Research on System-level Calibration of Automated Test Equipment based
Least Square Method

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Abstract — Automated test equipment require periodic calibration. Traditional calibration method is only for some core components, but for the whole integrated equipment as a system-level calibration. This paper studies deeply the application of the least square method in the system-level calibration of automated test equipments, and propose an implementation method of the system-level calibration. Firstly, we discuss the necessity of system-level calibration and hardware structure. Secondly, we analyze the least square linear regression analysis theory and its application method in the system-level calibration. Finally, we introduce the application process of the least square method in the system-level calibration with the aid of virtual instrument design software LabWindows/CVI. Experimental results show that this method improves significantly the measurement accuracy of the test equipment.

Keywords - least square method; system-level calibration; virtual instrument design software; test equipment

I. INTRODUCTION

In the modern industrial production, automated test equipments are used widely in quality control, performance evaluation and the functional verification of electronic products. Accuracy and reliability of test equipments are the key to judging and evaluating the tested product quality. An Automated test equipment typically consists of signal acquisition, signal conditioning and conversion, and display components, and so on. Calibration is usually only for the core components such as power supply, data acquisition, communication boards, and so on. This may cause some core parts are qualified, but the errors the whole equipment by system integration are difficult to estimate, and thus the overall test accuracy of equipment is affected [1]. Therefore, based on the least square method and powerful data analysis and processing function of virtual instrument software, the system-level calibration for automated test equipments is feasible and necessary using a mode of manual and automatic combination [2,3].

II. PRINCIPLE AND STRUCTURE

The test for an analog input (hereinafter referred to as AI) signal is one of routine test items. So taking AI signal test for example, the principle of system-level calibration and hardware structure are introduced. The amplitude varies with the function of the AI signal in different test equipments. For example, a tested power supply voltage on a car system circuit board is ±28V, a tested "Audio" signal in an "ejection" device is the square-wave which voltage is +15V, and so on. The principle of AI signal test and system calibration is shown in Fig.1. The switch S is connected to the terminal A, the system is in the state of normal test. The tested AI signal is sent to the AD data acquisition card flowing through the signal conditioning circuit, and then is tested automatically used by the computer program. The measurement range of the input voltage of the AD data acquisition card is generally -10V ~ +10V. A linear attenuation or amplification circuit is required for the AI signal which is beyond the amplitude range. In order to
eliminate the interference of test equipment to tested product in the test process, electrical isolation between the two is usually required. Signal conditioning circuit on the one hand can make the AI signal to attenuate or amplify linearly, on the other hand can complete the photoelectric isolation between the test product and equipment. Thus, in the automation equipment, data acquisition card input is not directly connected with the output of the tested product, but through the signal conditioning circuit switching. Traditional AI signal calibration is only for the calibration data acquisition card. But we can see by the system structure, even if the data acquisition card has been calibrated, the overall test system also can be introduced into other system errors due to the presence of the conditioning circuit or other switching circuits. Therefore, calibration must be carried out for the whole test system as shown in Fig. 1. The switch S is connected to the terminal B, the system is in the state of calibration. From the AI terminal of calibration panel area on the test equipment, a set of standard analog signals are inputted by time-sharing control. After the upper industrial control computer collects the signals, the calibration software written according to the least square method will process the data precisely and record, save, display processing results. So the system-level calibration of the tested AI signal is completed.

![Image](composition block diagram of AI signal system-level calibration function)

III. THEORETICAL ANALYSIS

In order to solve some practical engineering problems, according to several groups of experimental datas about the two associated variables x and y, the approximate analytic expressions(also known as empirical formula) of the function relation between them need be found usually to make a judgment about the relationship (in addition to the experimental datas) between x and y. The principle of solving this problem is to minimize the sum of squares of deviations of the values of the fitting function in the point \( x_i \) and the experimental values. That is, the expression

\[
\sum_{i=1}^{n} [f(x_i,a) - y_i]^2
\]

can obtain the minimum value. This method which can realize the best fitting for the experimental datas in the sense of variance is called the "least squares method" [4-6]. N groups of datas, which have been measured, about the two associated variables x and y are shown in Table 1. Taking x as the horizontal coordinate, taking y as the vertical coordinate on the xOy coordinate plane, the corresponding n coordinate points \( P_i(x_i,y_i) \) ( \( i=1,2,...,n \) ) can be obtained. If these points are roughly distributed around a straight line, the relationship between the two variables can be considered as linear. The relationship expression is \( y=ax+b \), and \( a, b \) are undetermined constants. Selecting the appropriate values of \( a \) and \( b \) can minimize the sum of the \( \{ y_i-(ax_i+b) \}^2 \) ( \( i=1,2,...,n \) ) to ensure that the line \( (y=ax+b) \) is closer to the connection line of all experimental data points. So the problem comes down to: Determining values of \( a \) and \( b \) in the expression \( y=ax+b \) to make

\[
W(a,b) = \sum_{i=1}^{n} [y_i-(ax_i+b)]^2 = \min \sum (y_i-ax_i-b)^2
\]

minimum, and to make that the line \( (y=ax+b) \) is closer to the connection line of all \( P_i(x_i,y_i) \) ( \( i=1,2,...,n \) ) points.

<table>
<thead>
<tr>
<th>Table I. EXPERIMENTAL DATAS OF ASSOCIATED TWO VARIABLE X, Y</th>
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<tbody>
<tr>
<td>( y_1 ) (voltage values of standard AI signal)</td>
</tr>
<tr>
<td>( y_2 )</td>
</tr>
<tr>
<td>( y_3 )</td>
</tr>
<tr>
<td>( \cdots )</td>
</tr>
<tr>
<td>( y_n )</td>
</tr>
</tbody>
</table>

The above-mentioned values of \( a \) and \( b \) in the least square linear regression expression can be solved by
the method of the extremum of multivariate function. Solving the partial derivatives of \( a \) and \( b \) in the function

\[
W(a,b) = \sum_{i=1}^{n} (y_i - ax_i - b)^2
\]

we get:

\[
\frac{\partial W}{\partial a} = -2\sum_{i=1}^{n} (y_i - ax_i - b)x_i = 0
\]

\[
\frac{\partial W}{\partial b} = -2\sum_{i=1}^{n} (y_i - ax_i - b) = 0
\]

If \( \frac{\partial W}{\partial a} = 0 \), then

\[
\sum_{i=1}^{n} (y_i - ax_i - b)x_i = 0
\]

and then

\[
a \sum_{i=1}^{n} x_i^2 + b \sum_{i=1}^{n} x_i = \sum_{i=1}^{n} x_i y_i
\]

\[
a \sum_{i=1}^{n} x_i + nb = \sum_{i=1}^{n} y_i
\]

Solving the simultaneous Eq. (2):

\[
\begin{align*}
& a = \frac{n \sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i) (\sum_{i=1}^{n} y_i)}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \\
& b = \frac{\sum_{i=1}^{n} x_i^2 (\sum_{i=1}^{n} y_i) - (\sum_{i=1}^{n} x_i) (\sum_{i=1}^{n} x_i y_i)}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}
\end{align*}
\]

The simultaneous Eq. (3) can be simplified as:

\[
\begin{align*}
a &= \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \\
b &= \bar{y} - ax \bar{x}
\end{align*}
\]

where \( \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \) and \( \bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \). So the empirical formula \( y = ax + b \) can be gotten.

### IV. DESIGN AND RESULTS

When the automated test equipment is in the state of calibration, it can measure a set of standard analog signals from the AI terminal by time-sharing control, and save this group of associated experimental datas. The values of standard AI signals is as the dependent variable ‘\( y_i \)’. The initial measured value is as the independent variable ‘\( x_i \)’. The empirical formula \( y = ax + b \) can be worded out by the data processing of the least square method.

When the automated test equipment is switched to the state of normal test, the initial measurement value of one AI signal can be obtained by the equipment system, which is recorded as \( x_0 \). Bringing \( x_0 \) to the empirical formula, the revised precise measurement value of the calibration can be obtained, which is recorded as \( y_0 \). So the calibration work of one AI signal has been completed.

#### A. Upper Computer Software Design for Calibration

The upper computer software for the system-level calibration is developed based on LabWindows/CVI produced by NI company[7,8]. The main functions of the operating software cover: (1) record completely the multi group standard input and measured voltage values; (2) linearly fit above datas with the least square method to obtain the empirical formula; (3) save the \( a \) and \( b \) parameters in the empirical formula to facilitate using during the normal testing process[9,10]. The design flow chart of the operating software is as shown in Fig. 2.
B. Calibration Process and Experimental Results

After the design and assembly of the calibration circuit of an automated test equipment were completed, we have calibrated 16 AI signal channels on the system-level. The calibration of one of AI signal channels is taken as an example to expound the system-level calibration process. The voltage range of this AI signal channel is -15V~+15V. The test system is switched to the calibration status, as shown in Fig. 1. Then the standard source voltage signal is added to the AI calibration terminal. In the calibration operating software interface of the upper computer, as shown in Fig.3, select the corresponding channel number, enter the known standard voltage value, click on the "Test" button, through signal conditioning circuit, AD data acquisition card, the upper computer can get the measured voltage values, display them, and record them in the left side table according to the serial number. In order to ensure that the AI signal can be accurately calibrated in the whole voltage range, the standard source voltage output amplitude is manually adjusted by each increase of 1V voltage from -15V to +15V voltage. Adjusting and measuring the same AI signal channel 31 times, the measured data are shown in Fig.3. As you can see that there is a certain deviation between every measured value and the associated standard input value. The measured data is as the independent variable ‘x’. The standard source voltage data is as the dependent variable ‘y’. Clicking the "linear fitting" button in Fig.3, the original data from equal precision measurement are calculated by the least square method to obtain the empirical formula. As shown in Fig.3, a=1.01 and b=-0.009 in the empirical formula.

When the test equipment is switched to the state of normal test, the tested AI signal can input from the channel which has been calibrated. The voltage amplitude value of the input signal is called as $U_i$. The uncorrected measured voltage value is called as $U_i'$. With the calibration results to correct the measured data, the measured voltage value which has been calibrated is called as $U_o$. Then

$$U_o = aU_i' + b = 1.01U_i' - 0.009 \quad (5)$$

The measured values are corrected based on The Eq. (5), the experimental data are shown in Table 2. Comparative data before and after calibration show the system-level calibration method can improve the measurement accuracy of the signal significantly.

<table>
<thead>
<tr>
<th>Table II. EXPERIMENTAL DATAS OF AI CALIBRATION FUNCTION</th>
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<tbody>
<tr>
<td>Standard input voltage values (V)</td>
</tr>
<tr>
<td>----------------------------------</td>
</tr>
<tr>
<td>-8.6</td>
</tr>
<tr>
<td>-4.5</td>
</tr>
</tbody>
</table>
V. CONCLUSIONS

Based on the least square method of monadic linear regression analysis, an implementation method of the system-level calibration of automatic test equipment is proposed with the help of virtual instrument design software LabWindows/CVI with powerful data analysis and processing functions. Traditional calibration method is only for some core components, but for the whole integrated equipment. Experimental results show that this system-level calibration method can solve the above problem, and improve significantly the measurement accuracy of the test equipment. The implementation method has been applied in some test platform. After the assembly, debugging and field trial operation, the system-level calibration module has been checked and accepted by users and is regarded as working well.

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