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Development of software for performing acoustic time reversal with multiple inputs and outputs

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At Brigham Young University, acoustic time reversal experiments are conducted in solids and fluid media. The experimental setup involves synchronized generation and acquisition hardware. The synchronized hardware allows for multi-channel generation, and in some cases, multi-channel acquisition of time reversal focusing. A LabVIEW application has been compiled to increase ease of use and repeatability for the students conducting experiments. Forward and backward steps of time reversal are conducted through this simple user interface. The software is also able to control a 2D positioning system that allows for the measurement of the spatial extent of a time reversal focus. Modifications to traditional time reversal processing, such as inverse filtering and one-bit processing, may be easily implemented in the software. This paper describes the hardware and software that facilitates time reversal research.

1. INTRODUCTION

Time reversal (TR) is a signal processing technique for focusing waves.^{1,2,3} It was originally performed by broadcasting an impulse and recording the response at another point⁴ called the forward step. Broadcasting the response from either the source or receiver would produce a focus of waves at the other point, called the backward step. The amplitude of TR focusing increases and the amplitude of sidelobes decreases with additional sources used in the TR process due to the additional modes that can contribute to the focusing.⁵ Similarly, TR focal amplitude benefits from reflections which can be seen as additional sources of converging waves.^{6,7} Using a chirp instead of an impulse response has been shown to improve the signal-to-noise ratio for the simple reason that more power can be put into the system at each frequency during a long sweep rather than a short impulse.^{8,9} When using a chirp signal during the forward step, the impulse response is obtained through a cross-correlation rather than a simple temporal inversion.

Using additional sources necessitates obtaining the impulse response from each source at the receiver location. The signal responses must be obtained sequentially, and time synchronized. The synchronization is essential because each source is going to attempt to create a focus and if the separate focusing events are not synchronized then the temporal and spatial resolution of the focus will be degraded. Synchronization can be achieved by enforcing simultaneous sampling from the source and receiver or by knowing the delay between the start times of the source and receiver recordings.

The purpose of this paper is to describe the challenges and solutions for creating a synchronized MIMO (multiple-input, multiple-output) system. This paper also lays out some of the capabilities that enable several TR processing methods, filtering of results, and spatial scans of the pressure field. Conducting TR experiments requires the necessary hardware as well as an intuitive software solution for the many students that will be using the system. This paper describes the hardware configuration used at Brigham Young University as well as the considerations and software solutions used in the program.

The original interface was inspired by software designed by T.J. Ulrich and Pierre-Yves Le Bas of Los Alamos National Laboratory who each developed software for similar purposes.

2. HARDWARE

The hardware setup used at Brigham Young University for TR research is a set of three Spectrum Instrumentation PCIe cards synchronized by a Star-Hub add-on module. The Star-Hub mounts directly to one of the cards and distributes the host card's clock to all the synchronized cards (including the host card). Two M2i.6022-exp arbitrary waveform generation (AWG) cards, each with 4 channels are hardware synchronized to a single M2i.4931-exp digitizer card. The Star-Hub distributes a sampling clock to all the cards in the system with minimal phase delay, enforcing the desired output-input synchronization.

To conduct 2D scans of the signal/focus response, two Applied Motion Products STAC 6i controllers are each connected to an Applied Motion Products HT23-550D stepper motor. Each motor controls the axis of a custom Macron Dynamics Inc. translation stage (see Fig. 1). This translation stage allows for 4 m² of scanning area with sub-millimeter precision. The frame can be assembled standing up or lying flat for measuring in a vertical or horizontal plane, respectively. Typically used by acoustics classes at Brigham Young University, this scanning system has been used in other research.^{10,11,12}

Also at Brigham Young University, impulse response measurements are made in a water tank with a similar hardware configuration but with a derivative software interface.¹³

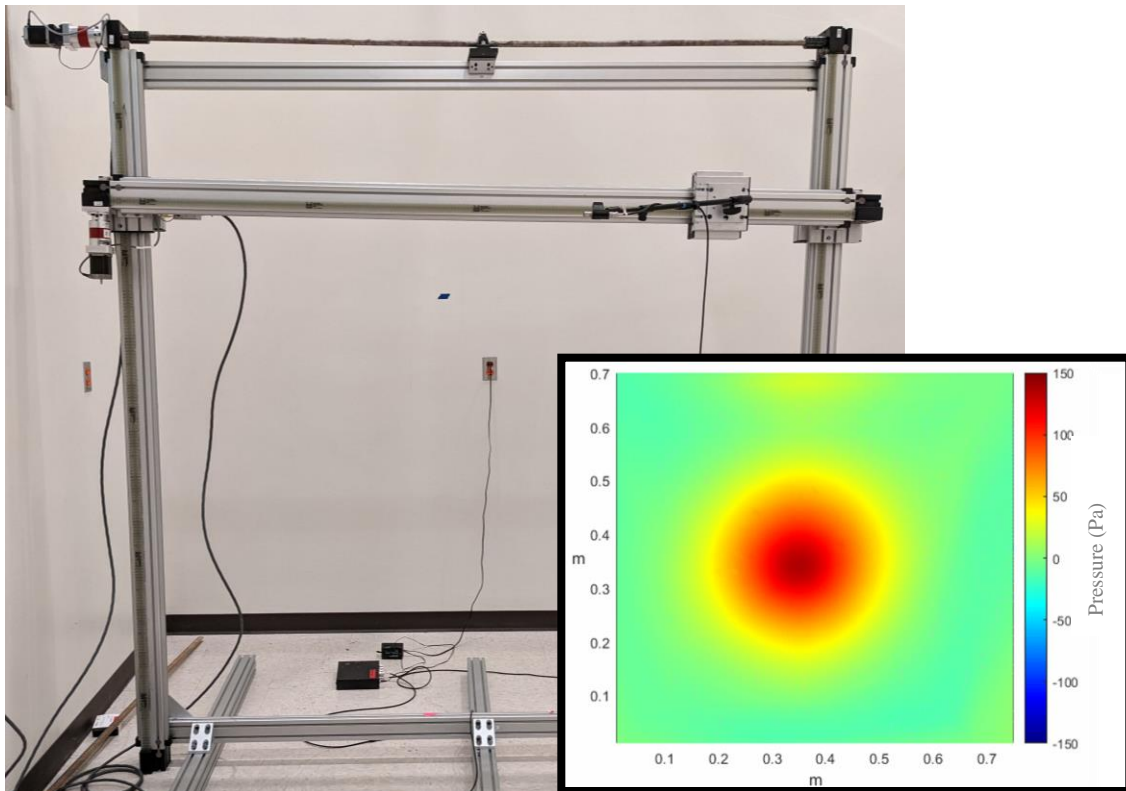


Figure 1. The Macron Dynamics Inc. translation stage used at Brigham Young University. The y-axis motor is horizontal at the top left. The crossbar is raised and lowered by the y-axis motor using the belts on the left and right connected by the rod at the top. The x-axis motor is on the left and controls the translation stage along the crossbar. Inset: An example result of a spatial scan of a focus obtained using TR.

3. SOFTWARE

Considering the hardware came from multiple manufacturers, LabVIEW was chosen as the most convenient programming language capable of interfacing with the internal and external hardware. With the goal of making a simple interface with the Spectrum cards, the software was named Easy Spectrum Time Reversal (ESTR). As shown in Fig. 2, the main function (termed Virtual Instrument or VI) serves as the hub for interface and commands but presents the user with access to the input/output subVIs or subfunctions. These subVIs generate, capture, and store the data that is used in ESTR. When initializing, the main VI and these subVI's (including the Motion VI) exchange references to their action queues so they can communicate in real-time.

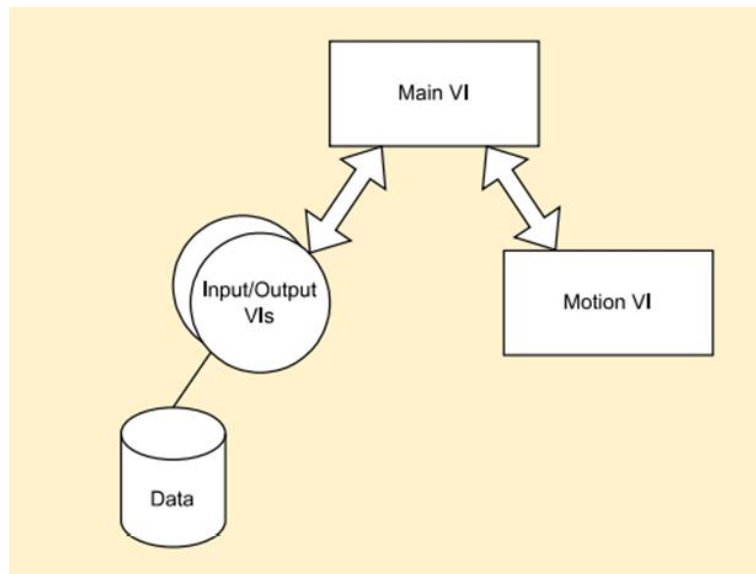


Figure 2. The hierarchy of ESTR is shown. The Main VI handles communication and operations between the subVI's as well as TR calculations. The subVI's for input and output handle the data and the subVI for motion control interfaces with the translation stage.

When ESTR starts, an initialization routine is run to discover the number of cards currently connected to the computer. Sets of controls are then made visible on the front panel for each card that was discovered. The user interface of ESTR consists of two copies of output/input displays (see Fig. 3). The set on the left is for the forward step of the TR process, i.e., for broadcasting the output signal sequentially and recording the signal responses from the single output to the enabled inputs. The set on the right is for the backward step of the TR process, i.e., for simultaneous broadcasting of all enabled output channels and recorded by all enabled input channels. Controls at the top of ESTR start the forward or backward steps. These options allow for averaging measurements as well as inserting a delay so that any reverberating sound remaining in the system can decay before the next recording starts.

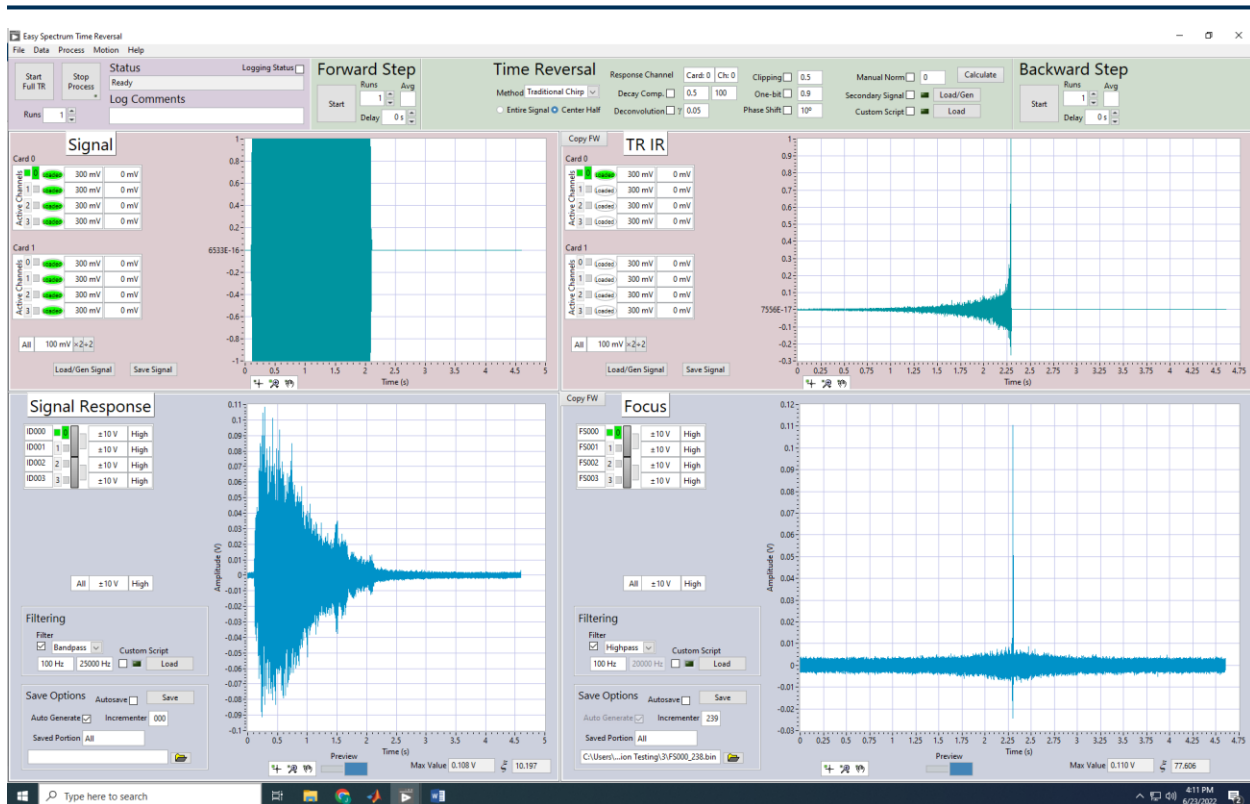


Figure 3. The main ESTR user interface is shown with the four panels labelled “Signal”, “Signal Response”, “TR IR”, and “Focus”. ESTR is currently showing controls for 2 output cards and 1 input card. Each card is equipped with 4 channels. The experiment shown used a chirp from a single channel to generate the focus seen in the bottom right.

Each of these pink and blue colored panes is run as an asynchronous VI that holds its own set of data. This data is an object containing the canonical data as well as metadata about the origin of the data (see Fig. 4). The data object is passed to the main VI when saving so that the metadata from all the steps can be brought together and saved in a corresponding log file. The dataset object (as well as the data contained in the object) are passed by reference within LabVIEW. The dataset object can contain up to three copies of the data with associated metadata as well as waveform objects for graphing. The first copy of the data is called the canonical copy and serves as the most reliable set of data. It is referenced and copied but never edited. The second copy is used when the user applies a filter. A copy of the canonical is made and the filter is applied to the copy. Lastly, the spectral data is the Fourier transform of the canonical data and is calculated once if the user changes the graph to view the spectrum.

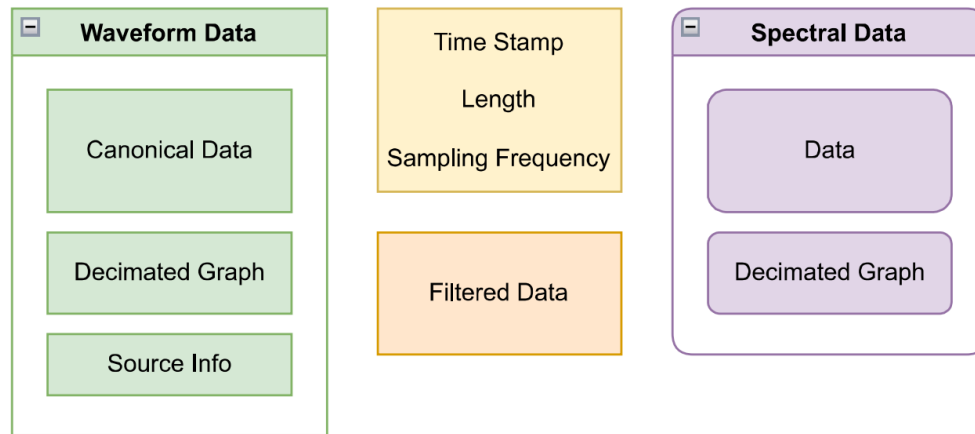


Figure 4. A schematic of the data object passed between the subVI's that make up the output/input and the main ESTR vi that processes and saves the data. Three copies of the data are shown with a canonical, filtered, and spectral datasets.

The user begins by generating a signal within ESTR or loading a data file to be used as the signal. Importing a signal starts when the user selects “Load/Gen Signal” button, and a new VI launches with signal generation options (shown in Fig. 5). The user selects the channels to load with data and then to whether to generate or import the data. The generation allows for a linear or logarithmic chirp, or a gaussian-modified sinusoidal pulse. The data is made of a signal portion with leading and trailing portions (zeros) with no signal. The trailing portion is for capturing the full impulse response ring down after the signal has finished playing. The leading portion allows verification that any reverberation from a previous broadcast has died down to the background noise before the next broadcast begins.

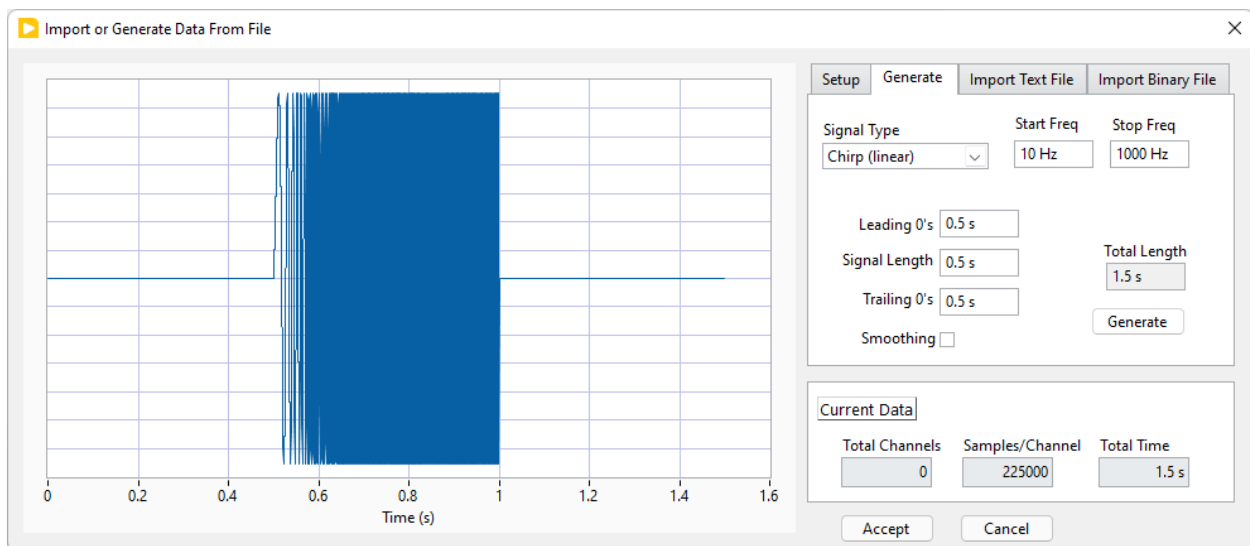


FIG. 5. The window for the subVI that handles importing or generating signals. The user selects the target channels and sampling rate, then the user can either import or generate a signal. Shown is a linear chirp signal from 10-1000 Hz without smoothing. If the user accepts the signal, then it is transferred to the output subVI.

After generating or importing data, the waveform is shown in the signal graph in the top left. The forward step can then be performed, and the signal response recorded (the recorded signal has the exact same time duration as the broadcast signal). After this forward step, ESTR can calculate the time-reversed impulse response (TRIR) using the signal and its response. Methods for calculating the TRIR are contained in a pane at the top of ESTR. This pane is shown in Fig. 6. The user can choose any set of options, including

combinations of options, and the TRIR(s) is(are) immediately calculated and displayed. This immediate feedback is helpful when enabling methods that use a threshold to distinguish between the parts of the signal to amplify or reject as noise. The order of the options in the Time Reversal pane is also the order that the calculation is performed. Finally, the TRIR(s) are normalized to maximize the available gain. Several of these options for calculating the TRIR are the result of published methods. The options include:

1. Response Channel. Although multiple input channels can be enabled, one of them must be chosen as the response channel when calculating the TRIR. The other enabled input channels are not used for the TR process but may have other uses.
2. Method. This option dictates whether the response is assumed to be the impulse response (e.g., when a pulse signal is played), in which case the TRIR is just the time-reversed response, or whether to perform a cross-correlation to obtain the TRIR from the signal (e.g., a chirp signal) and its response.
3. Entire Signal/Center Half. After the cross-correlation is performed, the resulting TRIR is twice the length of the signal. The beginning and ending of this cross-correlation are often near the noise floor. This option allows the user to only use a TRIR that is the same length of the signal and is taken from the center half of the TRIR (deleting the first and last quarters of the signal).
4. Decay Compensation.^{14,15,16} Using an envelope of the decay of the TR, the decay is removed to allow the maximum amplitude of the TRIR. A larger amplitude is obtained than when simply reversing the impulse response and this method has been shown to introduce less harmonic frequency content into the TRIR signals than the clipping and one-bit techniques introduce.
5. Deconvolution.^{17,18,19,20} As a modification of the IR, the deconvolution, or inverse filtering method compensates for frequencies with low amplitude in the IR by inverting the spectrum. When performing the inversion, frequencies outside of the signal bandwidth, or frequencies with a response below the noise floor, may be inverted to become very large. A modification to the deconvolution method places a constant bias in the denominator and stabilizes (regularizes) the deconvolution function, giving an upper bound to the output.
6. Clipping.^{21,15,16} Clipping changes the maximum value to a fraction of the normalized TRIR. Samples with a magnitude greater than the threshold are placed at the threshold and the TRIR is normalized again.
7. One-bit.²² Similar to clipping, the one-bit method uses a threshold and samples with a magnitude exceeding the threshold are placed at the threshold. Samples below the threshold are placed at zero. The TRIR is then normalized again.
8. Phase shift.²³ This allows for arbitrary phase shift added to all frequencies to manipulate the focus (e.g., to change the TRIR to focus the derivative of the response).
9. Secondary Signal. This is used for convolving a secondary signal with the TRIR prior to the broadcast of the backward step. In this way the impulsive focus can instead be a focus of the secondary signal (to communicate or deliver a desired signal).
10. Custom Script. This option allows the user to load a MATLAB script to manipulate the data in a way not already available in ESTR to truly create an arbitrary waveform.

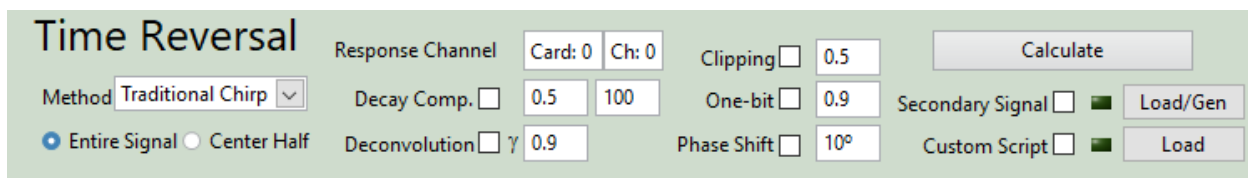


Figure 6. Options for calculating the time-reversed impulse response. Although changing any option immediately calculates the TRIR, the “Calculate” button allows using the default settings.

The filtering and save options for the forward or backward steps are located at the bottom of the input windows. This pane is shown in Fig. 7. The filtering is done with a zero-phase, 1st-order, Butterworth filter so that the timing of the waves is not affected. Because the canonical data is preserved, the filtering can be

turned on and off and the user can immediately see the results. The user can also load a MATLAB script to perform custom filtering. The save options include autogenerating filenames. The filenames consist of the channel name and an incrementor. To prevent accidental deletions, no overwriting is allowed.

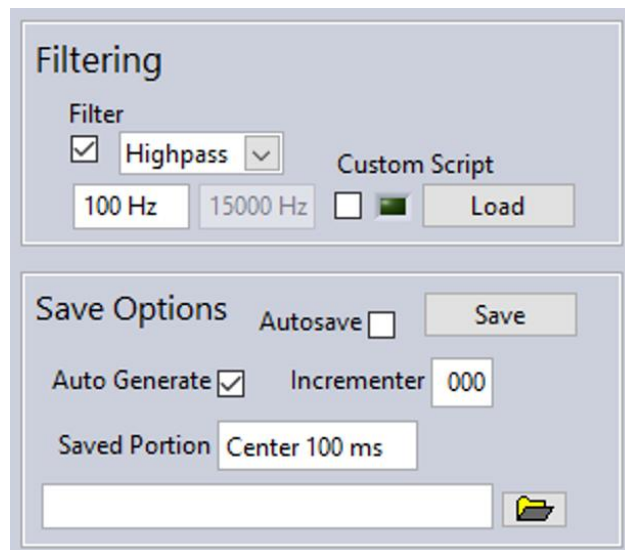


Figure 7. Options for filtering and saving the recorded data. These requests are handled by the input subVI.

4. MEMORY MANAGEMENT

The Spectrum cards have a maximum sampling frequency of 30 MHz. Utilizing the high sampling frequencies must include memory management considerations. Typically, LabVIEW performs its own memory management and garbage collection but in the case of large data sets (256 MB/channel) several tools are available and utilized in ESTR.

The first tool is passing by reference instead of by value. The data objects that are associated with each channel, are stored as a LabVIEW Data Value Reference. Within the object, the canonical and filtered data are each stored by reference. The output/input VIs must individually destroy the reference when the data is discarded, but this hierarchy is natural, and all data storage is left to the individual output/input VIs. In this way, the data is not duplicated while being viewed by the separate VIs performing calculations or saving. The memory requirements have been brought down to consist almost entirely of the data stored in the data object.

Another tool is when the data is first loaded into ESTR, the LabVIEW graph object is generated so that it can be called with minimal delay and without reproductions of the waveform object. In addition, the waveform objects are decimated when the data has many more points than the screen has pixels. In ESTR, the plots are limited to one million points. If the signal consists of more than one million points, the data is separated into 500,000 bins and the minimum and maximum of each bin stored in a new waveform object. If this decimation is performed, a warning label is made visible on the graph that informs the user that zooming in on the data will show inaccurate information.

Lastly, to save on time and memory requirements, the cards are not reloaded with the same data that has already been loaded. The Spectrum cards allow for playing the same signal several times without loading the waveform again. Because many TR experiments involve averaging or repeating the same signal, this saving of memory is also a time savings. To determine if new data needs to be loaded to the cards, the timestamp information from the loaded dataset is compared to the timestamp of the new dataset. If the timestamps are the same, then the data is not loaded to the cards and the previously loaded data is used instead. This simple comparison has found to be successful and sometimes necessary to reduce the time for some of the longer spatial scans. For a different system with a higher bus speed, this step will not save as much time.

5. MOTION CONTROL

ESTR uses a subVI for performing spatial scans (see Fig. 8). Initialization of the subVI starts an optional homing routine that moves the translation stage to trigger a magnetic proximity switch in both axes. After this routine the positions entered by the user are consistent between experiments. Several combinations can be performed which include performing a fully new TR experiment at each point, conducting the forward step at one point and the backward step at all points, or to perform just the forward or backward step at each position.

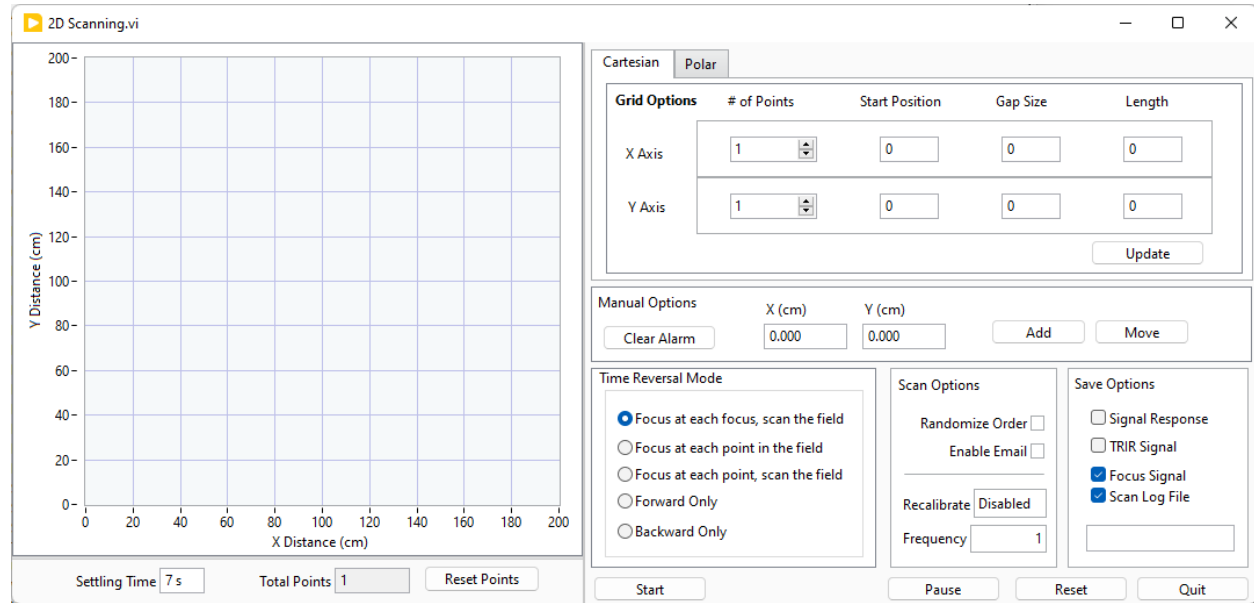


Figure 8. The 2D scanning subVI with the graph of points on the left and the grid and scan options on the right. The scanning system can also be moved to manual points by entering the X- and Y-coordinates or by clicking on the graph and then the move button.

The grid can be generated with regular spacing in each dimensions using rectangular or polar spacing. After generating a grid of points, the user can right-click a single point and designate it as the focal position. Currently the movement between points is a spiral originating at the focus and moving outward. This spiral progression allows for the highest accuracy in the measurement of the focal event, including the measurement at the focal location and the nearby surrounding locations, since temperature or other conditions may slightly change over time. If there is no focal position specified, the next position is just the one closest to the current position. Moving between the points can also be randomized which greatly increases the time to scan but ensures that temporal artifacts (e.g., a brief temperature fluctuation or a brief change in background noise) do not become spatial artifacts. Rastering options are being added as well as an option to do line scans.

Like the delay between successive recordings in ESTR, a settling time allows for the noise generated by the motors, (as well as vibration of the microphone arm), to decay after each movement of the positioning system.

6. CONCLUSION

This paper has described the hardware configuration for the TR MIMO system used at Brigham Young University. The 2D scanning system has also been described. The user interface for performing TR measurements and calculation along with the control of the 2D scanning system has been shown. Various TR processing techniques can be implemented, along with allowing for custom signal processing. Some of the considerations for data integrity and memory management have been describe and the architecture has

been outlined. Development continues on ESTR, but this paper provides insights into the core construction of the software.

Since its beginnings several years ago, ESTR has gained many capabilities and has proven to be an essential part of the experimental TR work being performed at Brigham Young University. Although the students come and go, ESTR continues to gain features thanks to the next generation of students. Focusing on data integrity, repeatability, and ease of use, ESTR allows new student researchers to start making meaningful measurements with little training overhead.

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