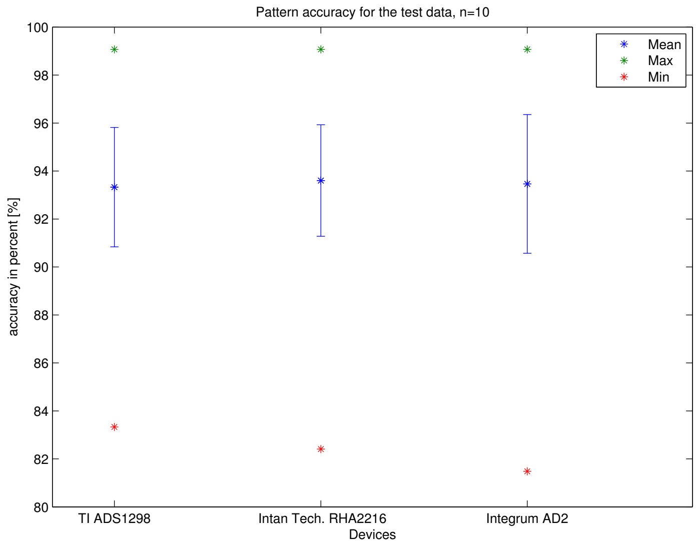

Figure 16: Performance results form the train networks.

4.3 Correlation between the devices

The three devices show strong correlation between each other in the beginning of the recordings, see figure 17, but the Intan Tech RHA2216 is drifting in respect to the other two devices. This is because the clocks that are controlling the devices sample rates are not perfect, and thus introduces drift.

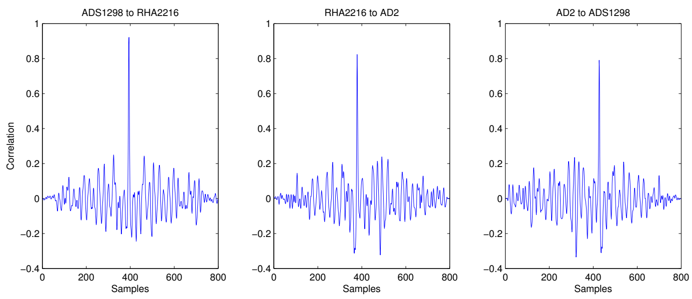

Figure 17: Correlation between the recodings from the different devices for a 200 ms time window.

5 Conclusion

Two of the most promising Analog Front End ICs found on the market have been tested and evaluated for EMG signal recordings for robotic prosthesis control. Both devices tested shows to have good accuracy when running pattern recognition and their performances are comparable to the first prototype used for EMG recordings at Integrum.

The Intan Technologies device RHA2216 has lower CMRR, 82 dB, which makes it more susceptible to extrinsic noise sources such as power line interference and other electromagnetic noise sources that affects both input electrodes similarly. This device has however low input referred noise over a wide bandwidth. By using oversampling and averaging this could lower the intrinsic noise influence even more. When the noise isn't completely stochastic or of low frequency, as many extrinsic noise sources, averaging will not help.

Texas Instruments ADS1298 has high resolution despite that the gain of the amplifier is only 12 times. This is compensated by a high resolution ADC, which makes the signal resolution higher than the input referred intrinsic noise level. However, since the low noise of this device is based on high order of decimation in the Sigma-Delta ADC the noise level increases at higher sample rates. This makes it less suitable when demanding bandwidths over 2 kHz for low amplitude signals. Another potential problem with the Texas Instruments ADS1298 is the extremely low lower cutoff frequency, which increases the risk of saturation of the amplifier. Since the gain is very low, the amplitude of the noise needs to be high to make it saturate but it could still be a problem when introducing motion artifacts for example. However, high CMRR, proper cable, electrode design and electrode position may eliminate the saturation problem.

One of the benefits of having a discrete amplifier solution as the AD2 designed at Integrum is that it may be designed with proper filters such as notch filter for power line harmonics as the latter biopotential amplifiers employed at CTH/Integrum. As long as the amplifiers don't saturate and the signal is low pass filtered to avoid aliasing, additional filters could be added in the microprocessor or DSP software instead.

By implementing an Integrated Circuit Analog Front End size and power consumption could be decreased. Two devices that are available on market have been tested to verify that they work together with former EMG setup used at Integrum. Drivers have also been written for the Stand-Alone Hardware Platform under development at Integrum to ease the integration to a portable robotic prosthesis for clinical trials.

5.1 Future Work

To further verify that the tested Integrated Circuits works for the final implementation some more tests must be done in a more realistic environment. Movement artifacts and common noise sources should be increased to see what effect it may give on the different devices. Especially test the common mode noise limit for the Intan Technologies RHA2216 and saturation risk of the Texas Instruments ADS1298. It is also necessary to test the performance of the pattern recognition algorithm for a higher number of movements.

One of the features that might improve the Texas Instruments ADS1298 that hasn't been tested during this study is the built in RLD feature. This feature may improve CMRR and lower risk of saturation.

Next step would be to design a PCB with the AFE together with the signal module of the Stand-Alone Hardware Platform to make it fit in a portable prosthesis. The drivers may be updated to include Right Leg Drive functions and real time drivers for the TI ADS1298.

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