

Introduction: When tackling the problem of real-time plotting and retention of ADC data, there is a host of instrumentation and software open and available for researchers. Each available third party product provides incredible depth and flexibility, making them all viable in the space of electrophysiology research. What is not present, however, is a product catered to a general purpose operational amplifier. Each product on the market, not to their fault, lacks the horizontal integration to cover the entire breadth of a general purpose OP AMP. However, while borrowing pieces of open source software, gaining inspiration from the backend of third-party products, and a host of original code, our team was able to create a product successfully bridging the gap between ADC data and a UI. To center the research and product planning, the design specifications and needs of the product were laid out as follows:

The product was designed around the process of electrophysiology research as it stands. Common practices, like data post-processing, real time peri-event oscilloscopes, and industry-standardized metadata files were all taken into account when designing the software. Research teams, in many cases, already have time-honored ways of conducting research, and the product couldn't interfere with that. To account for this, the design needed to have familiar file formats, easily usable UIs, and a product with the same features that researchers depend on. Additionally, the knobs and buttons on standard electrophysiology equipment needed to be mirrored as digital controls, giving researchers the adaptability they need to feel comfortable with a new product.

The product needed to comply with specific data rates. While working with high speed analog to digital converters, like the AD7961, data is coming in for processing and retention at such a high speed, that every single choke point had to be accounted for and pre-planned before the eventual deployment of the product. With many of the ADCs running at around 5MSPS at 18 bits, transfer speeds needed to exceed 10 MB/s, all while processing and saving data for post processing. With these speed specifications in mind, not only could hardware be selected, but also software that utilized burst reads in order for personal computers to have the power and reliability to replace more traditional methods of electrophysiology research.

The following sections will cover each product that the OP AMP took inspiration from, its relationship to the electrophysiology community, and how a portion or design feature was implemented into the product, followed by the eventual integration of these parts into a working whole.

pClamp: The pClamp 11 Software Suite by Molecular Devices is the current industry standard for electrophysiology experiments. The software suite includes three major products, including the Clampex Software, the Clampfit Software and the AxoScope software (Molecular

Devices LLC, 2016). Clampex Software is most relevant to the project, controlling data acquisition and real-time graphing. The software is used to measure any analog parameters passing through their own DigiData 1440a system, including measurements like end-plate currents, and fluorescence signals. From there, the data is graphed and saved as an Axon Binary File Format file (Molecular Devices LLC, 2013). Although most universal file reader packages can read ABF files, both the Clampex Software and pClamp Software give researchers the ability to read ABF files inside their own viewing window. Most importantly, the ABF files are useful for post-processing, and Clampex gives users the ability to pull ABF files straight from the viewer and use any third-party post-processing software that they want to use. Clampex includes countless other features, like high-speed mode, gap-free mode, etc. but it essentially works as a recording oscilloscope, and is recognized as the premier software in the electrophysiology community.

The pCLAMP suite was inspirational, but was too specific to their native catalog of hardware. While the OP AMP runs off a OpalKelly Xem7310 board for data transfers, the software hinges on using the DigitData 1440 system. Instead of using their software, aspects of the design became inspiration for the OP AMP. The data retention system was especially useful, and was the most influential in modelling the software after pCLAMP. The ability to save data into a hierarchical file format, both readable and useful for post processing, is exactly what researchers need. The project ended up using the HDF5 file format for post-processing and JSON for metadata, but the idea of using a binary encoded file format for post processing was directly adopted from pCLAMPs design. With a total of 4 ADCs, running at 5MSPS at 16/18 bit resolution, pCLAMPs file formatting and rapid read/write design was perfect for implementation into the project.

dPatch: The dPatch amplifier system by Sutter instruments is the leading design for patch clamp amplifiers. While most patch clamp amplifiers were designed over 20 years ago, the dPatch, designed through the 2010s, was able to capitalize on newer technologies like FPGA design and Arm Core processors. This allows the dPatch to run at 5 MHz sample rate at 22 bit resolution, which was unheard of until the advent of the dpatch (Sutter Instruments, 2018). To achieve this, dPatch Front Panel includes a trigger system, which is instrumental to reading data at high speeds. A temporary storage location, which could be as deep as 8MB or as shallow as 64 bits, is continuously filled with data from a pipe, and a “trigger” is set at a certain depth to output “filled” or “not filled.” This trigger tells the host computer when to read the buffer, instead of a continuous read. This can speed up the read rate, and make sure that the storage location is never full, and drop data.

Although the OP AMP is using a Xilinx FPGA to customize the hardware instead of the dPatch amplifier system, it uses triggers for a faster continuous read of the ADCs. The ADCs in the project, AD796Xs, deliver 5MSPS at 16-18 bits and push the host computer to its limits, especially when using multiple nodes (Analog Devices). To achieve the speeds needed, the ADC-host communication uses transfer lengths of 64kB per read, triggered by a “half-full FIFO”

signal. A FIFO, or First-in First-out, system holds data in buffers, which can be read by the host computer in larger chunks, increasing the transfer speed, and making sure each ADC output is read and collected. With the use of a OpalKelly 7310 board, the OP AMP was able to use OpalKelly's FrontPanel API, which gives robust communication between Verilog endpoints, and the Python terminal. Most importantly, the API gave a bridge between the verilog triggers and the host computer, allowing the team to focus on each respective portion of the product. Most importantly, having a direct wire between the half-full verilog output and a host-computer trigger gave the host computer the ability to read bursts of ADC data at the right intervals. Additionally, the FrontPanel API made metadata retention easier to develop and more accurate than relying on researcher input. With the API, when the FPGA is configured, Board ID, device version, etc. are pulled straight from the board and into the JSON file. Researchers, with metadata, can look at larger trends in the data without having to worry about any independent variables like device or device version. From the dPatch amplifier system, the hardware/software integration design helped to design the product, and compensate for disparities in transfer speed.

PyQt Package: The PyQt5 toolkit is one of the most powerful and popular cross-platform GUI libraries for Python. Created by RiverBank Computing, it contains a whole host of components, including their QtCore application settings, QtGui GUI software and their pyqtgraphing software, which borrows from Matplotlib as its workhorse (What Is PyQt?). Although other software packages like tkinter offer robust UI packages, the PyQt library was most useful due to its native graphing software. Other languages may be better for UI development, like JavaScript, but due to the intertwined nature of the FrontPanel Python API and the user inputs from the UI, the entire program needed to be written in Python, which limited graphing software options. Additionally, the PyQT package offers code flexibility, which allows the developer to design around the concept of Object Oriented design. This computer science concept gives the developer greater control over the creation and implementation of individual instances of "objects". Having each channel as a single "graphing object" helped to allocate channel addresses and downsampling factors for each individual ADC, and eventually gave the terminal commands better control over these attributes.

After choosing this package, the design was fairly straightforward. The UI centers around a single runnable python script, which allows the user to input the ADCs to graph, the downsampling factor for each channel, and the waveforms written to the SDRAM. From these user-defined values, the main script begins writing the waveforms to the SDRAM. This on-board memory allows the HDL to read waveforms without using another ADC, and gives the user complete control over the DAC output waveforms. Next, the script creates each channel and subsequent graphing window for each ADC channel. With addresses and downsampling factors tied to each channel, on each update of the plot, the PyQt graphing window updates with a less data-heavy version of the current channel, and saves the entire data set into an array. This array, when the filemaker is called, is turned into a binary-encoded format and used as the dataset for the HDF5 file.

Integration: The goal, when integrating a host of third party hardware and software into a coherent product, was to avoid “Frankensteining” parts together, and instead, create a hierarchical design for the project before writing a single line of code. In order to achieve this, the communication between Python scripts and HDL relied on Python dictionaries filled with key values. A Python dictionary allows you to pair key values, like hexadecimal addresses, with a key word instead of an index value. With the registers stored by name into their respective chip, the script was able to specify the chip, register and command all in one human-readable line of code. This helped to design across the entire repository all with a couple source files, containing the chips and register maps associated with the hardware. With this system, the team was able to work on each respective part of the project without worrying about memorizing chips and addresses to read/write to. Additionally, every integration obstacle between third party products would be more manageable in a semantically consistent environment.

The first major integration obstacle was the glaring disparity between the FPGA speed and the speed of the host computer. While working with AD796Xs, the host computer is sampling significantly faster than it could read, convert and update the plot. To account for this, FIFOs are used to hold data before being dumped into the host computer. The host computer is not necessarily limited by the amount of data it can read at one time, but instead bounded by the time between each reading. By reading the ADC pipe into a FIFO, 64 kbs deep, each reading of the pipe could be time effective. In the verilog code, where the FIFO is created and lives, a half-full signal, tied to the depth of the FIFO, tells the host computer when to take another snapshot of the staged data. If the FIFO filled before a read, data would be lost, and if it was read empty, reading from the FIFO would be wasteful.

The second major integration obstacle was the disparity between the speed of the ADC data coming into the host computer (accounted for in the first integration obstacle) and the speed of the PyQt graphing software. Although the PyQt graphing package updates significantly faster than Matplotlib, or other Python packages, it still cannot compete with AD796Xs or any other ADC. For playback and post-processing, downsampling anything going straight into the HDF5 file wasn't an option, but the RAM-heavy graphing software doesn't need every point to be shown. So, to account for this integration obstacle, a downsampling factor for each individual ADC was added into the researcher-inputted source file. When the researcher chooses any downsampling factor higher than 1, the amount of data sent to the PyQt widget is trimmed into a smaller set, while still representative of the original set. This allows the host computer to allocate more RAM to data retention, while still giving a human-readable graphing window centered around general trends, rather than showing every individual data point.