Development of Broad-Band Amplified Detectors and Self-Contained Measurement Instrumentation for the Electronics and Manufacturing Industries and Scientific Research.

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Project Summary

The proposed project entitled, "**Development of Broad-Band Amplified Detectors and Self-Contained Measurement Instrumentation for the Electronics and Manufacturing Industries and Scientific Research**," will develop an electronic instrument designed to permeate a technological void and market niche in today's test and measurement industry. Essentially, the end-user, albeit an engineer, scientist, or technician, will use the proposed instrument to excite a test circuit or sample cell using the embedded function generator and collect real-time data from the excited test circuit or sample using the amplified digitally-based and computationally-superior detector system. The instrument will allow the end-user to fully analyze, with both statistical and graphical tools, and store the data with the potential to completely monitor and control the instrument from a distant remote site.

The instrument will have five operational modes, controlled with embedded system software and user interface, and scalable multiple detector inputs for simultaneous studies of multiple test points, production quality assurance, or sample cells. The operational modes will allow the proposed instrument to directly compete with leading manufacturers in the test and measurement market, i.e. Tektronix, Agilent Technologies, Stanford Research, and Pendulum Instruments, as well as, the impedance, admittance, and dielectric market, i.e. Princeton Applied Research, Signal Recovery, Solartron Analytical, NovoControl, Agilent Technologies, and Brinkmann Instruments. This document will briefly outline the commercial feasibility, practical applications, generalized usage, and technical objectives for the proposed test and measurement instrument.

Commercial Feasibility and Practical Applications

The initial idea for the proposed instrument began with the concept of creating a lock-in amplifier with better specifications than the Stanford Research SR830 and SR850 DSP Dual-Phase Lock-In Amplifiers. The SR830 and SR850 are the best commercially available lock-in amplifiers and are used in numerous instruments, production facilities, and scientific laboratories. Any research or instrumentation having to do with electrical wave frequencies, such as ultrasensitive A.M. radio, scanning microscopies, such as STM, AFM, and NSOM, magnetic and electric molecular instrumentation, such as NMR and EPR, micro-temperature and material stress studies and monitoring with a Wheatstone bridge, as well as, semiconductor material and component testing and quality assurance, laser construction and research, frequency stabilization, and various spectroscopies, would require either the SR830 or SR850.

Stanford Research is based in Sunnyvale, CA, employs approximately 200 employees, and earns over $40 million annually. The company possesses a wide-range of scientific and electronic measurement equipment. Their products are known for their reliability and fair pricing. The company is privately held and initially started with federal grants and private investment approximately 25 years ago.

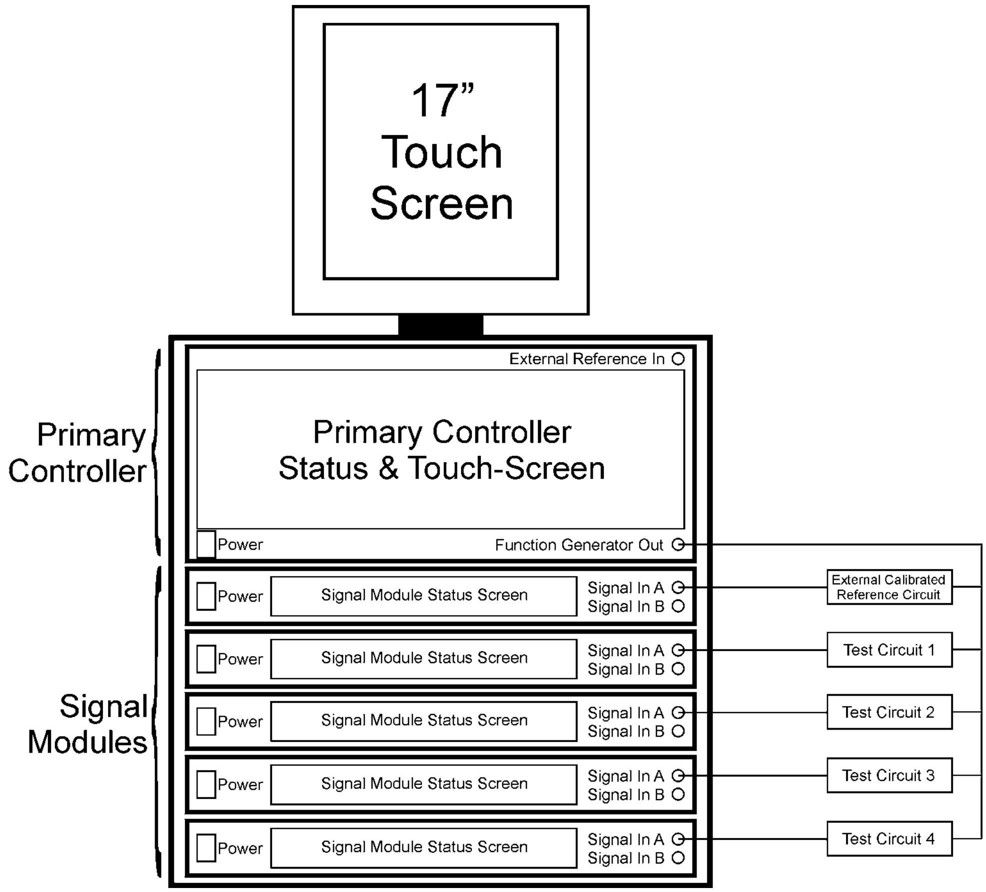
After considering the electronic components and hardware required to build the proposed instrument, it was realized that five operational modes are possible with the introduction of advanced software. These operational modes would allow the proposed instrument to compete with other test and measurement equipment, such as oscilloscopes, dynamic-signal and spectrum analyzers, as well as, impedance, admittance, and dielectric analyzers and spectrometers. The primary corporations that manufacture these devices are Agilent Technologies, Tektronix, Pendulum Instruments, Princeton Applied Research, Signal Recovery, Solartron Analytical, NovoControl, and Brinkmann Instruments.

Tektronix and Agilent share the largest share of the test and measurement market. The annual gross revenue of the test and measurement market is $12.4 billion. It comprises automated test, communications test and monitoring, and general purpose test and measurement equipment. Tektronix is publicly traded on the NYSE in which their net revenues were over 1 billion annually for the last two years, and over 900 million for their 2003 fiscal year. Tektronix is the leading manufacturer of oscilloscopes, but augments their recent sales increases with new innovative lines of successful signal sources, spectrum analyzers, and logical analyzers. Agilent, originally Hewlett-Packard, is publicly traded on the NYSE and their net revenues were over $5 billion for the last two years, and over $4 billion for the prior two years. Agilent is the leading manufacturer of spectrum and network analyzers, but has traditionally manufactured a broad range of radio and microwave general test and measurement equipment, with a primary focus on testing and quality assurance of electrical and semiconductor component production. Neither Tektronix nor Agilent produce any form of highly sensitive detectors similar in nature to lock-in amplifiers, therefore Stanford Research stands alone and essentially unchallenged in this market.

As stated above, the proposed instrument, with its five operational modes, will compete with the leading manufacturer of lock-in amplifiers, as well as with oscilloscope, dynamic-signal and spectrum analyzer, frequency counter, and spectrometer equipment and instrument manufacturers. The practical applications of such an instrument has the potential use in any test and measurement capacity of any electronic component, test circuit, sample cell, or electronic device or instrument in the electronics and manufacturing industries and scientific research. The practical applications include, but are not limited to, sub-radio and radio spectroscopies for the fundamental physical studies of chemistry, biology, and material research, fluorescence spectroscopy, electrochemical and neuro-physiological spectroscopies. The electronics and manufacturing industries will utilize these measurement technologies to characterize components or manipulate equipment or production lines, respectively.

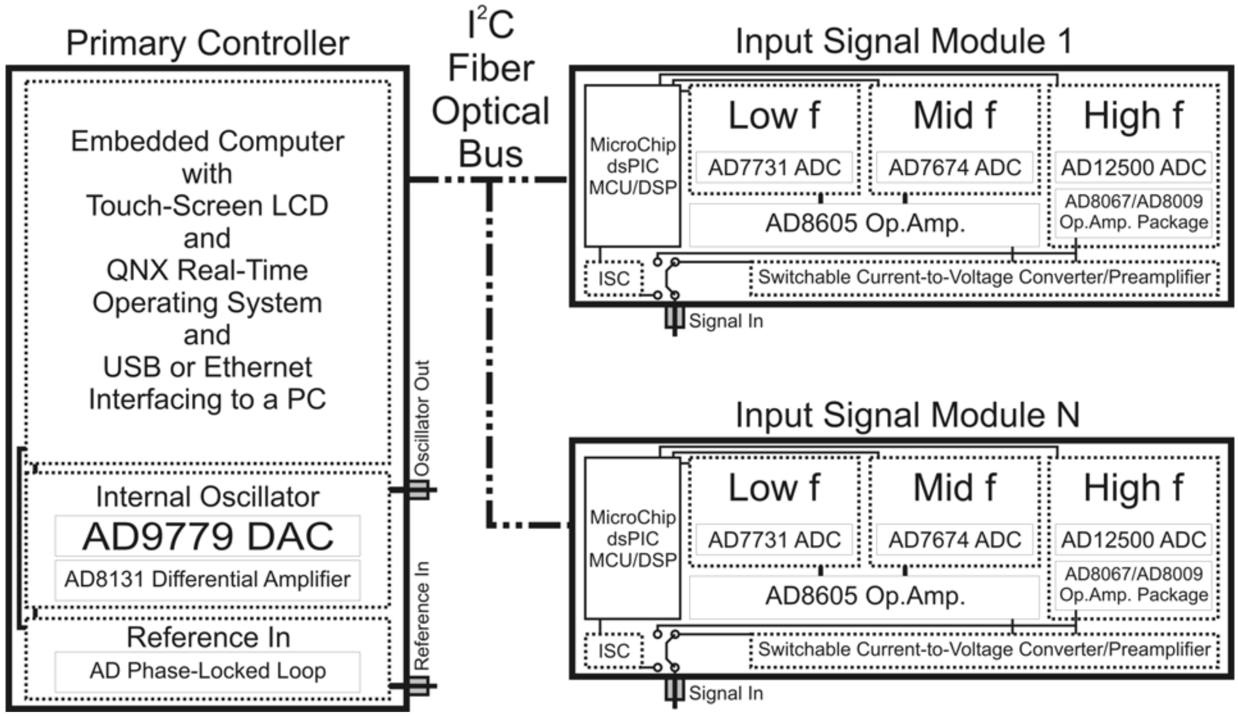
Technical Overview and Usage

Generally, test and measurement begins with the excitation of a test circuit or sample cell. The excitation is performed with a function generator or oscillator which outputs a time-dependent periodic voltage. The simplest periodic voltage is a sinusoidal wave. This voltage provides electrical energy or power to the test circuit or sample cell and is shown in the following diagram.



Once the test circuit or sample cell is powered by the function generator, then the response can be studied by some sort of appropriate detector, such as an oscilloscope, dynamic-signal or spectrum analyzer, digital multimeter, frequency counter, lock-in amplifier, or impedance or dielectric analyzer or spectrometer. All detectors, meters, analyzers, and spectrometers work in a similar fashion, they measure the voltage or current response from the test circuit or sample cell and then present the response in specific manner or format. Some of those formats are numeric, statistical, graphical, or any combination, thereof. Essentially the hardware required to measure the voltage or current response is the same for all of these devices. The software is what distinguishes the presentation of the signal data. Therefore, a major proposal of the proposed instrument is to design the hardware to meet all of the required specifications, while using advanced programming to create software to present the data in any manner applicable to the end-user and the application

The proposed instrument will have a primary controller and multiple signal modules to allow for complete scalability for the end-user and final application, as shown in the following diagram.



The primary controller will contain a multi-processor embedded computer which will allow all monitoring and all control software for the instrument itself, as well as, the software for the user interface, statistical and graphical analysis, and presentation applications. The user interface will be a 17” LCD touch-screen with the option of a keyboard and mouse. Ethernet, USB, and a CD/DVD burner will also be available for data storage and remote monitoring and control.

The primary controller will also contain the pseudo-arbitrary function generator, otherwise known as the oscillator, for excitation of the test circuit or sample cell, the Rubidium time-base, (i.e. an atomic clock, for 12-digit precision time and frequency calibration), the internal oscillator for the Lock-In operational mode, and a phase-locked loop for frequency referencing from an optional external source generator.

It is expected that up to 48 input signal modules can be controlled by a single primary controller. The only limitation to the number of signal modules is the data throughput limitations of the I^2C bus and the computational resources of the embedded computer. Each signal module will contain an analog preamplifier, amplifier, and set of analog-to-digital converters. The digitized signal will be further conditioned and monitored by dsPIC digitally-based micro-controller. These are tiny computers that will control its individual signal module, its preamplifiers, amplifiers, perform internal self calibrations (ISC) and diagnostics, and communicate with the primary controller via the I^2C fiber optic bus. Therefore, each signal module is nearly a stand-alone analog-to-digital signal processing unit with smart preamplification, amplification, digitization, calibration, and diagnostics. Proper shielding and isolation of the digital components is necessary to ensure that the radiative and conductive noise from the digital circuits does not interfere with the analog components and signal processing. Two standard single and dual signal module systems will be offered along with the fully scalable rack-mountable system.

Technical Objectives

The physical limitations, i.e. sensitivity and frequency range, of the instrument will be defined by the electronic components and hardware of the system. The functionality of the instrument, i.e. the operational modes and graphical presentation, will be defined by the software of the system, which will be virtually limitless and only limited by the time and skill required to develop the software and its applications. The technical objectives are as follows:

1. **Five (5) Operational Modes: Time-Domain, Frequency-Domain, Wave-Count, Lock-In, and Spectrometer.** The operational mode will be controlled by the operator, in which the specific experiment or application will distinguish the optimal mode, or a cycling through different modes. All electronic signals are received in the time-domain, which are then digitized and manipulated by software. This allows the instrument to manipulate and display the data in any of the five operational modes, or multiple simultaneous operational modes.
   a) The Time-Domain mode is analogous to a current-art oscilloscope, allowing the end-user to view the raw waveforms in real-time. For example, the waveform of audio or sound through a microphone.
   b) The Frequency-Domain mode is analogous to current-art dynamic-signal, spectrum, and network analyzers. All of these analyzers collect data through the time-domain and perform a mathematical (Fourier) transform to display the raw waveforms as a frequency spectrum.
   c) The Wave-Count mode will display a real-time numerical value for the frequency or period of the waveform of the electronic signal. Since a Rb-timebase is proposed, the frequency counter can have a precision of 12-digits of resolution.
   d) The Lock-In mode will convert the AC electronic signal into a DC magnitude and phase difference as compared to the function generator. Digitally transforming and reporting both the magnitude and the phase of the signal is known as a DSP dual-phase lock-in amplifier. This mode will possess the greatest sensitivity because the electronic signal from the amplified detector and the embedded software will digitally reject all noise at a specific frequency, thereby creating an extremely narrow notch filter. Noise rejection will range from 80 to 180 dB, depending on the detection range.
   e) The Spectrometer mode is similar to the Frequency-Domain mode, however, the end-user will be able to determine if the spectra is generated from the Frequency-Domain mode, for fast spectra, or the Lock-In mode for slower incremental spectra but with far greater sensitivity. This mode will also allow for multiple signal modules to produce a single spectrum. For instance, a dielectric spectrum would require the arithmetic division of a sample cell over the response of a reference cell.
2. **Include a Rubidium (Rb) time-base, or atomic clock, for the function generator, overall calibration, and the internal Wave-Count and Lock-In operational modes.** There is currently no commercial function generator or lock-in amplifier available with a Rb time-base, and only two commercially-available frequency counters. A Rb time-base would ensure frequency and period calibration as that of an atomic clock, with a precision of 12-digits of resolution. Such precision would greatly increase the noise rejecting capability and absolute reproducibility of the Frequency-Domain, Wave-Count, Lock-In, and Spectrometer operational modes. This atomic clock would increase the accuracy and precision of the instrument as unmatched in any test and measurement device on the market. It would also increase the absolute reproducibility because the atomic clock is extremely resistant to changes due to shipping, temperature, or humidity. For example, the digital transformation required for the Lock-In mode would allow for greater significant figures in the multiplication, therefore increasing the Q-factor and dynamic-reserve, and perhaps decrease the settling time.

3. **Push the current sensitivity down to 1 fA in Wave-Count or Lock-In Operational Mode.** Current-art lock-in amplifiers possess the greatest sensitivity for voltage or current measurements. The best commercial amplifiers to date have a sensitivity of 2 fA to 100 fA, which are two-decade-old technology. It is proposed to use the most modern design and noise-reducing techniques to create a more sensitive frequency counter and lock-in amplifier.
4. **Push the AC frequency range from 1 μHz to 1 GHz, with a 0.1 μHz resolution.** Most commercial oscilloscopes, analyzers, and amplifiers distinguish low frequency (< 100 kHz) from high frequency (> 500 kHz), it is proposed to design this instrument to fill the frequency gap and seamlessly provide the full frequency range from 1 μHz to 1 GHz.
5. **Include components, circuits, and software for self-calibration and self-diagnosis to ensure consistent operational integrity and absolute reproducibility.** Introduction of the atomic clock will calibrate the frequency and wave characteristics to 12-digits of precision. Additional components, such as standardized resistors, capacitors, and inductors can be included to ensure the magnitude of the signals are equally calibrated.
6. **Include charge-to-voltage and current-to-voltage preamplifiers on all of the detector inputs.** Lower frequency studies, less than 1 or 10 Hz, would use the charge-to-voltage preamplifier, while higher frequencies would use the standard current-to-voltage preamplifier. Essentially, the charge-to-voltage preamplifier is an integrating operational amplifier, therefore, only an extra capacitor is used over the operational amplifier of the current-to-voltage preamplifier.
7. **Include switchable electrical shunts to ground.** When incrementally changing the frequency, to create a spectrum, and at frequencies less than 10 Hz, it is necessary to shunt all electrical energy in the cables and test circuit or sample cell to ground. This will ensure that any previous frequency-dependent energy is completely drained from the system before initiating a study at the next incremental frequency. Current studies have shown that the previous frequency energy will exponentially decay from the system once the new frequency is set; however, the decay at low frequencies is substantial. Also, if the previous frequency is close enough to the existing frequency, this can introduce quite a bit of noise and error to the existing frequency measurement. Therefore, draining that frequency-dependent electrical energy from the system will ensure that the existing frequency study is cleanly performed at only the single existing frequency.
8. **Allow the function generator to be partially arbitrary.** A pure function generator would generate a clean monochromatic sinusoidal wave. An arbitrary generator allows any complex function or set of voltage data points to create a periodic waveform. It is proposed to allow the end-user to excite the test circuit or sample with either a pure sine wave or multiple sine waves superimposed on each other at different frequencies and phases. This will allow the end-user to study the response of the test circuit or sample at various simultaneous frequency responses. The Time- and Frequency-Domain modes would allow the complex response to be studied directly at the various frequencies and harmonics. Or, while in Lock-In mode the detector can cycle through various predetermined frequencies of interest, whether they are incident frequencies or harmonics, thus allowing a complete study of the test circuit's or sample's response.
9. **Include the capability to simultaneously report on the magnitude and phase of multiple frequencies in Lock-In operational mode.** This feature is related to the latter in that the detector in Lock-In mode will cycle through a list of end-user predetermined frequencies, whether primarily incident from the function generator or harmonics from a primary frequency response, therefore providing the sensitivity of a lock-in amplifier while studying various frequency responses simultaneously.
10. **Modularize the amplified detectors for user and application scalability.** This feature will allow a single instrument the ability to add at least 24 input signal modules and connect each one to the primary system controller. This feature will allow the simultaneous study of multiple test points on a single test

circuit, or simultaneously test multiple circuits for quality assurance in a production facility, or allow the research scientist the ability to run multiple sample cells simultaneously. The instrument will be rack mountable to allow for the primary controller and any additional signal modules complete scalability. Two standard units composed of a single primary controller and a single and dual signal input module will be provided.

11. **Encapsulate the system into a self-contained user-friendly instrument.** The primary controller will communicate and control the multiple signal modules, contain the function generator and atomic clock reference, and an advanced multi-processor embedded computer interfaced to a touch-screen monitor, and optionally a keyboard and mouse. The front-end applications will be user-friendly and intuitive to provide complete control of the instrument and present the data in numerical or graphical form.
12. **Include real-time statistical and graphical tools for end-user monitoring, analysis, and advanced control of the instrument.** If advanced analysis and presentation software is included in the instrument, then the need for third-party software, i.e. LabView or MatLab, will not be necessary. Such inclusion of the analysis and presentation software will ensure that the software is optimized to reduce processor and memory resources of the embedded computer, while presenting all of the data in an end-user and application determined fashion.
13. **Allow the entire system to be monitored and control by a remote computer interface.** This feature will allow the end-user to monitor the test results on a production line or a dangerous area remotely through another computer. If the instrument is connected to the internet, then the end-user will be able to monitor and control the instrument from anywhere in the world.
14. **Automate incremental frequency scanning for complex admittance, impedance, or dielectric spectroscopies.** Admittance, impedance, and dielectric studies are standard measurements in the electronics world. These basic and informative methods reveal the essential responses of electrical components, test circuits, and sample cells. Automating these studies to provide detailed and accurate spectra will provide the end-user with component's, circuit's, and sample's frequency responses.
15. **Allow for complete update of the instrument's system software and applications.** This will allow firmware and software to be completely updated to fix any bugs and introduce new features. The update should be implemented via disk sent to the client or remotely through the internet.