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ACOUSTIC DETECTION AND LOCALIZATION OF IMPULSIVE EVENTS IN URBAN ENVIRONMENTS

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C h a p t e r 1

PROBLEM STATEMENT

A sound source can be localized by the human ear to varying degrees of accuracy given optimal circumstances; such as close proximity to the source such as to minimize the effects of attenuation, minimal interference by echoes and reverberations, and negligible distortions due to diffraction around buildings and structures. Conditions that cause erroneous localization of such a source all too common, being especially present in urban environments. The challenge is thus; accurately localizing the source which involves detecting the sound using an array of microphones, identifying the sound to eliminate 'intruder' signals, and processing the resulting multiple signals to eliminate the effects of reverberations, distortions and interference. All of this is specifically in the context of urban environment that exhibit reverberations.

The system will work like this; a sound signal generated by a gun will propagate and be detected by a microphone array in a known geometry (a tetrahedron in our case). The signals outputted by the microphones will be sampled and acquired by the National Instruments Compact Reconfigurable Input-Out system. The data is then either stored on a computer for offline algorithmic processing for sound identification, or in real-time for the localization of source. Figure 1 is a block diagram summarizing this system

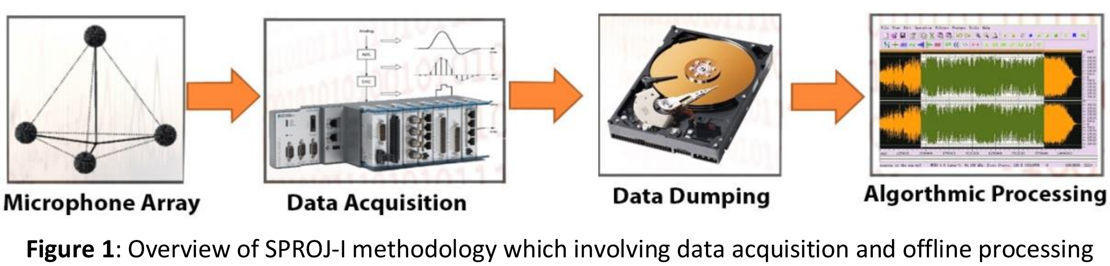


Figure 1: Overview of SPROJ-I methodology which involving data acquisition and offline processing

The overall goals for this SPROJ were as follows;

- The building and testing of a reliable high-speed acquisition system that fulfills Nyquists' criterion (to at-least 5 times the minimum limit, as per normal engineering conventions) and does it simultaneously over multiple channels. This meant implementing a system that operated at a sampling frequency of 100KHz (to cover the entire acoustic range) and did so without the synchronization problems that multiplexed ADCs cause. The system would then either dump this acquired data onto a computer for later processing or would perform computations on these signals in real time.
- The identification of appropriate 'impulsive' (sudden) events that most closely resemble the sound signature of a gunshot. This involves testing different methods, materials and techniques of attempting to generate gunshots without actually firing guns.
- The collection of experimental data via recordings in different locations of these impulsive events and the construction of a database of clean, echoic and reverberated signals.
- The implementation of correlation algorithms that perform signal and statistical analysis on the database of signals and determines the degree to which reverberations affect signal characteristics.
- The implementation of angle-of-arrival calculations that localize a source by computing certain loci from known microphone array geometries. This system would then control a motorized 'Rig' (turret) that would then turn towards the source and shoot it.

These goals are summarized in the block diagram in Figure 2 on the next page.

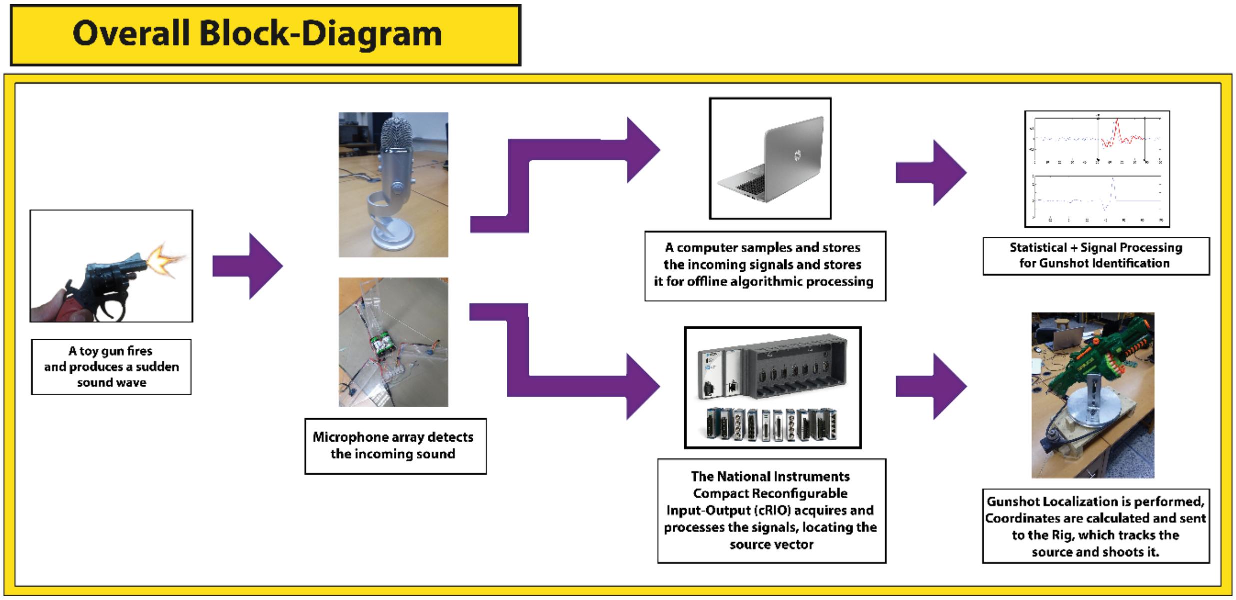


Figure 2: Chronological block diagram of the project implementation

Chapter 2

BACK GROUND AND RELATED WORK

2.1: PROJECT OVERVIEW

Our project is a complementary effort to projects done previously on the issue. A paper written by Talal Ahmed and Professor M.Uppal [1] details theoretical work on reducing the false positive detection statistics of sounds with specific signatures by using Linear Predictive Coefficients and a Cross-Correlation algorithm. The issue with this is that the false positive rates, when using these algorithms, increase when experiments are conducted in an urban environment in which sound waves (including both the shot and background noise) reverberate off walls, diffract around buildings, and interfere with the detected signals. To solve this, Abdullah Asghar, a masters student at the department, is working to develop de-reverberation algorithms to extract the original signals from a detected gunshot sound [2]. The goal in this project was to develop and provide an experimental setup such as to test the efficacy of this theoretical work; a block diagram of the overall project and its progression is given in Figure 3.

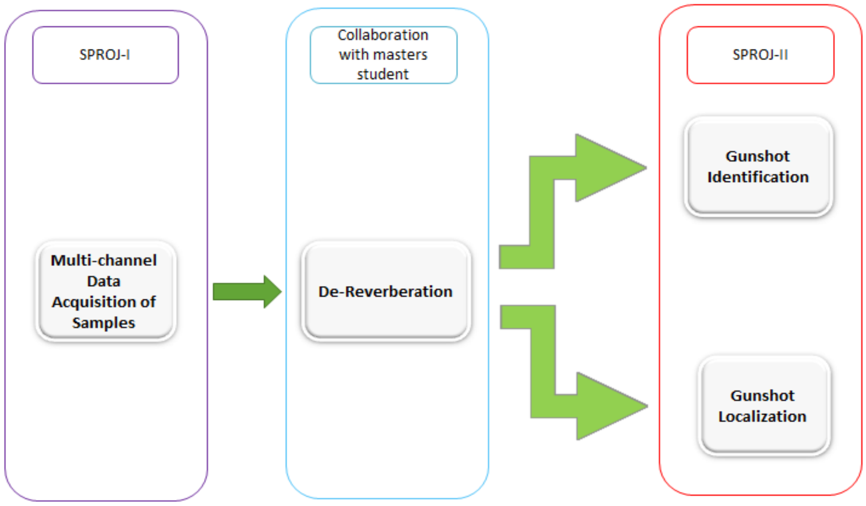


Figure 3: Block diagram of project aspects over the two senior project phases

Such a project has been implemented privately in San Francisco and is called the Shotspotter; it's primary purpose is in aiding law enforcement agencies battle crime. This shows that such a system has potential use. Yet after the same system was installed in London, it was abandoned after two years due to problems in inaccuracy [3][4]. This indicates that further research work is possible and an active area of interest, and as such, justifies the focus of this project.

2.1.1: THE CHALLENGES

The problem is simple; the focus of this project will be on building a system that accurately detects, identifies and localizes a gunshot originating from unknown sources specifically in an urban environment that exhibits echoes and reverberations. Both phenomena are basically repeats of a single acoustic wave-front that is detected again and again as they bounce off structures such as buildings and hills as shown in Figure 4. The difference is in circumstance; echoes do not interfere with the original wave-front and are detected only after the original has been detected in full. Thus the effects of echoes are not difficult to eliminate. Reverberations on the other hand, do interfere and cause a changing of the fundamental shape and characteristic of the signal. This project will have a focus primarily on identification and localization in environments that exhibit reverberations. An attempt was made to achieve the de-reverberation via the Blind System Identification and Input-Subspace methods. Unfortunately this was not feasible.

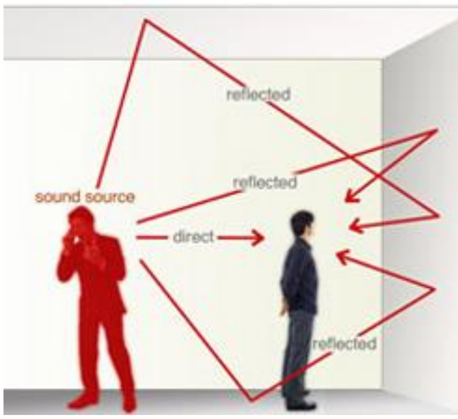


Figure 4: Acoustic effects present in urban environments [6].

Chapter 3

DESIGN METHODOLOGY AND TOOLS

3.1: DESIGN CHOICE FOR TOOLS AND APPRATUS USED IN IMPLMENTATION

3.1.1: Design Choices for microphones and the array

The microphones that were considered for the purposes of detecting the sound were of various types. Laptop built-in microphones were used initially for data collection until they were replaced by external microphones, primarily due to the need of isolating the microphones from reverberation inducing surfaces (such as a laptop's flat screen). Of the external mics, the first type was of low-cost apparatus of simple design that was available freely and cheaply. There were two of these; microphones made in a previous SPROJ and those ordered online from Adafruit by Professor Uppal that had Automatic Gain Control implemented on-circuit. Of these we selected the AGC microphones primarily due to their sensitive and quick response as well as good gain profile. The second type of microphone was of a much higher quality. These were studio apparatus by Audio-Technica and Blue (the AT2020USB and Yeti microphones, respectively) that were lent to us by Professor Zartash for the purposes of the project. The array structure we used one that was constructed earlier (than the SPROJ).

3.1.2: Design Choices for the controller

Such an implementation requires hardware quick enough to fulfill certain mathematical and engineering criterion (such as Nyquist's) essential for the ensuring of quick, reliable and efficient performance.

The National Instrument's cRIO [5], (compact Reconfigurable Input-Output), the STM32F4 discovery board (by STMicroelectronics), PC sound cards, or other equivalent hardware. It was preferable to use off-the-shelf components rather than making our own as then we would have to keep many other factors in mind, such as circuit characteristics and local component availability and capability. We went with NI primarily because of its ready availability in the department, modularity and powerful processing.

The STM32 was initially the preferred choice of hardware; portable and with low power-consumption. Its biggest flaw is its small memory which forces us to truncate a lot of the detected signals (especially since the sampling needs to be preferably simultaneous over at-least 4 channels), cutting out everything except for the first main peak of the detected signal. It is this flaw that led us to consider other options.

Next is the NI hardware (Figure 5); namely the cRIO. The Compact RIO has an inbuilt FPGA that is capable of multi-channel high speed sampling (100 Kilo-Samples per second for each of the four channels). Its Ethernet interface enables fast communication with a PC; dumping detected signals on hard disk for offline processing or processing them actively, as the need arises. Its modular nature and diverse programming potential make it extremely useful for prototyping hardware for research efforts such as this one.

Last in the ranking are PC sound cards and other hardware that may be available. Computer soundcards provide good sampling for acoustic signals but do so over only one channel. Cards that do provide multi-channel capabilities are developed and used by sound studios and are very expensive, thus cutting out their usage here. Along the same line, hardware that already achieves this (such as the TEAC GX1) is also very expensive.

3.1.3: Final selection choice of the controller

Thus the hardware to use was the NI hardware, considering all of our limitations and preferences of low-power consumption, portability, processing speed and memory, and the requirement that the components preferably be off-the-shelf, so as to eliminate worries

worries about parasitic inductances and capacitances in circuits we design, when we operate them at high frequencies. Dealing with NI's equipment also meant operating their hardware through the LABVIEW graphical programming language and interfacing it with the cRIO to obtain signals, process them, store them or control output motors. These are divided up into two or three stages;

Figure 5: NI cRIO and 9215E module used in this project

Acquisition, Identification and Localization. In this chapter, we will detail the acquisition aspect of LABVIEW control. The others will be presented later.

3.2: THE ACQUISITION PHASE

The initial LABVIEW circuit designed was too inefficient; as tested, the microphone response and hardware characteristics were not the source of the frequency change exhibited by the circuit.

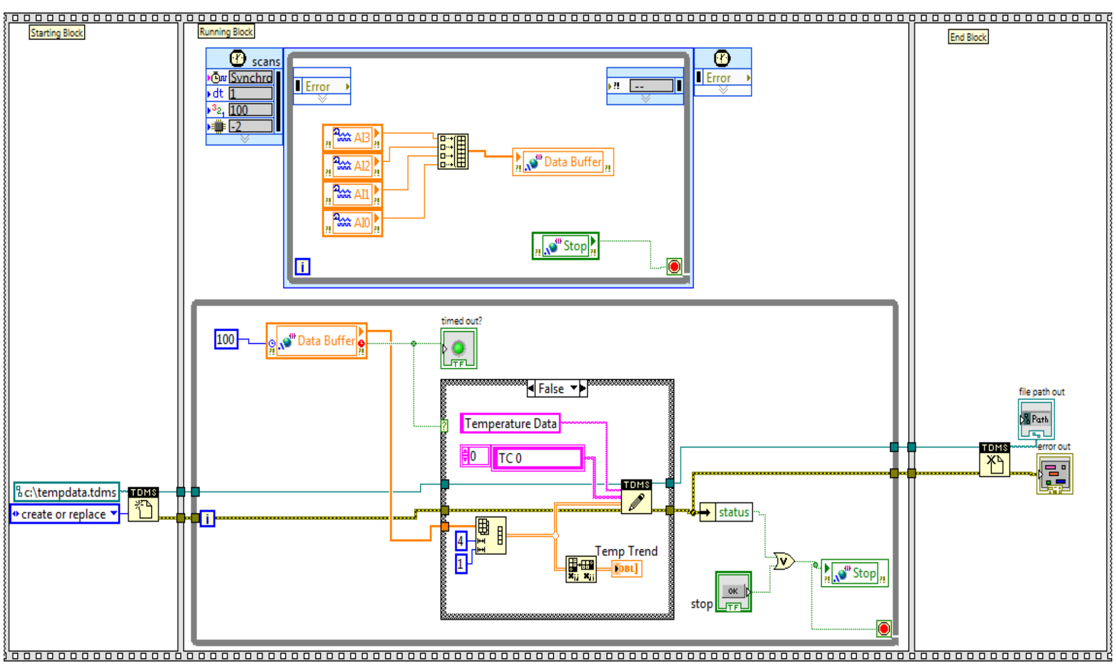


Figure 6: Producer-consumer method implemented with the scan engine interface

This led us to conclude that the choice of implementation had to be changed. The second circuit followed the (in NI's terminology) 'producer-consumer' method. The 'Producer-Consumer' implementation creates a 'buffer', or array that the RIO stores samples on. After regular intervals the RIO bulk exports this buffer to the host computer as a TDMS file (LABVIEW's own optimized file format for data acquisition) that gets written onto the hard-disk. The difference with the initial design is that the process of sampling, exporting, creating the TDMS file, and writing to hard-disk as an excel file is not carried out for each and every sample.

The circuit implemented is shown in the Figure 6.

This eliminated the problem of frequency change entirely. Immediately another issue arose; the frequencies for which this system worked and produced good results were limited to within 500Hz (1 KHz sampling rate) due to LABVIEW's Scan Engine interface. This forced us to implement the system on the FPGA that operates correctly with much higher input signal frequencies.

3.2.1 The FPGA implementation

The RIO's design is modular in nature. Parts of programs can be executed on different processors as per requirement; namely the FPGA processor, the RIO's own micro-controller and

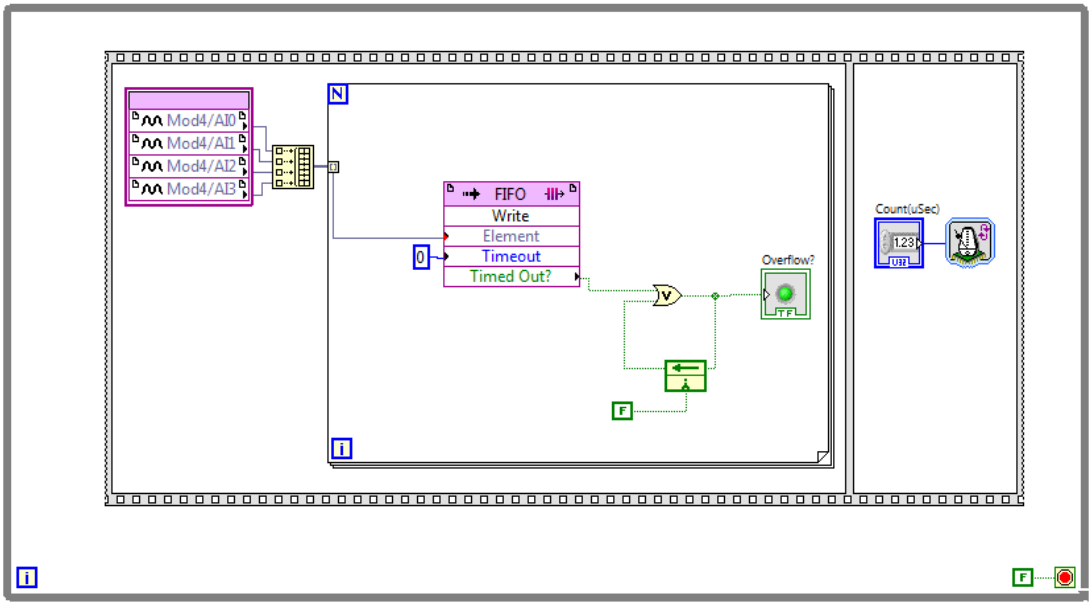


Figure 7: FPGA VI that interfaces with the RIO RT host controller

the host computer. The FGPA circuit that creates a FIFO and stores samples of the detected signal is shown in Figure 7.

This FIFO is the buffer that stores samples that are later read by the RIO's controller and exported to the host computer for storage and processing. It is more efficient that the earlier implementation because this time the host computer and its interface with the RIO, which was the limiting agent in the whole 'reaction', are not called upon as often to store the sampled data on the computer.

The simple LABVIEW acquisition circuit is shown in Figure 8.

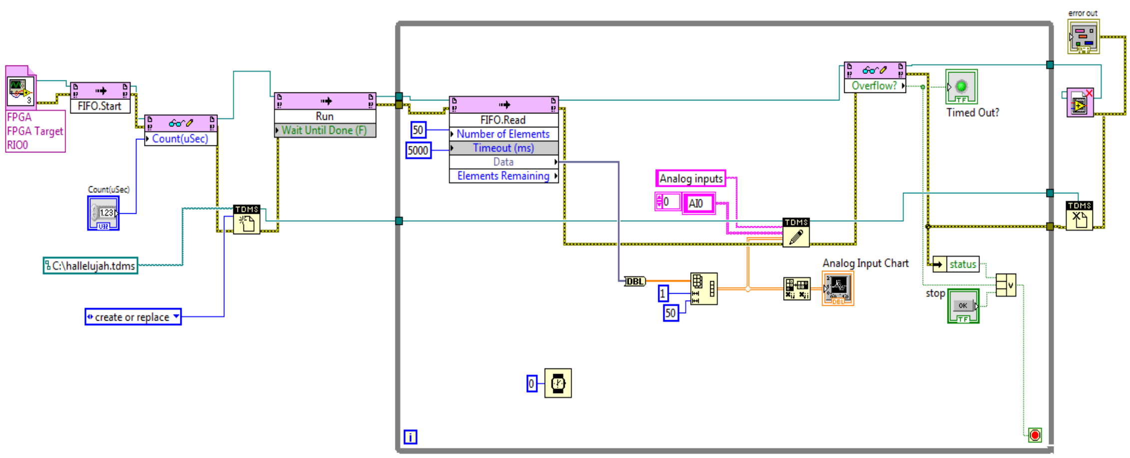


Figure 8: The early acquisition circuit obtained from a NI tutorial [7]

This circuit creates reads the FIFO created on the cRIO FPGA, creates a TDMS file and exports it to the host computer via an Ethernet interface wherein the host PC stores it on the disk for offline processing (conducted by MATLAB or LABVIEW itself depending upon ease of use and convenience).

This FPGA implementation operates in a much better manner than the previous ones. Figure 9 shows us capturing a higher frequency signal than before and for infinite windows (we can run the setup continuously. Here the signal captured corresponds to approximately a 100Hz frequency.

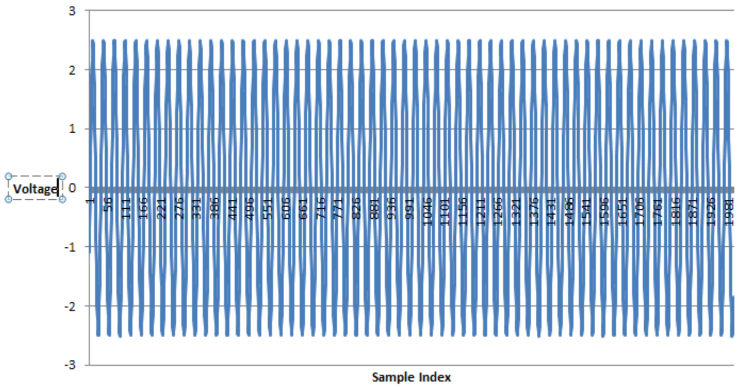


Figure 9: 100Hz signal acquired by earlier attempts to interface with the RIO

3.2.2 The Final Acquisition Circuit

Modifications to the design were made to accommodate higher signal frequencies by synchronizing the rate at which the FIFO is read by the RT host controller and the rate at which it is filled in by the FPGA. The final acquisition circuit, shown in Figure 10, was made with the help of Salman Azmat from National Instruments (an alumnus).

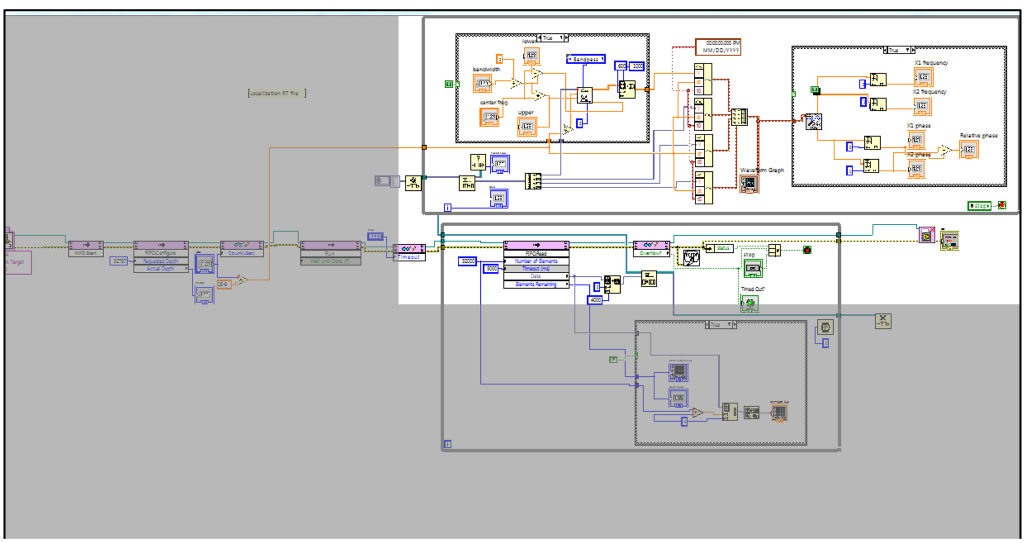


Figure 10: The displayed figure is the LABVIEW circuit that acquires signals and computes source angles

The displayed circuit runs the 9215E module at a 100KHz. As the implementation is simple; the 9215E acts as a simple circuit that returns a double-precision floating-point number when run. Thus the FPGA stores these numbers onto a FXP (fixed point representation) FIFO. The FIFO is then read by the host controller, emptying the FIFO of 32000 samples per loop iteration. These samples are stored in an array which is then decimated into 4 separate channels. These arrays are then built into waveforms by attaching sampling period information to them and synchronizing their indexes to a common time. The circuit then writes the waveforms onto a TDMS file. This completed the acquisition setup needed to record information from a microphone array and store the signals onto the RT controller's non-volatile memory for later offline processing. The results of the circuit are shown in Figure 11 where input signals are applied at 20KHz and RIO acquires them. At a 100KS/s sampling rate, a 20KHz periodic signal should have a discretization of 5 samples per period (white signal) and this is exactly what we observe.

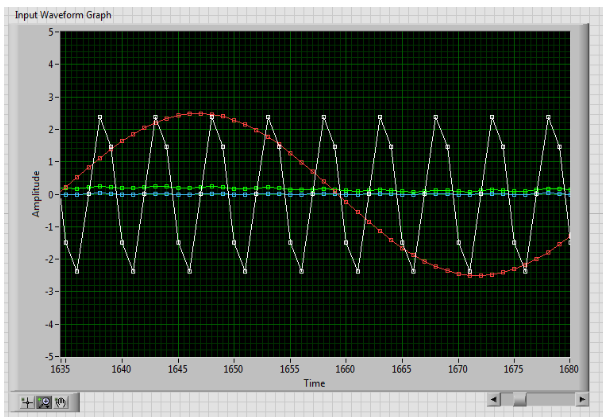


Figure 11: 20KHz acquired Signal

Thus having been successful in acquiring high-frequency, multi-channel inputs the next steps are;

- Identifying an 'impulsive' (sudden) event that closely resembles (offers a good approximation to) the signal we desire (a gunshot|).
- Building a database of such signals in environments which are both clean and reverberation-inducing. This involves collecting lots of recordings in different locations and performing statistical analysis on them.
- Performing correlations on the reverberatory signals with respect to a clean template signal that is the closest approximation to a gunshot and analyzing how reverberations introduce greater error-rates on detection and identification. These parts are part of the Gunshot Identification part of the project.
- Building a system that acquires the signals and tracks them.

C h a p t e r 4

DESIGN AND IMPLEMENTATION: RESULTS AND APPLICATION

So far we have discussed the design of a system that acquires signals. With that completed the obvious next step is to use such a system to acquire signals and then process them in different ways. Thus were we will delineate the next two steps of the project; Gunshot Identification and Gunshot Localization.

4.1: GUNSHOT IDENTIFICATION

Sound Identification involves attempting to acquire sound signals and determining whether if the detected signal is the desired one or not i.e. a gunshot. How this is achieved is by correlating the detected sounds with a pre-ordained gunshot 'signature' and finding out which signal possesses the desired characteristics and hence, is a gunshot. This method, of course, is not limited to gunshot identification and has a broader application range.

To the end of performing correlation on sampled data we first had to have a pre-ordained signature we knew as definitely what we were seeking. Lacking actual gunshots the first task was to identify a suitable approximation to them. This was done by generating sudden (or 'impulsive') sounds or events by toy guns and comparing them to signals obtained by taking recordings at a gun range. These become our 'clean' signals. The identification of such clean signals involved taking recordings around 5-6 different environments from the cricket grounds to the top of the law building.

Within the scope of this discussion it becomes important at this point to denote the problems inherent in identifying clean signals, especially in urban environments, which is the focus of this project. Echoes, as shown in Figure 12, are repeats of a signal that are detected after the original signal has been detected in full. Reverberations on the other hand, are self-interferences of the signal; repeats that interfere with signals before the original event has been fully detected. This changes the characteristic of a signal and makes it difficult to identify signal. In order to conduct our analysis, first a database of clean, echoic and 'reverberatory' signals had to be built. To this end, over

400 recordings were taken in different locations on campus and statistical and signal analysis was conducted on them.

An example of reverberations that interfere with the original wave-front, is shown in Figure 13.

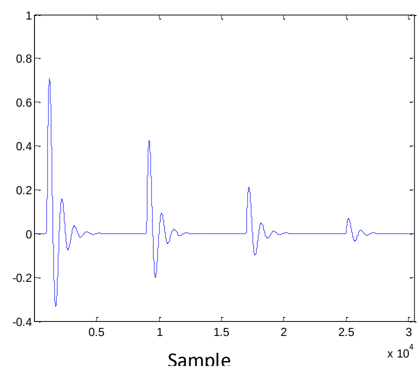


Figure 12: Not Reverberation: Signal's Echo not interfering with each other

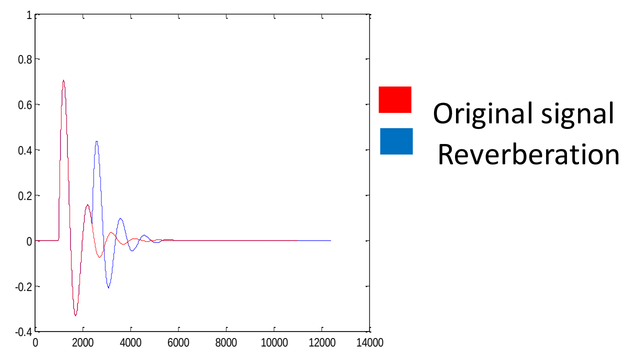


Figure 13: Reverberation: Signal's echo interfering at the detector with the original signal

4.1.1: IDENTIFYING A TEMPLATE SIGNAL

In order to run any sort of correlation or algorithm on a recorded signal, a template signal is required that we know to be the best approximation to a gunshot that we can acquire. To do this we tested a number of different 'generators' of impulsive sounds and compared their characteristics with those of a recording taken at a gun range. Examples of these generators are; toy guns, balloons popping, hammers banged against metal, among others. The waveforms of these signals are shown on the next page in Figures 14 through 17.

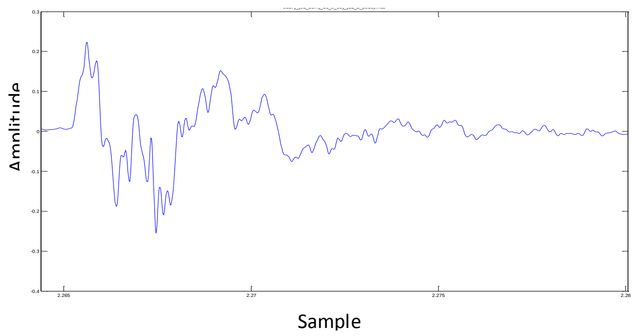


Figure 14: Waveform of a balloon being popped

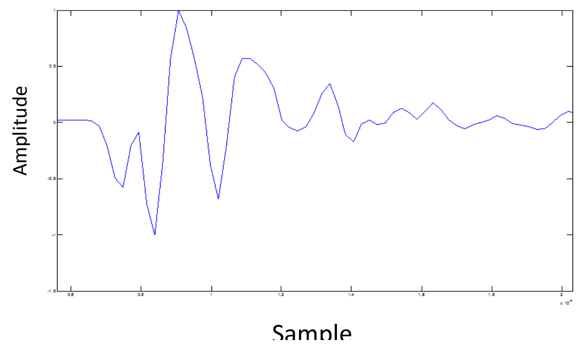


Figure 15: Waveform of a toy gun

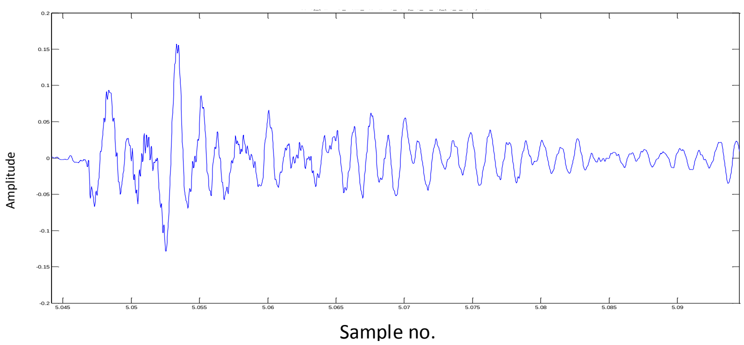


Figure 16: Waveform of a hammer striking a metal surface

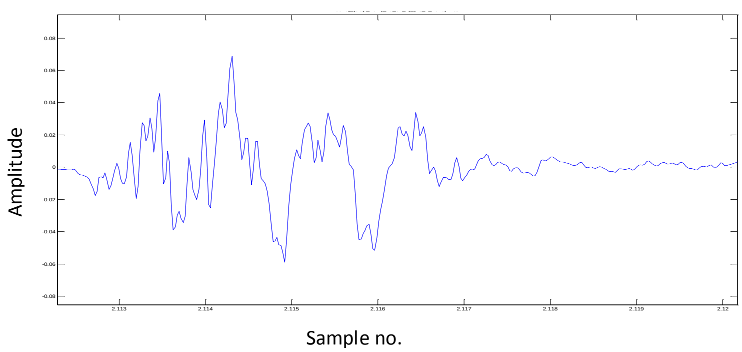


Figure 17: Waveform of a clap

Figure 18: Toy guns

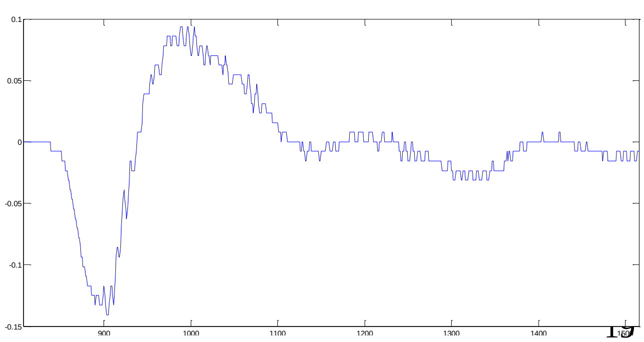


Figure 19: Actual gunshot signature [2]

If all waveforms in Figures 14-17 are compared to an actual gunshot recording in Figure 19, then it is noticed that the toy guns shown in Figure 18 are the generators that most closely approximate an actual gun.

The other signals exhibit either too many high-frequency components, their shapes do-not resemble the original gunshot, or they are too long in duration.

When an appropriate generator was found, clean, reverberation free recordings were to be taken. This turned out to more difficult than expected; intuition tells us the cricket ground are open and large enough to be reverberation free for a short (approximate 1 milliseconds) but in practice this was not so. To counteract this we took recordings on top of the law building and SSE building roofs. The law building experiments turned out the most fruitful results with repeating signal turning out to be echoes rather than reverberations.

Reverberatory environments are more common than clean ones. The SSE basement, the areas around the male hostels, and the corridor between the PDC and the Academic Block are some of the places where we conducted our experiments. Figure 21 shows the large variety of locations where experiments were conducted. The main problem that arose with all locations was uncertainty; some locations were surprisingly reverberation-free; such as the PDC corridor. This was due, in all probability, to the numerous trees, vegetation and acoustically damping surfaces

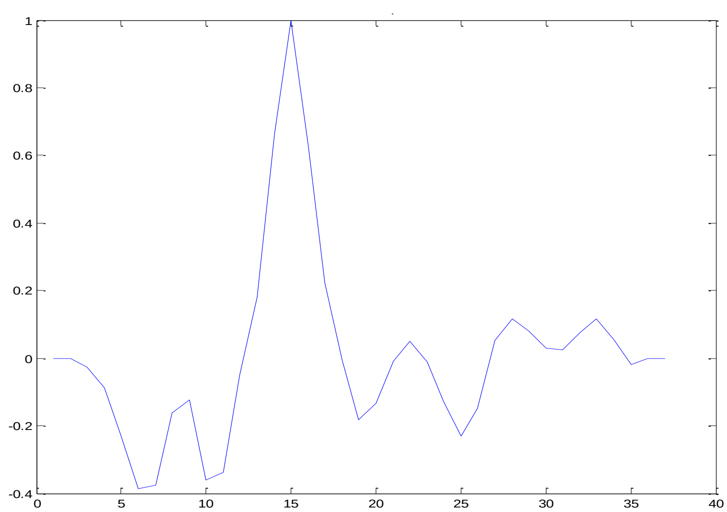


Figure 20: Template Signal

that absorb sound. This makes the effort harder and less straightforward, where careful empirical analysis was required to shift through the available data and separate the clean signal from the reverberated ones. As a result, in the end, to choose our template signal, we empirically selected the best clean signals (which conformed most to the actual gunshot) and took an average of them. This generates the waveform shown in Figure 20, which became our template.

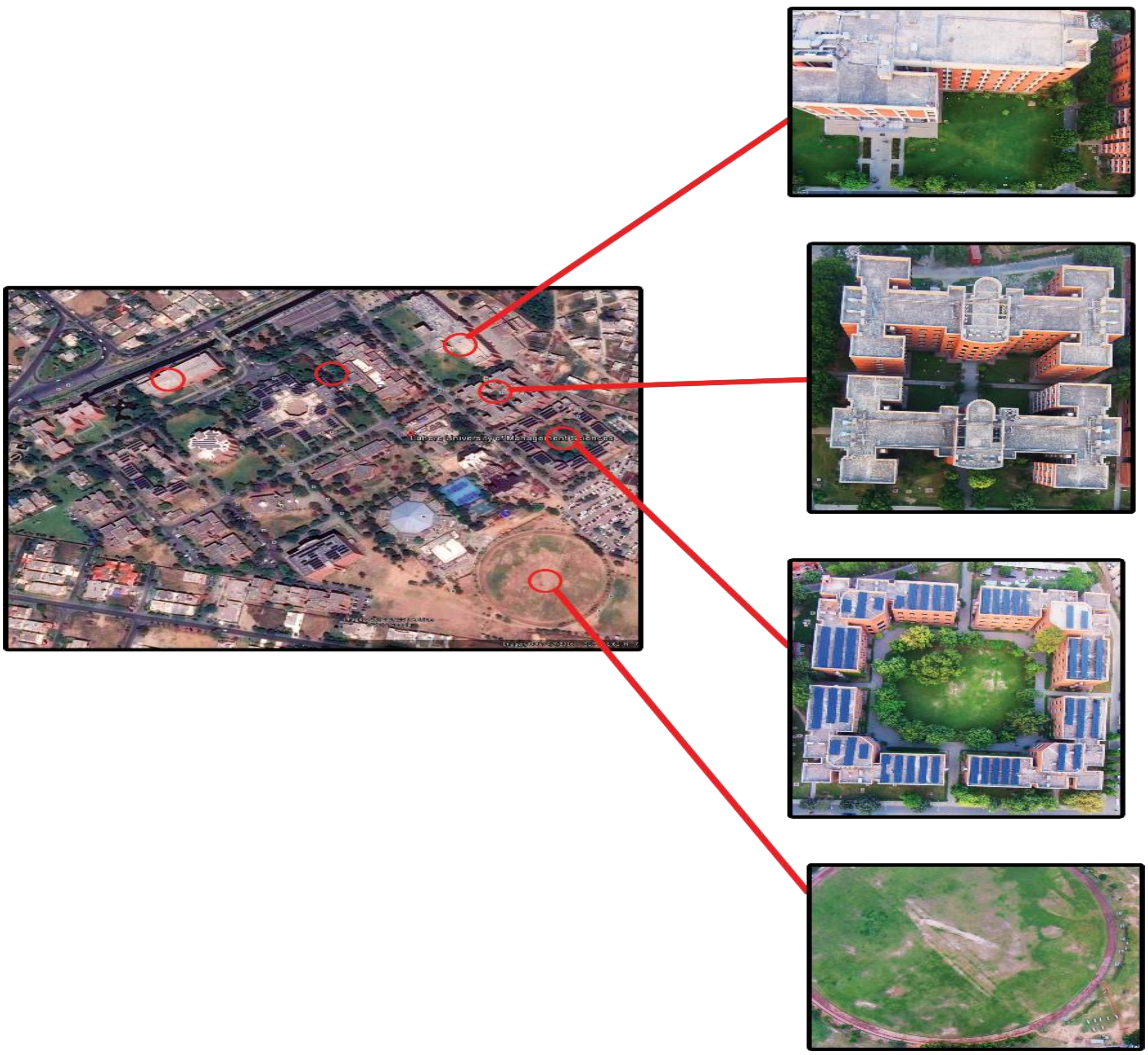


Figure 21: Campus Map where data was collected

4.1.2: Correlation of the template with the recordings

Now that a template had been obtained, what remained was to correlate it with the recorded signals in reverberatory and echoic environments. This would show us the extent to which a reverberation-inducing environment affects the original signal's characteristics and shape.

Normal correlation is problematic in the follows way; if the signal detected is noise but is shaped slight similarly to the template, then the correlation coefficient returned is high. Simply setting an amplitude threshold for the signal is not a solution for if the detected signal is, in fact, a gunshot which is very far away and hence has a low amplitude, then the signal can be mistaken for noise and rejected.

Thus the solution to this problem is in using energy-normalized correlation where the correlation coefficients are normalized with respect to the signal energies. This gives better result.

Another problem arises in the computation of correlation. The choosing a whole signal to correlate with drastically slows down the computer. Additionally, a clear correlation coefficient is not returned with normal correlation computation (when shifting one of the signals). To counter this, windows were chosen over which correlation was done. This again amplifies the problem of noise, and not because of problems with the experimental data but inherently in the way the algorithm was implemented. To achieve optimal computation, a hybrid approach that computes energy normalized correlation with an empirically chosen window was implemented.

The results of our correlation computation are shown in the histogram in Figure 22. The three types of bars (differentiated by colour) represent coefficients returned by running the algorithm on clean, reverberatory and outsider (not gunshots, such as the claps) signals. A clear shift in coefficients is observed in the graphs which shows the effect of reverberations on signals; lowering the correlation coefficients associated with the signals but interfering with the sound wave-fronts.

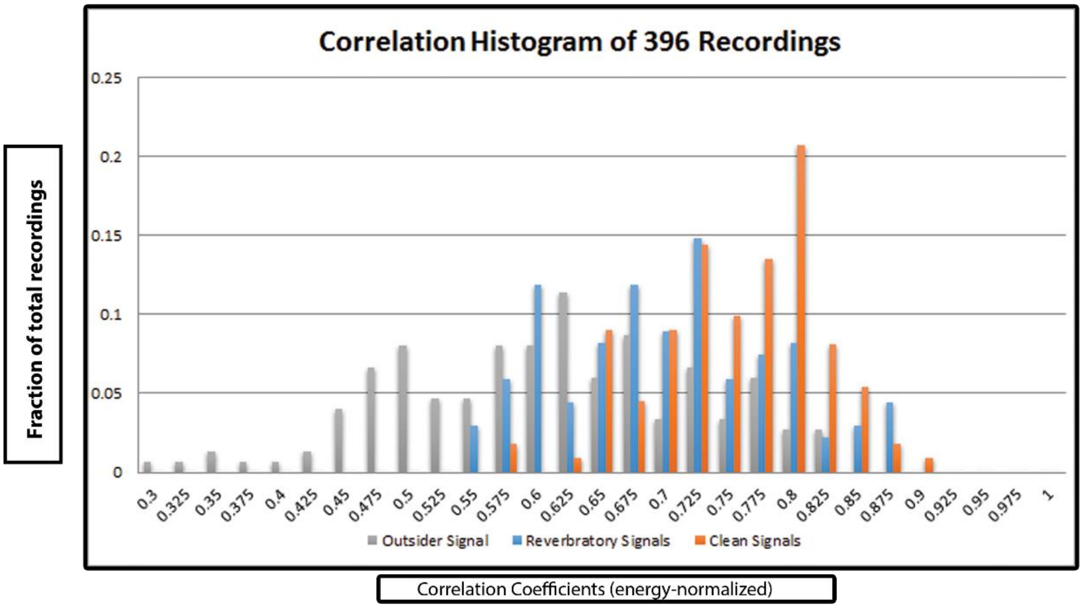


Figure 22: Correlation Performance

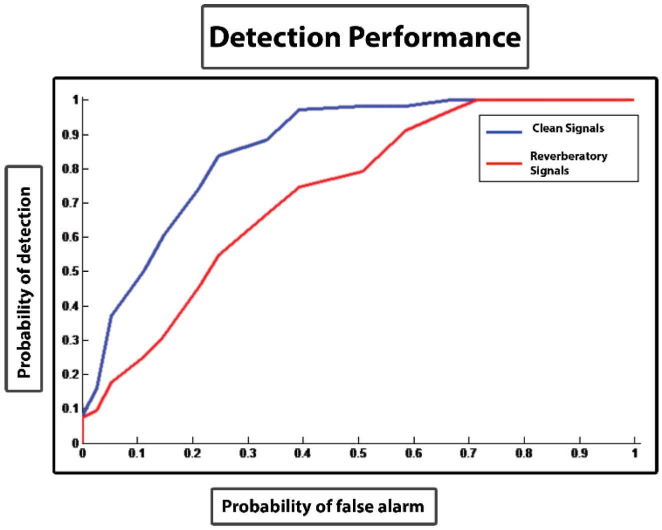


Figure 23: Detection Performance

To further illustrate the effect that these non-linear type environmental effects would have on such an acoustically operating system, a system performance curve is shown in Figure 23. It is seen that the probability of false detection rises with the reverberated signals and the probability of correct detection falls.

4.2: GUNSHOT LOCALIZATION

Simultaneously developed was a system that actively acquired multiple signals synchronously and calculated a source angle from those detected sounds. The system works as follows; a microphone array detects an incoming impulsive event and transduces the acoustic waves to electric signals. These signals are sampled and acquired by the NI 9215E module attached to the cRIO. A multiple-channel waveform is constructed by synchronizing the signals and LABVIEW subsequently processes these inputs. By calculating the time-differences in arrival between the three to four microphones and analyzing the geometry in which the microphones are placed (which can be changed), a source angle is calculated and outputted to a secondary feedback control loop that connects to a digital output module (NI 9274). The control loop monitors the position and speed of a turret 'RIG' that we constructed. This turret then turns towards the source and shoots it.
The LABVIEW acquisition and localization circuit that generates waveforms and performs localization is displayed in Figure 24.

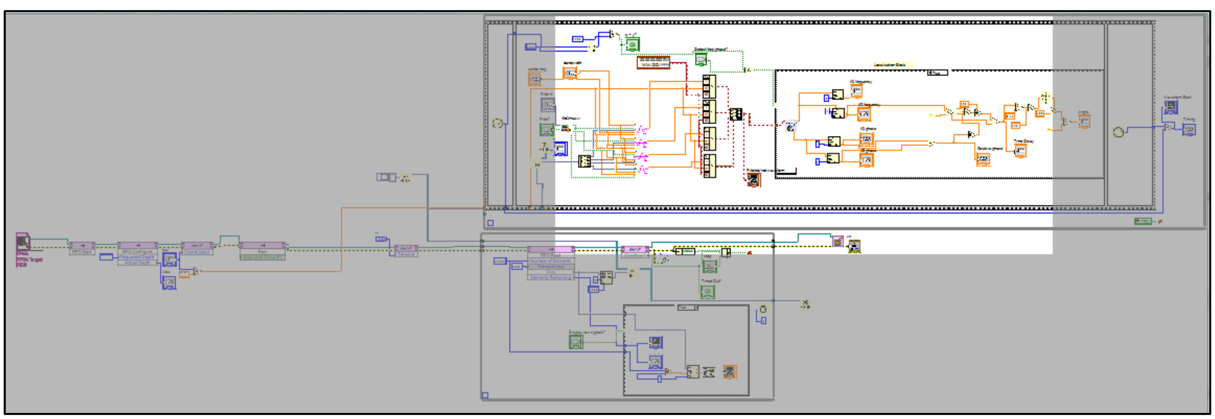


Figure 24: LABVIEW Signal Acquisition and Localisation Circuit

This acquisition loop was completed by using one of the 9215E channels as a sensor feedback path and adding control capability to the RIO's code.

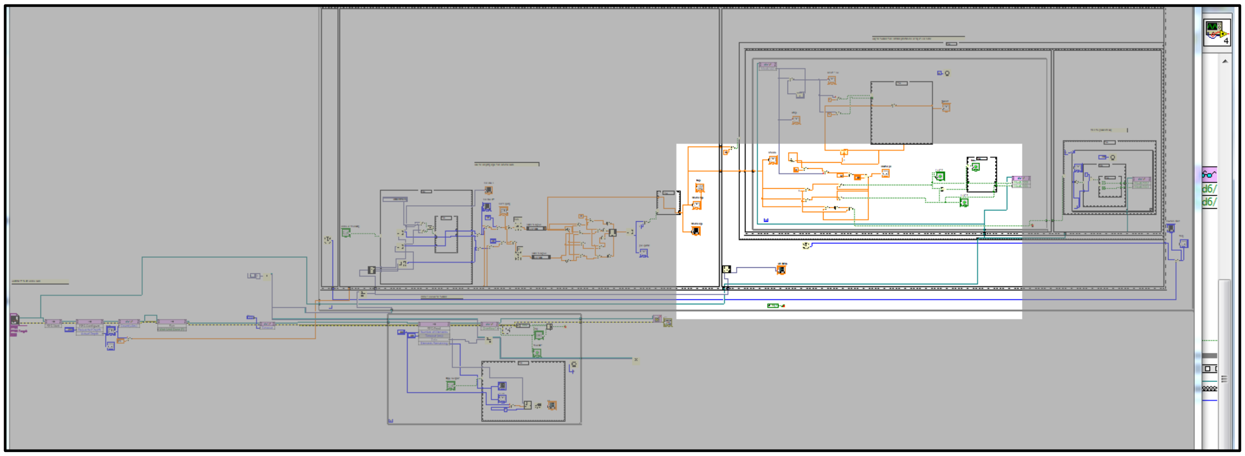


Figure 25: LABVIEW circuit with additional Control capability through Sensor Feedback

When a control loop is added to the acquisition loop as shown in Figure 25, it becomes possible to control a motorized sentry turret, or 'The Rig,' shown in Figure 26.

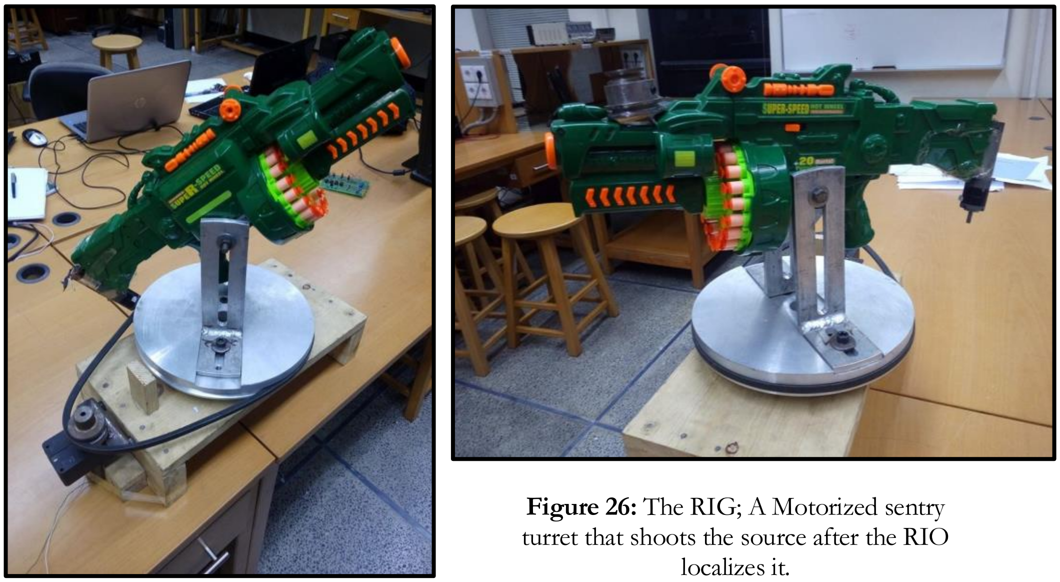


Figure 26: The RIG; A Motorized sentry turret that shoots the source after the RIO localizes it.

To future refine the motor speed and position control, proportional-integral control was implemented as part of a digital control systems project. The LABVIEW code using PI control is shown in Figure 27.

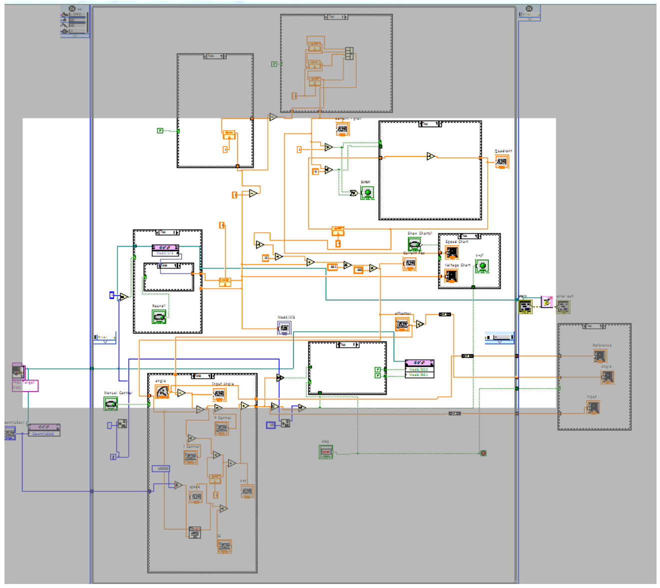
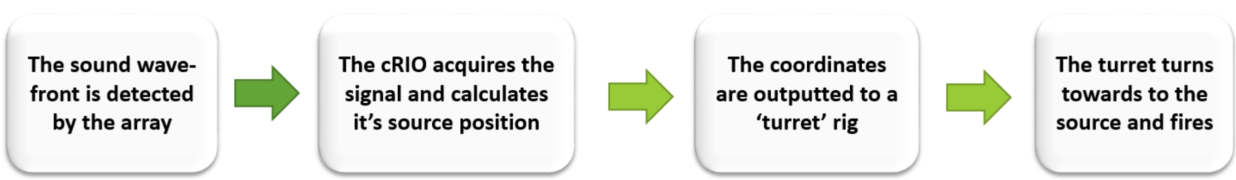


Figure 27: LABVIEW proportional-integral control circuit

The exact position and speed of the motors were given by rotational encoder sensors. These are given a separate channel of the 9215E module and relayed feedback information to the cRIO and from those, position and Rig velocity were determined. In essence, the implementation was that of making a servo motor.

4.2.1: Discussion: Localization System; Principle and Performance

This section discusses the principle and performance of the localization system. The block diagram shown below summarizes the principle of the localization system;



The principle of localization of sound works as follows; if a sound source is far enough away from a linear microphone array such that the sound's spherical wave-front can be approximated as a plane-wave as shown in Figure 28, then the angle that the source is located at related to the time-difference of arrival of the wave-front between the source and this can be exploited to compute an azimuthal angle from reference point to the source[8],[9],[10],[11]. However, with two microphones there is an inherent ambiguity or degeneracy in the angle and to eliminate this, a third microphone must be used to determine the actual source angle. Adding a fourth microphone gives us the elevation angle of the source.

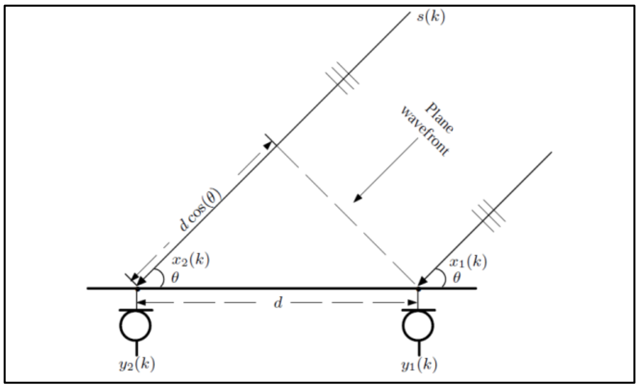


Figure 28: Two microphones and plane wave-front [8].

The final system operated as follows; the microphone array would detect sounds based on amplitude. Sophisticated identification was not used here mainly due to computation speed constraints. The cRIO would then use the physics and geometry outlined above to compute a source angle and then move the RIG towards the source angle. The system performance was limited only by synchronization issues of input and output of the cRIO. otherwise the detection and localization was almost instantaneous. A small issue exists of there being a slight error in angle output. This is mainly because of there being a geometry translation of the RIG and the array. This can be added to the setup to improve accuracy.

Chapter 5

POSSIBLE ENVIRONMENTAL IMPACTS

Environmental analysis is extremely important in an engineering project to determine the effects an undertaking may cause upon its neighbors in proximity. A suitably damaging implementation may be rejected overall mainly because of its environmental drawbacks.

Our project does not involve many moving components aside from the Rig motors. It is not large in scale and does not involve any engines or internal combustion implements (as in the case of generators). The components could all be run on a single UPS battery if certain voltage requirements are met; indeed, the microphone array is powered solely by batteries. Aside from this, the NI RIO requires minimal power to run (drawing a maximum of 0.2A at 22V). Due to this, the environmental impacts of this project are negligible.

Power consumption aside, the system can improve noise pollution in Pakistan's cities as rates of aerial firing would be reduced as law enforcement would have irrefutable evidence of guns being fired in a location.

Chapter 6

RELEVENCE TOWARDS SOCIETAL/COUNTRY NEEDS

The focus of this project is primarily on gunshot detection and localization. Some of the straightforward applications inherent in such a tilt are militaristic in nature. If implemented, such a system can extend the protection and information available to soldiers in a battle or when sniper fire is a threat. Should someone fire upon a group of soldiers, such hardware can accurately and reliably recognize and localize a gunshot, cancelling out the effects of echoes and reverberations, especially in an urban or mountainous environment. This is not something the human ear system can do; there exists an aural 'cone of confusion' (partly due to the fact of humans having only two detectors) that can cause mistakes in determining source directions. Yet this system need not be implemented only in a militaristic context; indeed, law enforcement can use this in a large scale deployment to detect and determine gunshots fired. This can offset the reliability issue inherent in witness reports and accounts. A similar system is implemented in San Francisco and is known as the 'Shotspotter' [12]. Due to its proprietary nature, its algorithms and implementation are not public information, limiting is usefulness is developing advanced applications, but its precedent is clear; law enforcement can benefit from the increased amount of information available to them. The context in our society is clear; such a system can immediately affect and lower the rate of crime, as well as affecting the aerial firing phenomenon that is so prevalent in our society.

The nature of the algorithms and methods used in this project are not limited to gunshot detection and localization only and as such they can be used in applications of varying natures. The signal processing used here can also be used to develop better video conferencing and seminar tools that track speakers and eliminate outsider signals, noise and interferences. Other applications can be the development of sound-scaping products based on the principle of echolocation or sonar.

Chapter 7

COST ANALYSIS

The material utilized in this SPROJ, for the most part, costs very little. The 'generators' of the impulsive events, the toy guns, their powder, the acrylic structure for the array, the microphones (those with the built-in AGC) and electric circuits |(H-bridges and simple gear motors) are all obtained for a few hundred rupees or are built by hand ourselves.

The setup for the Rig, which includes the base, platform and metal supports had to be machined and costs more (a few thousand rupees). This cost could have been reduced, and project complexity reduced, if 3D-printed materials were utilized in the construction. Due to time and feasibility constraints, this was not possible.

The main cost incurred in such a project is of the computing hardware involved. The National Instruments hardware we used to implement the controller for the Rig plant costs a few thousand dollars and is hence very expensive. This makes it unfeasible as an integral component of a product or in product development. Thus the justification for using the RIO in such an undertaking becomes then the usefulness it exhibits in prototypical design and development. The RIO hardware is actively used in current physics and engineering research for its modularity, processing and durability.

Chapter 8

CONCLUSION AND FUTURE RECOMMENDATIONS

In summary, the work that was done in this project involves building a multi-channel acquisition system that acquires and stores/processes 4 channels simultaneously. In addition to this a database was constructed that contains a template gunshot signal and other signals of similar types in clean and reverberation-inducing environments. Correlation algorithms, both simple and energy-normalized, with empirically found windows were found that show degradation in system detection performance as the environment becomes more and more reverberatory. These show, in conclusion, the clear trend that reverberations cause problems in the detection and identification of signals and that future work on this topic could prove fruitful. Finally, a hardware Rig was built that was interfaced with the RIO. The array detected the incoming sound, the RIO computed its source angle, and the Rig turned towards the source and shot it.

For future work, it is important to consider and develop good de-reverberation algorithms that eliminate the effects of reverberations in the detected signals. Hardware used in this setup can be used alongside the code developed in LABVIEW to use the RIO and the array to perform the reverberation experiments and in future, perform real-time processing on it. It is recommended to look into the implementation of optimized algorithms, especially in LABVIEW's context so that processing can be done on the RIO, though this does not mean data storage should not happen; the collection of experimental data is essential.

REFERENCES AND FURTHER READING

[1]. Ahmed, Talal, Momin Ayub Uppal, and Abubakr Muhammad. *IMPROVING EFFICIENCY AND RELIABILITY OF GUNSHOT DETECTION SYSTEMS*. Thesis. Lahore University of Management , 2013. N.p.: n.p., n.d. Print.

[2]. Asghar, Abdullah. *Acoustic Localization of Gunshots in Urban Environments*. Masters thesis (in progress).

[3]. "Police Microphone Network to Detect Gunshots Does Not Work." *The Telegraph*. N.p., 24 Aug. 2012. Web. 19 May 2016. <http://www.telegraph.co.uk/news/uknews/law-and-order/9497318/Police-microphone-network-to-detect-gunshots-does-not-work.html>

[4]. "UK Gun Crime: Should Police Retry Gun Sensor Technology?" *BBC*. N.p., 14 July 2014. Web. 19 May 2016. <http://www.bbc.com/news/technology-28004190>.

[5] "NI CRIO-9074." *National Instruments*. N.p., n.d. Web. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/203964>.

[6]. N.p., n.d. Web. <www.friendsofwilson.com>.

[7]. "Getting Started with NI CRIO and LABVIEW." *National Instruments*. National Instruments, n.d. Web. <http://www.ni.com/pdf/manuals/372596b.pdf>.

[8]. Benesy, Jacob, Jingdong Chen, and Yiteng Huang. "Chapters 1 and 9." *Microphone Array Signal Processing*. Vol. 1. N.p.: Springer, 2008. N. pag. Print. Springer Topics in Signal Processing.

[9]. Ch.Marty, P.Naz, S.Hengy, and P.Hamery. "Acoustic Detection and Localization of Small Arms, Influence of Urban Conditions." (n.d.): n. pag. 2006. Web. 2015.

[10]. Maher, Rober. "Modeling and Signal Processing of Acoustic Gunshot Recordings." *IEEE*. IEEE, 27 Sept. 2006. Web. <http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4041069&tag=1>.

[11]. Valenzise, Gerosa, Tagliasacchi, Antonacci, and Sarti. "Scream and Gunshot Detection and Localization for Audio-surveillance Systems." *IEEE*. IEEE, 7 Sept. 2007. Web. <http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4425280>.

[12]. "Shotpotter." SST Inc., n.d. Web. <http://www.shotspotter.com/>.