Pilot Biometrics

ECG Waveform Captures

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Table of Contents

1 - Introduction

1.1 - Project Statement

Pilot Biometrics is a project to develop a device that will capture, monitor, and analyze the Electrocardiograph (ECG) waveform of a US Navy pilot in flight, to be used during training operations. The ECG waveform is a measure of the electrical activity of the heart, useful in measuring cardiac stress. The device uses three high-fidelity ECG sensors to collect an accurate waveform, then filters out background noise and interference. Finally, the device analyzes the waveform data in real time, using an artificial neural network to detect if the pilot is in distress. A copy of the data is stored while data is also packaged for real-time transmission to the ground through a component in the cockpit. The device operates on its own power supply and is capable of running continuously for 4-5 hours.

1.2 - Purpose

The purpose of this project is to provide critical medical information to decision makers on the ground about the conditions of US Navy pilots in flight during training missions. While in the air, pilots must be capable of performing harsh maneuvers which induce serious G-forces. These forces can have a significant impact on the health of the pilot, especially when other factors are influencing their health. If a pilot in flight is experiencing a high level of distress, they are at risk of falling unconscious and injuring themselves or other pilots in the air. It is also important for medical officers to be able to evaluate the health of pilots throughout their training. Our project aims to provide this information in real time.

1.3 - Project Goals

- Establish linux development environment on microcontroller
- Develop algorithm for detecting cognitive stress in ECG waveform
- Create device driver for collecting data off microcontroller
- Configure ADC for use with ECG sensors
- Interface ADC with microcontroller
- Determine filtering needs and design hardware filters
- Design power supply for 5 hours of continuous operation
- Collect raw data at various levels of cognitive stress
- Combine hardware components in case

2 - Specifications

2.1 - Operational Environment

The ECG sensors will be attached to a user via disposable pads under a flight suit and used in military aircraft test flights. It will experience rough shaking, inconsistent vibrations, movements from the pilot, and high-g maneuvers. We expect conditions inside the cockpit to be clean, the cabin partially pressurized, and within a reasonable range of temperatures. Our device will not come into contact with water or weather conditions and humidity in the cockpit will be minimal.

2.2 - Intended Users and Uses

Our product is intended to be used by US Navy fighter pilots in training. These pilots are already trained and certified to fly the aircraft, and will be practicing maneuvers and training missions involving multiple aircraft. The device is intended to gather and report ECG waveform data, as well as analyze the data in real time. Extracted data will be used by health officers and trainers on the ground to make decisions about the health of the pilot during and after the mission.

2.3 - Functional Requirements

- Accurately detect cognitive stress of a user
    - Capture ECG waveform of user in flight operations
    - Identify signs of distress based on ECG waveform
- Operate in real time on an ARM microcontroller
- 4-5 hours of continuous operation
    - Consistent and reliable power supply
- Securely store and transmit data
    - Store 4-5 hours of operational data on device
    - Output data to component in cockpit for ground transmission

2.4 - Nonfunctional Requirements

- No interference with primary pilot tasks
    - Flight operations
    - Emergency ejection
- No interference with pilot flight suit and safety harness
- No interference with aircraft communications

2.5 - Standards

Our project abides by military standards for medical record data, as well as ECG waveform capture standards for data storage. Our device also complies with US export control standards through Rockwell Collins. For data transmission and storage, our project uses the Advanced Encryption Standard (AES) as required by the US Government.

For communicating medical data, our project abides by Health Level 7 (HL7). HL7 is an international set of standards for communicating medical information. It defines how a message should be formatted when transmitting medical data. This standard is used because it is the most accepted standard for medical information transmission and it will make it easy for other systems to communicate with our device.

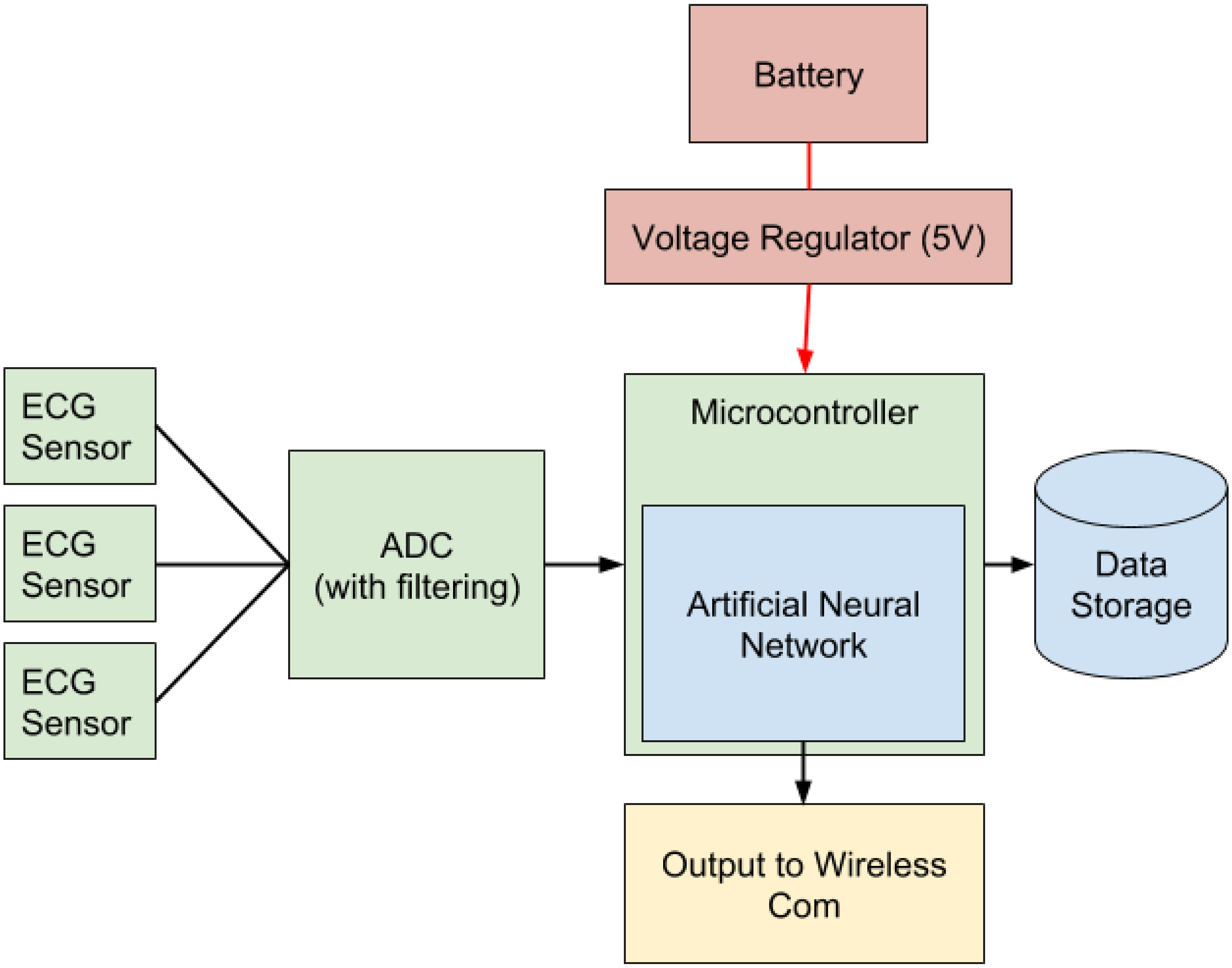
To store ECG waveform data, our project abides by IEEE Standard 11073-10102 for annotated ECG data. This standard describes the different components of an ECG waveform as well as how to store and annotate the data. This standard was selected because it is widely accepted for digital storage of ECG data and allows our project data to be easily used by medical professionals.

3 - Design

3.1 - System Block diagram

Below is our System Block Diagram, showing all the components of the ECG waveform capture system. Red blocks indicate components of the power system, with red wires indicating power transmission. Green blocks indicate main hardware components. Black lines indicate data transmission. Blue blocks indicate subcomponents of the system, and yellow blocks represent a data output format.

Figure A.



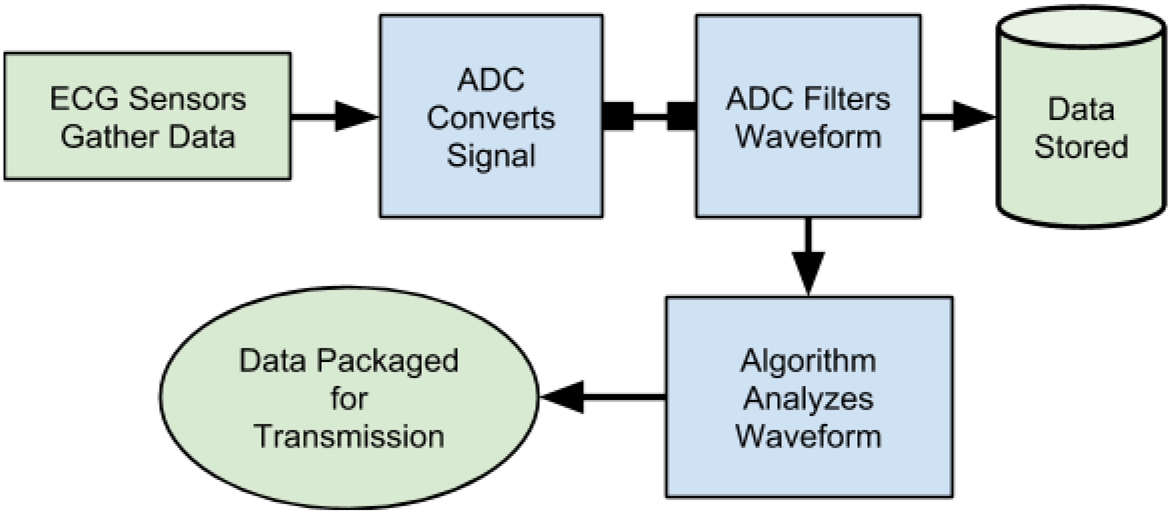
This figure shows major hardware and software components of the project.

3.3 - Project Components

Our design consists of several hardware and software components. For hardware, our design utilizes three ECG sensors, an Analog to Digital Converter with built in hardware filters, a microcontroller, and a battery with voltage regulator. For software, our project uses a device driver to collect data and an artificial neural network for detecting stress, both running on the microcontroller. The microcontroller will also interface with hardware inside the cockpit to allow communication with the ground.

Three ECG sensors take voltage readings from the user. This raw data is passed into the ADC which converts the analog signal into digital data and acts as a bandpass and notch filter to remove interference. The data is then sent to the microcontroller where a copy of is stored on the device. At the same time, the data is passed into an artificial neural network which detects high cognitive stress. Finally, the data is organized into packets and sent to a component in the cockpit to communicate with personnel on the ground.

Figure B.



This figure shows the system process from ECG measuring to data transmission.

3.3 - Hardware

STM32F767 Microcontroller from ST Micro is used to store, transmit, and interpret ECG data.

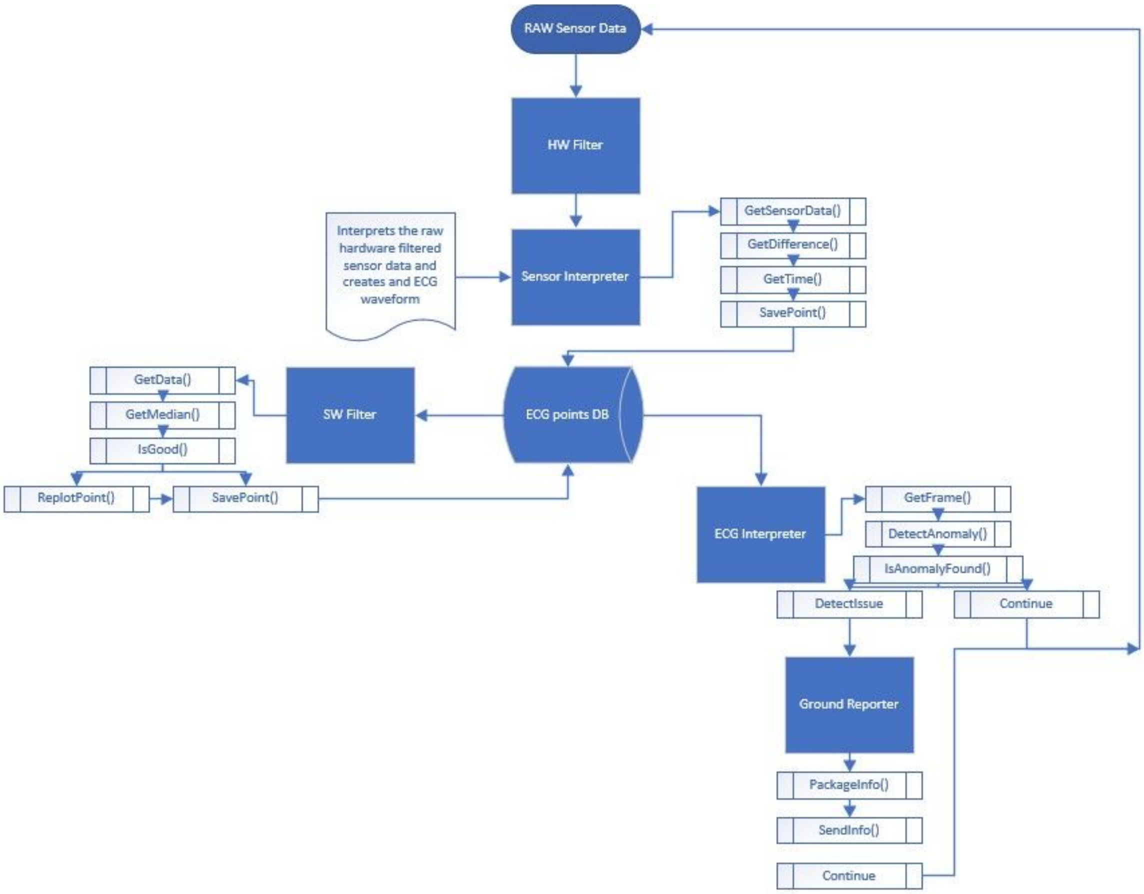
ADS1298RECGFE-PDK is an Analog to Digital Converter (ADC) used to convert analog data received from the ECG sensors into digital data sent to the microcontroller.

ECG sensors ADS129R will take voltage readings from the user and send it into the ADC.

3.4 - Software

An embedded C++ program runs on the microcontroller, handling all data management. The actual ECG interpretation is handled by an artificial neural network, which receives the waveform data and detects signs of distress. The diagram below shows the details of all software components. This diagram also illustrates how data moves through filtering and the main algorithm.

Figure C.



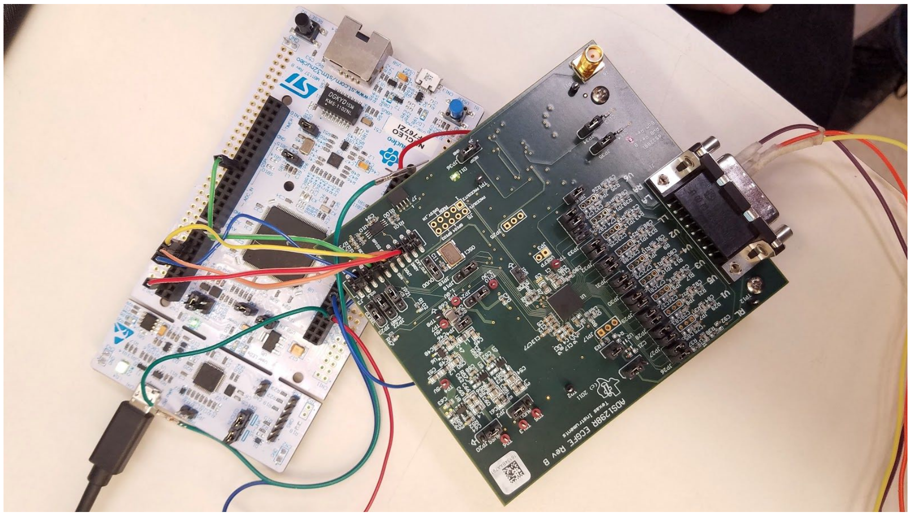
This figure shows details of the software and data components of the system.

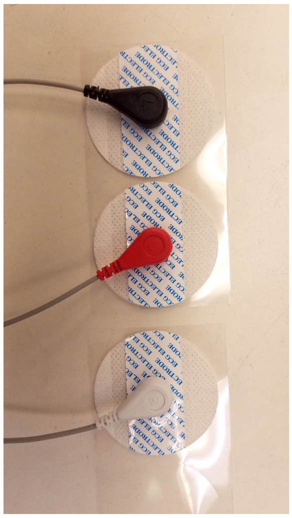
4 - Implementation and Testing

4.1 - Implementation Details

Three ECG sensor pads connect to leads which run into three channels on the ADC. The ADC is configured to apply a bandpass filter at the frequencies 0.05Hz and 300Hz to block interference outside of the ECG waveform range, as well as a notch filter at 60Hz to block power line interference. ADC output pins are connected to pins on the microcontroller which write to board registers.

A native C++ application runs on the board, grabbing values from the registers and pulling them into memory. Batched copies of the data are written to a file for permanent storage on the device. At the same time, data is formatted into output packets which will interface with a component in the cockpit for ground transmission. As the data comes in, the time between waveform peaks is calculated and fed into the artificial neural network algorithm. The algorithm has been trained to detect stress based on heart rate variability. When detected, the device is able to output a message.





4.2 - Testing Strategy

Our testing strategy focused on three main areas: individual component testing, ECG waveform data collection, and artificial neural network testing.

Component testing consisted of individually activating and measuring results from each piece of the system. The main components tested were the Analog to Digital Converter (ADC), the battery with voltage regulator, and the microcontroller. To test the ADC, we used an arbitrary waveform generator to create sample data and confirm the correct output. We played with various ADC configurations to ensure the device was working as needed. To test the battery and voltage regulator system, we measured power output through various charge and discharge cycles. For the microcontroller, we ran various benchmark algorithms to test the speed of the ARM processor. We also generated large amounts of data to test storage requirements and data transfer speeds.

Once the ECG capture system was fully functional, we began careful data collection. Large amounts of raw data was one requirement from our client, and was also needed to train the artificial neural network for detecting cognitive stress. In order to collect this data, we performed a stress induction test on members of the team. First, we connected the ECG sensors to each participant and collected control data in a comfortable environment with everyone at rest. Next, we began the stress test. For this test, participants were given a spatial navigation task - to land a flight simulator aircraft on a runway. Participants wore headphones which were giving conflicting audio feedback. As the test continued, participants were asked to simultaneously complete the Stroop Color Word Test, a standard for inducing cognitive load. At the same time, participants were continuously asked to self report their stress level by pointing to a one through ten scale. Once the test had completed, the ECG waveform data was compared against sample data found online to verify that it matched the self reported stress levels. This data was taken with the control data to create a training set for the model.

Finally, testing of the artificial neural network could begin. Using a combination of data previously collected, the model was trained and evaluated with different weights for each node in the network. Weights were saved and slowly tweaked to improve the accuracy of the model. Once training and adjustments were complete, the neural network was also evaluated with live data. Participants were again connected to the ECG sensors and given a battery of tasks to induce cognitive stress. The output of the neural network was then evaluated for accuracy.

4.3 - Results

Component testing proved very successful. We confirmed that the ADC was working as intended, and were able to experiment with various configurations. Through our testing, we were able to find a configuration using three ECG sensor inputs that produced an accurate waveform. Testing the power system lead to several changes in the design of the voltage regulator and battery, and we were ultimately able to confirm that the system could run continuously for at least 5 hours of operation. With the microcontroller, we were able to make the necessary changes to our main algorithm and data flows to meet minimum performance requirements. We were then able to test at this performance level and confirm the device could gather and store data for at least 5 hours.

On the data side, we were able to gather several hours of real ECG waveform data from members of the team, including resting data and stress induced data. The stressed data was then labeled with self reported stress levels and compared against sample data found online from similar studies.

4.4 - Issues and Challenges

Our team faced several challenges in the development of the ECG waveform capture system. The first challenge was in configuring the ADC and interfacing all the hardware components. The ADC is extremely robust and includes functionality beyond the scope of the project. This required carefully examining the data sheet and working through several levels of configuration parameters to get the device working.

The second challenge our team faced was in establishing a linux development environment on the microcontroller board. This was necessary so our client could continue working on the board after our project concludes. However, the only board support package available did not allow us to boot linux directly from onboard memory. It took many alterations to allow the board to boot from a custom linux image.

A third challenge we faced was determining our waveform filtering needs. Without access to a military aircraft cockpit, we could only make educated guesses about the exact inference we would need to account for. We expect interference from our power supply and electrical components in the cockpit, but it is also possible that the high vibration and high-g environment will cause its own issues.

One final challenge the team faced was in inducing stress to generate test data. This required developing a research study to match the high cognitive stress conditions that US Navy pilots face. Our approach utilized a spatial navigation task coupled with auxiliary tasks which require a level of concentration. We administered the test on members of the team and relied on self-reported stress measures to label the data.

5 - Related Work

5.1 - Previous Literature

Several methods exist for accurate ECG capture and analysis. ECGs are extremely common in medical applications, for monitoring and diagnosing a wide variety of health conditions. We have also found significant documentation on number, placement, and configuration of ECG sensors. For diagnosis, a 12-lead design is common, with 4 leads across the body and 8 surrounding the heart. For capturing a general waveform, a 3 or 4 lead design is common.

Significant research exists for filtering noise out of ECG waveforms, using both hardware and software designs. Any ECG capture device can expect low frequency baseline wander interference as well as high frequency radio or electrical equipment interference. Both are commonly handled by a hardware bandpass filter. The device would also see power line interference within the ECG frequency range, which can be handled in hardware by a notch filter. Finally, there is muscle noise from random contractions throughout the body. This can only be handled in software, and most ECG manufacturers have proprietary algorithms for filtering this.

Research also exists for determining overall heart stress based on ECG waveform. Research suggests heart rate variability and morphologic variability of ECG signal data is an accurate indicator of mental stress. A significant number of studies have used these metrics to measure the cognitive stress of participants, similar to our project. Research also recommends using machine learning models to analyze ECG waveforms for signs of distress. Training a model for detection is significantly more accurate than designing a new detection algorithm and can be easily verified using labeled data.

5.2 - Similar Products

ECG waveform capture devices are common in medical environments but are rarely used to detect stress, and not common outside of medical fields. Although studies exist using ECG waveform capture to detect stress in vehicle operators and other users, we have not been able to find a complete product with this functionality. This is the first time our client Rockwell Collins has experimented with biometric devices. We have seen growing interest in military medical equipment, especially for high demand personnel like pilots. Because of the lack of competitors yet high number of related research projects which verify the concept, our product is well suited for use in a pilot program.

6 - References

Client: Rockwell Collins
Point of Contact: JR Spidell
Faculty Advisor: Dr. Akhilesh Tyagi

ECG Waveform Resources:

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2. ECG Library, a collection of real ECG recordings. https://ecglibrary.com/ecghome.php
3. Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov PCh, Mark RG, Mietus JE, Moody GB, Peng C-K, Stanley HE. PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals. 2000 (June 13). https://physionet.org/physiotools/software-index.shtml
4. Bharadwaj , Ajay, and Umanath Kamath. “Techniques for Accurate ECG Signal Processing.” EETimes, EE Times, 14 Feb. 2011, www.eetimes.com/document.asp?doc_id=1278571
5. N. Munla, M. Khalil, A. Shahin and A. Mourad, "Driver stress level detection using HRV analysis," *2015 International Conference on Advances in Biomedical Engineering (ICABME)*, Beirut, 2015, pp. 61-64. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7323251&isnumber=7323232
6. Castaldo R., Melillo P., Pecchia L. (2015) Acute Mental Stress Detection via Ultra-short term HRV Analysis. In: Jaffray D. (eds) World Congress on Medical Physics and Biomedical Engineering, June 7-12, 2015, Toronto, Canada. IFMBE Proceedings, vol 51. Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-319-19387-8_260

STM32 MCU Nucleo Microcontroller Resources:

1. STMicroelectronics, NUCLEO-F767ZI Description and technical documents. http://www.st.com/content/st_com/en/products/evaluation-tools/product-evaluation-tools/cu-eval-tools/stm32-mcu-eval-tools/stm32-mcu-nucleo/nucleo-f767zi.html
2. EMCraft, uClinux BSP provider. https://emcraft.com/index.php/products/413

7 - Appendices

7.1 - Operation Manual

Operation of this device is currently in a very low level state. Due to this it is recommended that the person following this manual be well versed in hardware interfacing and communicating with devices over SPI communication.

Setup

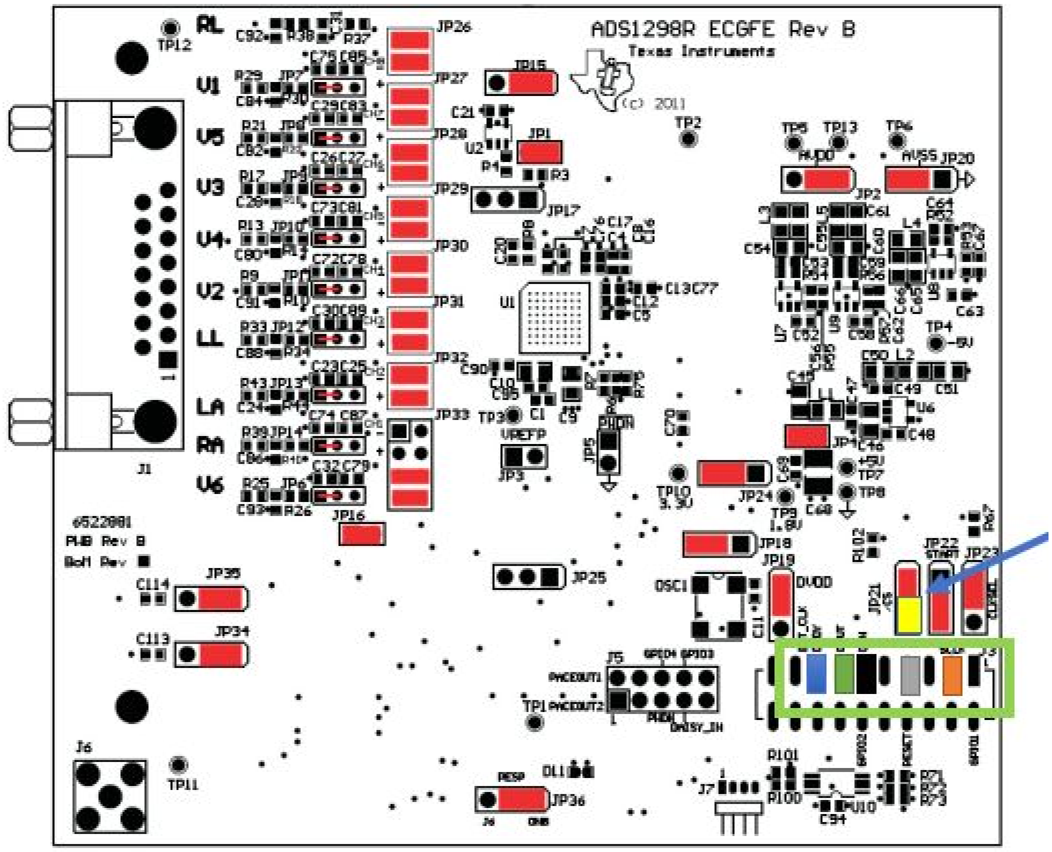


Figure 2. ADS1298RECG-FE Default Jumper Locations

1. Change the jumper configuration so that the CS jumper is in the yellow spot instead of the red spot. This needs to be changed so that the CS communicates with the microcontroller correctly.
2. When communicating over SPI there are 5 important wires the microcontroller will need to deal with. These wires are located in the Green box
    a. Blue – DRDY (Data Ready)
    b. Green - Dout
    c. Black - Din

    d. Gray - ~CS
    e. Orange – Sclk

Note: When connecting to the microcontroller the microcontroller serial pins could be named ‘MISO’ (Master in Slave out) and ‘MOSI’ (Master out Slave in). Therefore think of the ADC as the Slave so the MISO goes to the ADC’s Dout and the MOSI goes to the ADC’s Din.

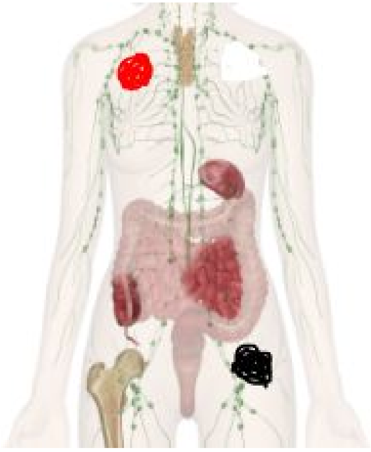
3. Powering the ADC by plugging wires from the power supplies on the microcontroller
    a. When the adc is on its back with the J1 connector pointed to the right
    b. There will be a 10 pin connector in the center that is used for powering. Connect as shown below:

Opt(Gnd)	Gnd
	Opt(1.8V)
5.0 V	3.3V

4. Plug leads into appropriate ports on ADC
    a. RA – Pin 9
    b. LA – Pin 10
    c. LL – Pin 11

Note: See ‘DataSheet ADS1298R - Demo_Kit’ page 62 for in depth block diagram of PCB

5. Connect leads to appropriate location on body.



    a. RA - Red
    b. LA - White
    c. LL - Black
6. Run “Read_ADC.c” on the microcontroller
    a. This will begin collecting the ECG data for the specific person connected
7. The peaks of the waveform are then compared and the time in milliseconds between each beat are calculated and input into the main algorithm.

7.2 - Alternative Versions

Earlier designs of the project had planned to use a separate hardware filter before the ADC, then a software filter before the detection algorithm. We found that the ADC had a built in system for filtering which met the needs of our hardware filter. As the project continued, we found that the software filter was both very difficult to implement and ultimately unnecessary if we used some kind of machine learning model for stress detection. The original intent of the software filter was to account for interference from muscle movements. By training the machine learning model on data that included the kind of expected muscle movements, there was no need to do filtering.

7.3 - Other Considerations

One interesting challenge in our project was the need for human testing with medical data. Human testing can be very difficult to get approved by the university, especially when it involves personal medical data. As a result, we were only allowed to conduct the stress tests on members of the team. With only six available participants, our detection model almost certainly has flaws and biases. For future development, it would be ideal to gather data from actual intended users - in this case US Navy pilots - in order to train the most accurate model.