Development of a Computer-Assisted Instrumentation Platform for High-Tc Superconductor Phase Transition Measurement with LabVIEW and ELVIS II

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ABSTRACT

The article proposes the development of a computer-assisted instrumentation platform for high-Tc superconductor phase transition measurement with LabVIEW and ELVIS II for the undergraduate laboratory. We demonstrate the strategies to establish the knowledge and the skills to overcome the challenges in precise measurements, including (a) the construction of human-computer interfaces of the circuit system; (b) synchronized acquisition and analysis of big and fast variation data; (c) a real-time demonstration of resistance-temperature dynamics; and (d) problem shooting and solution proposing from physics and engineering perspectives. The work also demonstrates that the strategies to complete the measurements with self-designed simple circuits and available alternatives and intelligent-service program effectively turn passive reliance into creativity and stimulates technical practice with imagination.

INTRODUCTION

The fast development of the Internet of Things [1] is driving the stream of the fourth revolution of industry (I-4.0) [2]. Beyond automated manufacturing, I-4.0 expects that the integration of hardware instruments, software development, and cloud computing will lead to the promotion of intelligent manufacturing. Therefore, the cultivation of domain knowledge and innovative design thinking are two fundamental issues in education for industry and in developing multi-talented students. The objective of this project is to inject industrial elements into a scientific sketch via the development of an undergraduate physics experiment to bring about the realization of multi-disciplinary practice and integration.

This paper demonstrates the development of a computer-assisted platform for undergraduate students to investigate the high-T_c superconductor phase transition phenomenon using LabVIEW and ELVIS II. The primary objective of the experiment focuses on the real-time depiction of the phase transition curve and the specification of the critical temperature $T_{c.}$ To achieve this goal, combined knowledge of instrument control, big data processing and analysis is crucial.

Additionally, while a precise measurement depends either on a reduction in fluctuations or an increase in signal strength, the first is the most significant concern, especially in low-temperature experiments. Accordingly, measurement of the superconductor phase transition phenomenon in academic research was conducted with a phase lock-in amplifier and a temperature PID controller, which are usually unsupported in undergraduate teaching laboratories. How to integrate basic concepts of low-temperature physics, instrumentation, and quantitative limitation by constructing a simple setup is a challenge in the development of an undergraduate curriculum.

In the second section, the experimental setup and the configuration of the human-computer interfaces are discussed in detail. Based on the automated instrumentation system, dynamic displays with a fully-supplied GW-Keithley-ELVIS (GKE) kit and a self-designed LM-Keithley-ELVIS (LKE) kit provide dual confirmation. The success of the latter approach provides an example of an aggressive and creative spirit in practical education. On the other hand, the observation of the non-adiabatic response of conductivity in the temperature decreasing process inspires the investigation of the generation of fluctuations and the proposition of a deep-thinking solution concerning the underlying physics. Furthermore, the post-experiment inspires creative and imaginative design so as to realize the user's visual optimization and parametric judgement, thus helping deliver the conceptual recognition of cyber-physical systems.

Finally, we briefly summarize the achievements of this work. The development of the graphic-based instrumentation platform removes the huge barrier to learning remote-control knowledge [3], reduces the repeated execution, and examines the experimental procedures. The replacement of the existing instruments with simple circuits or available alternatives turns passive reliance into creativity, while the design of the intelligent-service program stimulates technical practice with imagination. The work verifies the practice of experimental innovation, bringing the key ingredient of industry into physics, thus bridging interdisciplinary science and industry.

1 EXPERIMENTAL SETUP

The structure of the system is created in terms of voltage measurements via which the connection between bulk resistance and temperature is established. For precise measurement of the superconductor, the 4-point probe method was adopted; it consisted of six terminals of which two are for the input current, two are for the output bulk voltage, and two are for the thermocouple's output voltage. While Ohm's law directly gives the bulk resistance, the corresponding temperature has to be converted indirectly from the thermal voltages.

Measurement of the phase transition phenomenon faces several challenges, including (a) synchronized data acquisition of voltages and current from two digital multimeters and a power supply, respectively; (b) difficulties in manual recording of voltages and current with extremely fast variations; (c) the necessity of dealing with big data of more than 2,000 counts and the knowledge to do numerical interpolation for voltage-temperature conversions; and (d) a real-time demonstration of resistance-temperature dynamics.

The experimental setup in an academic laboratory can be supported by two dual phase lock-in amplifiers [4], one temperature controller [5], current power supply and a large cryogenic Dewar flask. Filtering out the low-temperature signals from the background thermal and electronic noises with phase lock-in technology is the most important task in order to attain precise quantitative measurements. Referred by SIGNAL RECOVERY Model 5210, the full-scale voltage is sensitive to the range of 100nV~3V. As a comparison, appliances in this work are restricted to ELVIS, voltage power supply, and a 500 ml Dewar flask.

Our experiment involved two schemes, schematically demonstrated in Fig. 1. Manual operation was taken to be the first training scheme. In this scheme, the complete bundles of data were recorded by a camera and then imported to EXCEL using a long-term procedure. Next, the post-deal data conversion was accomplished by interpolation evaluation in C language. The resistance-temperature diagram was plotted using the phase transition process. The data were compared with previous literature results, both qualitatively and quantitatively. In the second scheme, the course objective was to establish abilities to perform remote control. To fulfil the educational goal, the experimental setup was further separated into two subschemes:

I. The fully-supplied GKE kit to establish connections among the superconductor, the GW power supply, the Keithley multimeter, and the ELVIS virtual instrumentation platform [6].
II. The self-designed LKE kit to establish connections among the superconductor, the LM-317 constant current circuit, the Keithley multimeter, and the ELVIS virtual instrumentation platform.

1.1 Subscheme I.

We applied built-in VISA modules to complete the human-computer interface protocols within the Configuration→Write→Read→Close structure, and completed data acquisition with the string commands ":CHANel1:MEASure:CURRent" and the "DATA?", and "DMM" values from ELVISmx.

1.2 Subscheme II.

We hoped to realize more To-Do training so as to reduce the reliance on external suppliers. The strategy left the choice and construction of the circuit system to the students. In this report we chose one strategy to generate the applied current using the self-designed LM-317 constant current circuit. Data acquisition was accomplished using the high-level ELVIS instrument, the DAQ Assistant.

2 RESULT & DISCUSSION

The first task was to complete the program design for the human-computer environment, while the second was a parallel display of multi-directional data on the user-defined panel. The back-end data processing involved an integration of imposing an external data sheet for voltage-temperature conversion, data accessing, call of the dynamic array, 2D array sorting, and nonlinear interpolation. The difficulty of integration was overcome by using the graphical-based LabVIEW interface. We adopted the File

I/O module to perform file processing, applied modules of “Initialize Array/Insert Into Array“ to build the dynamic storage space, and completed the 2D array sorting and interpolating using the module “Index Array Function/Search 1D Array Function/Array Max & Min Function/Threshold 1D Array Function/Interpolate 1D Array Function“. Finally, the graph module “XY Graph” was adopted to dynamically display our measurements.

The program design is shown in Fig 2. Different types of modules were wired with different thicknesses and colors, which clearly distinguished the various types of data transmission.

Fig. 3(a) and (b) show the phase transition curves of BSCCO within the GKE and LKE kits, respectively. The measurement started at the boiling temperature of Liquid-Nitrogen and ended at the room temperature of 290 K. Both experimental schemes measured a critical temperature T_c located at 90 K~ 130 K and the electric resistance saturated at about 10 mΩ at room temperature, revealing good consistency with the literature [7].

In Fig. 4 we show a common mistake, measurement containing a failed temperature descending curve and a wrong ascending curve. Whenever two overlapping curves are expected by students, it is important to explore the mechanisms behind the great deviation.

From a physics perspective, there are some possible hypotheses:

[a]. Actually they should not overlap; the trace should demonstrate hysteresis.
[b]. The superconductor cube encounters non-uniform immersion; the sample bears a large thermal gradient.
[c]. The experiment is not operated adiabatically; the temperature cannot be defined in a non-equilibrium status.

From an engineering perspective, the problems may arise because:

[d]. Our instruments are not sensitive enough to follow the fast response; they fail to work in low temperature regimes.
[e]. The Dewar flask is too small to serve as a heat bath.
[f]. The low-temperature tolerance of the wires and contacts is insufficient.
[g]. The circuit loop gets short and corrupted with override currents.

Moreover, the resistance saturates to R = 8 mΩ, showing a quantitative inconsistency as shown in Fig. 3. To trace the difference, one has to clarify:

[a]. If the circuits are completely correct.
[b]. If all instruments are correctly arranged.
[c]. If the programs for instrumentation are correct.
[d]. If the programs for data analysis are correct.

Eventually, the first discrepancy helps clarify that (i) the hysteresis is associated with the magnetic field but not with the temperature; and (ii) the Dewar flask is too small to serve as a heat bath such that the immersion progresses barely within the thermal equilibrium. From the second discrepancy, we realize that without an external resistor, the circuits will short when entering the superconducting regime and the operation of the GW power supply in fixed current mode would be interrupted to prevent overflow breakdown.

Although an implementation of precise measurement seems to be innately restricted, students are encouraged to propose some strategies for further improvement. Many of them are surely amenable, for example,

[a]. Thermocouple → Silicon bandgap temperature sensor [8]
[b]. GW power supply → Keithley 220 programmable current source [9]
[c]. Manned manipulation → Cybernated robotic arm [10]

[d]. 500ml Dewar flask → MVE LAB cryogenic liquid Dewar (existing)
Since a silicon-based sensor is known to be extremely stable over time and environmental conditions, the special logarithmic signal response would prove to have better accuracy and reliability. The Keithley 220 programmable current source provides a maximum output of 100mA, with error tolerance to the order of μA. There are advantages to performing remote control with LabVIEW on commercial devices, but we still face the challenge of doing circuit design for integration of operational amplifiers whenever a large current source is required. While unexpected disorders may be unleashed in a manned manipulation of a sample drop, an Arduino-based cybernated robotic arm may carry the hope of stable movement. The last suggestion tries to mimic a heat bath to realize a thermal equilibrium environment. We believe the idea is helpful for solving physics problems, although it raises another task of designing a suspension holder. Its combination with a low-temperature-resistant robotic arm drives the cybernated connection in a paradigm for physics students to engineer in a smart manufacturing environment.

Fig. 5 shows a post-experiment program with user-supplied parameters. The program has the flexibility for users to arbitrarily input a set of random numbers, and after interpolation refinement the program will calculate the average slope of the piecewise curves and return the information that endures abrupt and tremendous variation. The program attempts to reveal a direct demonstration of crucial parameters and judgement that is able to serve as a prototype for smart visualization.

3 CONCLUSION & PERSPECTIVE

The integration of ELVIS II, the Keithley multimeter, and a GW power supply with a graphic-based LabVIEW instrumentation platform provides a smart human-computer interface design and configuration. Using built-in VISA modules such as ELVISmx DMM, and DAQ Assistant, the procedures for taking precise measurements and for data acquisition become easily available to physics students. Furthermore, the experiment provides strong support to systematically scrutinize the stability of the experimental structures by multiplying integrated high-precision signal sensing and numerical analysis. Via the design of the experimental platform, we have demonstrated the integration of software and hardware utilities which enabled the simplification of the development of an instrumentation platform, and greatly reduced the time for data processing. An efficient design shortens the distance between science and engineering, and can greatly benefit academic research and engineering technology.

For education purposes, we conducted the analysis and discussion on failed experimental results to explore the mechanisms behind the great deviation in physics and engineering perspectives. In addition to establishing physics knowledge, students were trained to propose a schedule of system inspection and problem detection and then to propose practical suggestions for further improvement.

The visual service plays the role of bringing physics together with a new age of engineering. In this work we have attempted to realize a direct display of T_c on a Graph panel via smart searching in a post-experiment program. We have completed the test program in terms of the slope variation and we are continuing the program design of critical point judgement. To reduce resource competition, the extended search would be initiated by user-defined conditions and nodes in the experiments. We expect an extensive construction would help the collection of a characteristic database for superconductor materials. Within this multiply-connected platform, a quantitative and optimal evaluation would provide a fast version for returning qualitative information on the materials. We expect that this idea could be a starting point to connect cyber-physical systems with scientific big data analysis.

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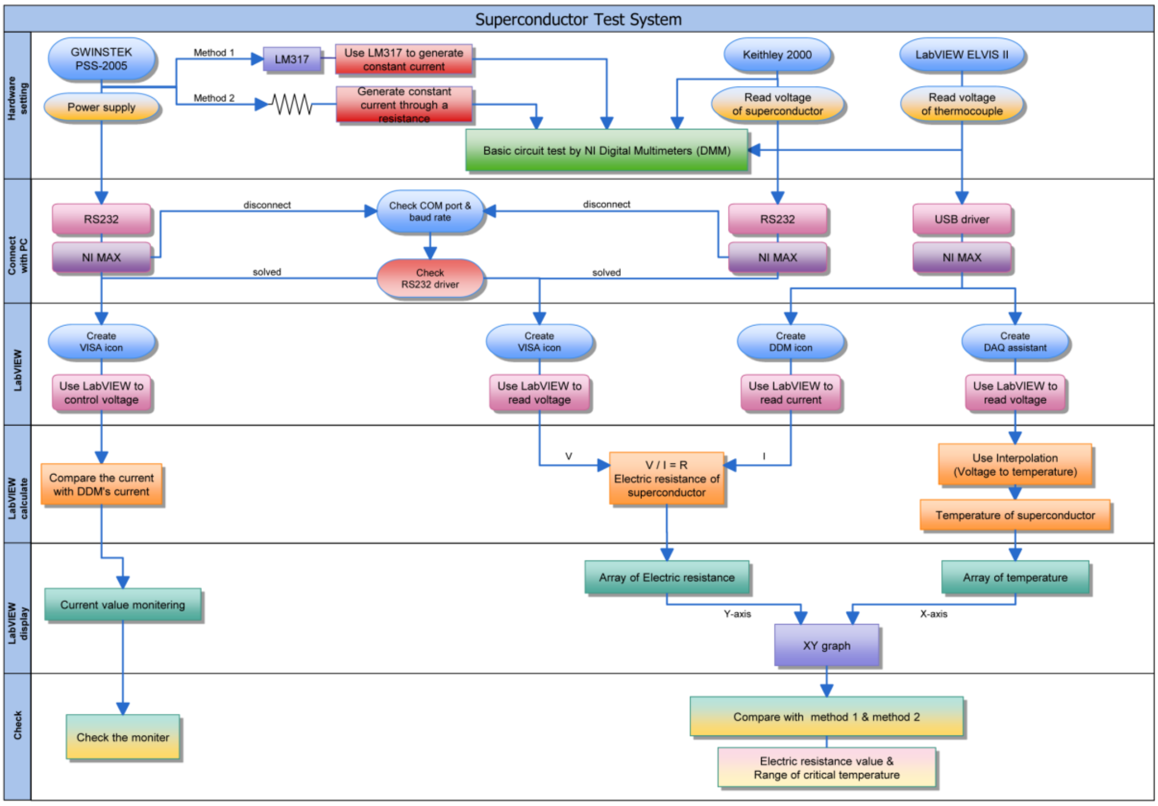

Fig. 1. A schematic diagram of the superconductor test system.

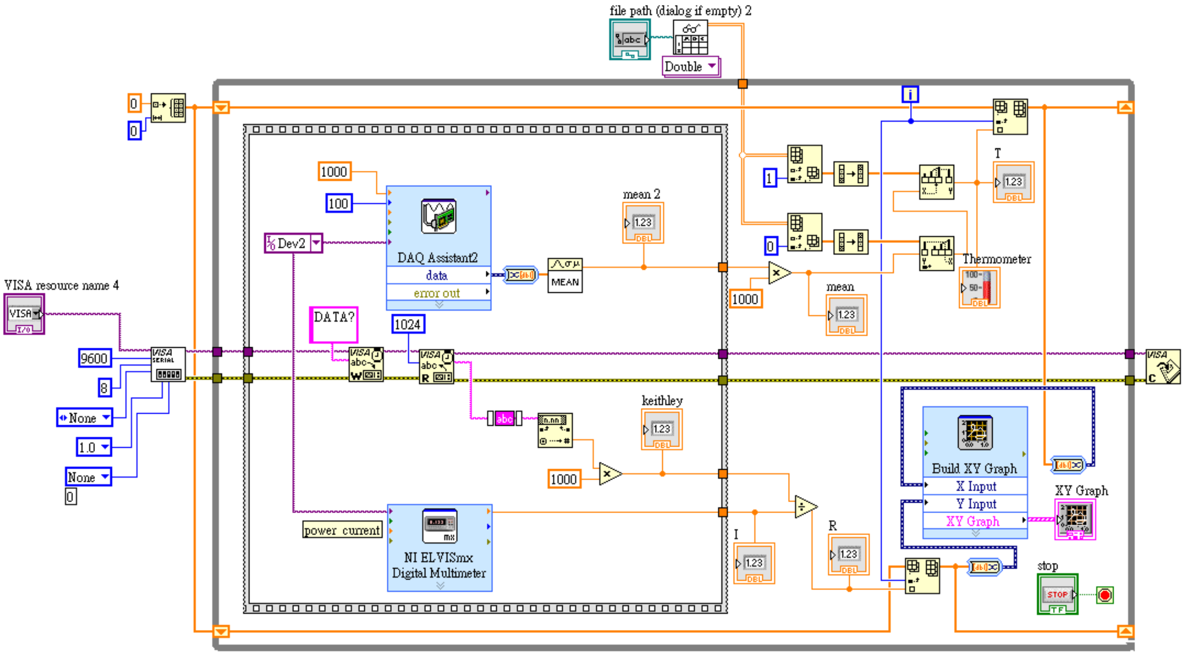

Fig. 2. Program of human-computer interface and data acquisition and analysis.

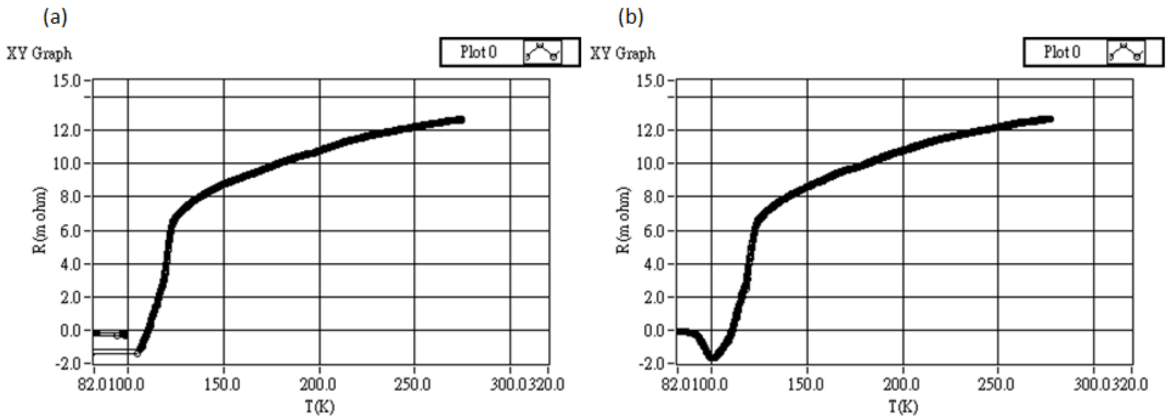

Fig. 3. Phase transition curves for (a) the GKE kit and (b) the LKE kit.

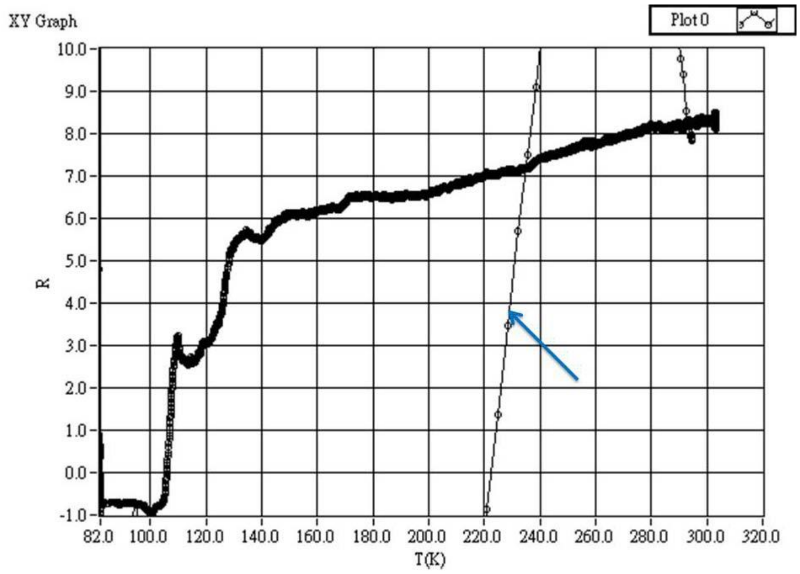

Fig. 4. Phase transition curves for temperature ascending (thick) and failed descending processes (blue arrow).

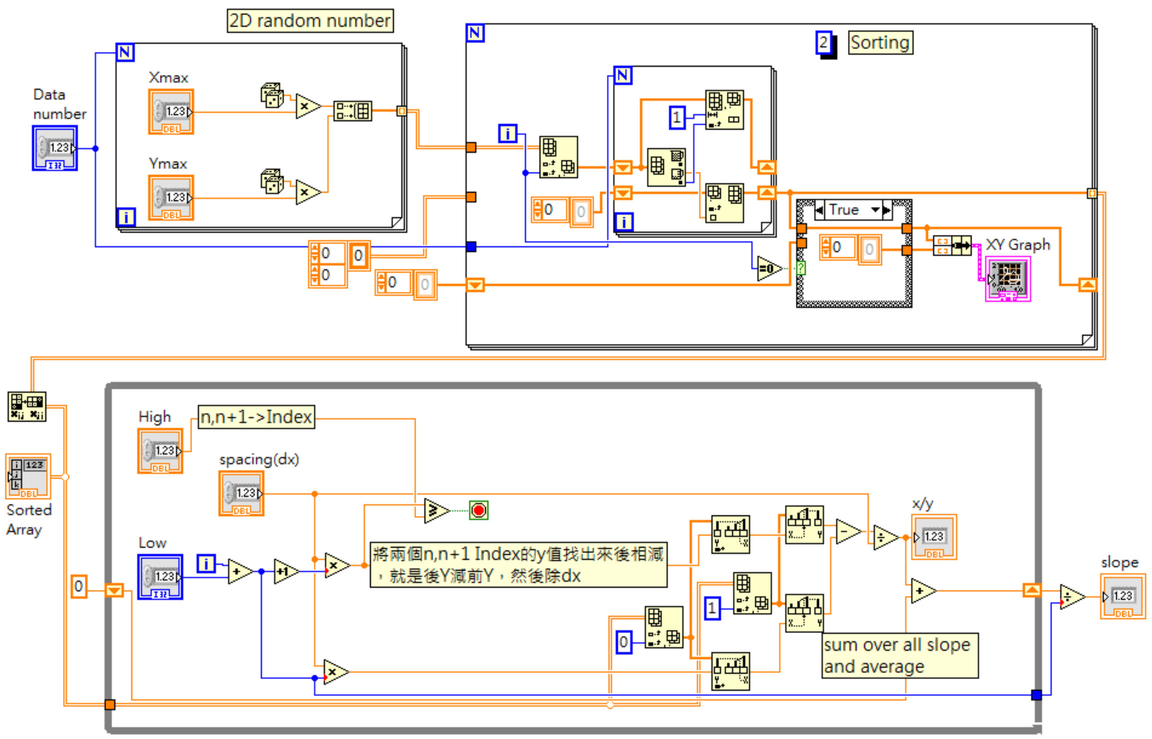

Fig. 5. The post-experiment program with user-supplied parameters serves as a prototype for smart visualization.