

# A Dependency Matrix-Based Approach for Designing ATE Calibration Strategy

Wei Jiang, Qi Zhang

*Department of Instrument Science and Technology, College of Mechatronics and Automation,  
National University of Defense Technology, Changsha, Hunan, P.R. China, 410073  
vivian\_nudt@163.com, zhang\_qi\_7233@163.com*

**Abstract** – In order to calibrate ATE (automatic test equipment) effectively and accurately, in this paper, a calibration strategy design approach based on dependency matrix for ATE is developed. According to the characteristics of information flow and logic relations which the trace chain of ATE included, the dependency matrix is derived to present the causal relationship between out-of-tolerance conclusion and calibration. Two weights are respectively defined using dependency matrix to select calibrations for detection and location of out-of-tolerance conclusion. Calibration strategy tree is used for the presentation of the selected calibration operation and its order. With this approach, the calibration efficiency could be improved and the cost could be reduced significantly. Finally, we applied the approach to a practical ATE and the results are analyzed, so as to verify the effectiveness of the proposed approach.

**Keywords**- ATE, Calibration strategy, dependency matrix

## I. INTRODUCTION

ATE is widely applied in various field, such as aerospace automatic test industry. Calibration for ATE can be defined as the verification of instrumentation accuracy by comparing the instrument to a known standard [1]. Calibration specification for ATE is set according to various manuals of instrument that ATE included, provided by manufacturers. Since ATE is highly integrated with huge numbers of measurement signal, it will surely cause serious burden on the ATE design and development to set measuring interfaces for each measurement signal to be calibrated, including increased design difficulty, raised cost of development, etc. The goal of ATE calibration strategy is to utilize the most economic and efficient scheme to achieve ATE regular metrology by optimizing selection of calibration resources and parameters and reasonably scheduling them. This paper develops an approach to design the calibration strategy for ATE based on dependency matrix, which is refer to the idea of dependency matrix in system multi-signal modeling for testability[2-7]. According to the logic relationship in the trace chain of ATE, this paper also defines a dependency matrix to indicate the causal relationship between calibration and out-of tolerance (OT) conclusions. If an OT conclusion inevitably leads to a calibration abnormal, or, on the contrary, if the normal

calibration means that the OT conclusion does not happen, then we can say that the calibration and the OT conclusions is logic relative. We design the calibration strategy using the information provided by dependency matrix.

This paper is organized in 4 sections. Section 2 amply introduces the design approach of calibration strategy based on dependency matrix. A practical example is given and the result is analyzed in section 3. The conclusions are shown in section 4.

## II. APPROACH FOR ATE CALIBRATION STRATEGY DESIGN

The approach used for the design of ATE calibration strategy includes three parts: the establishment of dependency matrix, the calculation of weight of OT detection and OT location, and the construction of calibration tree. More details about these three parts are given in the following.

### A. Dependency matrix

Since ATE usually consists of many modular instruments and benchtop instruments, in order to take full advantage of the test resources in the ATE, on-station calibration has become one of the main approaches to calibrate ATE. The instrument with higher accuracy can be used to calibrate the instrument with lower accuracy, then the instrument with the highest accuracy will be calibrated by external standard, thus the unbroken trace chain is decided according to the precision of instruments. The trace chain is a mode of information flow. The quantity information is transferred from the higher accuracy instrument to the lower. At the same time, the elements in the trace chain have logic relations [8]. For example, if the instrument with higher accuracy is out of tolerance, it can't be used to calibrate the lower accuracy instrument. The dependency matrix named *OC* matrix can be established according to the characteristic of logic information flow in the trace chain, which describes the relationship between calibration and OT conclusion. The detailed meaning is as follows:

The rows of the *OC* matrix refer to the calibrations corresponding to "1" in the row are abnormal if the instrument is out-of-tolerance. There are two kinds of abnormal conditions: one is that the calibrated instrument

is out of tolerance, and the other is lack of traceability. The columns of  $OC$  matrix explain that the corresponding calibration can verify which instrument is out of tolerance. As long as one element of “1” corresponding calibration result of OT occurred, the column’s calibration will be abnormal and the measurement result of ATE is unacceptable [9].

### B. OT detection

The detection of OT (OTD) is to determine whether the instrument included in an ATE is OT. For the purpose of detect OT with minimal detection operations, the calibration related to more OT conclusions should be done firstly, a weight of OTD is defined in this paper to help the determination of calibration for detection. Given the  $OC$  matrix  $OC = [d_{ij}]_{m \times n}$ , the weight of OTD of the  $j$ -th calibration  $W_{OTD_j}$  (it is a quantity for weighing provided information for OTD) can be defined as:

$$W_{OTD_j} = \sum_{i=1}^m d_{ij} \quad (1)$$

After each  $W_{OTD}$  is obtained, the calibration with the maximum  $W_{OTD}$  should be done at first. The  $OC$  matrix can be divided into two submatrixes according the corresponding column matrix  $V_j$ :

$$OC_p^0 = [d]_{z \times (n-1)} \quad (2)$$

$$OC_p^1 = [d]_{(m-z) \times (n-1)} \quad (3)$$

Where,  $OC_p^0$  and  $OC_p^1$  is respectively consist of “0” and “1” corresponding rows in the  $V_j$ ;  $z$  is the number of “0” element in the  $V_j$ ;  $p$  is just a subscript to express the sequence number of selected calibration.

After the first calibration is obtained,  $p=1$ . If the row number of  $OC_1^0$  is not 0 ( $z \neq 0$ ), then the  $W_{OTD}$  of each column of  $OC_1^0$  should be calculated to choose the second calibration operation and also to divide  $OC_1^0$ . Above procedure should be repeated until the column corresponding to the selected calibration has no element of “0”. When more than one calibration has the maximum  $W_{OTD}$  in this procedure, the calibration with easier operation and lower cost should be choose [10].

### C. OT location

OT location (OTL) is a process to determine the OT’s position. ATE is divided into two parts of normal and OT

according to the result of the first detection, only the part that has instrument OT would be calibrate next, until this part becomes a single model and the OT is calibrated. The average calibration steps should be as little as possible for an efficient calibration strategy. This paper also defines a weight of OT location  $W_{OTL}$  to choose the calibration operation [11].

This paper takes the idea of binary search algorithm as reference to define the  $W_{OTL}$ . Calibrations are regarded as a sequence arranged by associated OT number. The calibration associated with OT number which is the nearest to median of OTs to be location is preferable in each choice, so that about half of OTs can be excluded whether each calibration is pass or not. Let us provide  $C$  for the sum of positive number  $A$  and  $B$ , It can be proved that, the product of  $A$  and  $B$  is the largest only when  $A = B = C / 2$ ; therefore, the  $W_{OTL}$  of  $j$ -th calibration is given by:

$$W_{OTL_j} = N_j^1 N_j^0 = \left( \sum_{i=1}^m d_{ij} \right) \left( \sum_{i=1}^m (1 - d_{ij}) \right) \quad (4)$$

Where,  $N_j^0$  and  $N_j^1$  are respectively the number of “0” and “1” element in the column matrix  $V_j$ .

After each  $W_{OTL}$  is obtained, the calibration with the maximum  $W_{OTL}$  should be done at first. The  $OC$  matrix can be divided into two submatrixes according the corresponding column matrix  $V_j$ :

$$OC_p^0 = [d]_{z \times (n-1)} \quad (5)$$

$$OC_p^1 = [d]_{(m-z) \times (n-1)} \quad (6)$$

Where,  $OC_p^0$ ,  $OC_p^1$ ,  $z$  and  $p$  are the same as earlier defined. After the first calibration for location is determined,  $p=1$ . If the result of the first calibration is pass, the  $W_{OTL}$  of each column of  $OC_1^0$  should be calculated to choose the second calibration operation and also to divide the  $OC_1^0$ , otherwise the  $W_{OTL}$  of  $OC_1^1$  should be calculated. Above procedure should be repeated until the submatrix which has OT becomes single row. Similarly, when more than one calibration has the maximum  $W_{OTL}$  in this procedure, the calibration with easier operation and lower cost should be choose.

### D. Calibration strategy tree

The calibration strategy designed in this paper can be presented by a simple graph named calibration strategy tree (CST), which is refer to the idea of fault tree [10]. First, we draw two branches according to the results of

normal and OT of the first OTD calibration operation: For the normal branch (presented by “0”), we continue to detect using the second OTD operation and again draw

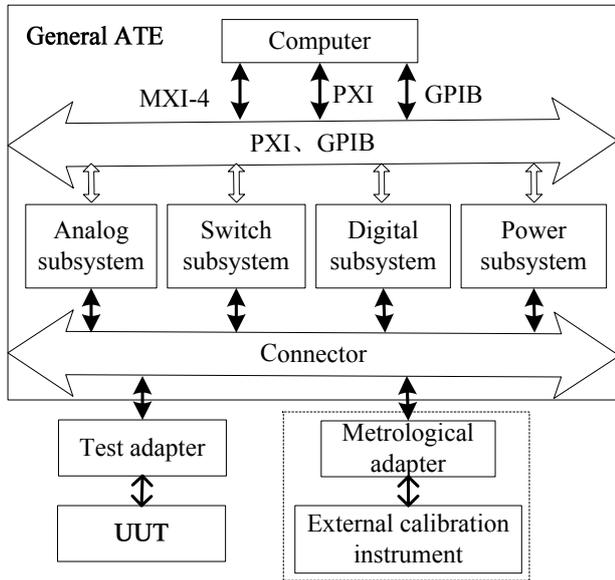


Fig.1 The ATE hardware

two branches of normal and OT. Above procedure should be repeated for the following normal branch until we reach the conclusion that ATE has OT or not, while the failed branch should be detected by calibration operation for OTL.

For the OT branch (presented by “1”), the first OTL calibration operation should be applied to it and also two branches can be obtained according to the result of OTL operation. These two branches continue to be detected with corresponding second OTL operation to get another two branches until we have located all OT conclusions.

To conclusion, the first calibration is the root, the obtained two branches is the crotch. Each branch can be divided into two branches again after the following calibration operation. Above procedure should be repeated until it is a single OT or normal state (namely, leaf) at the end of the branch. Thus, the CST is achieved.

### III. EXAMPLE

There is a practical ATE which adopts signal-oriented design idea. According to the signal features (signal type and signal intensity, etc.) and test mission requirements, its internal resources are divided into four main parts: analog subsystem, switch subsystem, digital subsystem and power subsystem, as is shown in Fig. 1. In dotted box of Fig. 1 is external connection structure for ATE metrology, the work for ATE metrology can be completed by connecting the metrology adapter to the ATE connector. Since signal strength is different among subsystems (such as power subsystem and digital subsystem), if possible, it is better to establish trace chain within each subsystem. Only when the difference of

signal strength is small or establishment within subsystem is difficult, it is considerable to search for calibration source in other subsystem to establish their

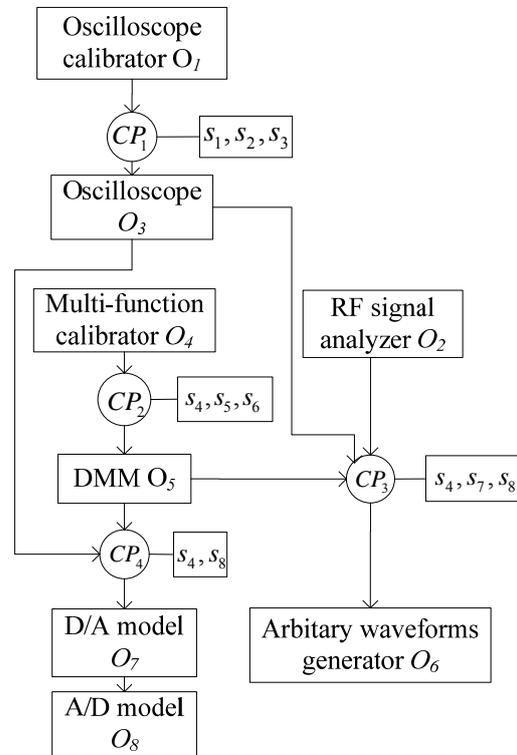


Fig.2 Multi-signal flow graph of ATE trace chain.

own trace chain. In short, ATE measurement chain is determined by the precision and input/output range of the instruments or function modules included in the overall technical indicators of general ATE.

In order to simplify the research and facilitate illustration and understanding, we take only the analog subsystem of this ATE as an example to demonstrate the implementation of above design approach and show the significance of the calibration strategy in this section.

The analog subsystem includes an oscilloscope, a DMM, a RF signal analyzer, an arbitrary waveforms generator (AWG), an AD channel and a DA channel. To ensure the accuracy of the ATE, all the instruments should be calibrated in a certain period of time. Since these instruments have several measurement ranges and different accuracy, we design the trace chain according to the accuracy of these instruments for the ATE, shown in Fig.2, the oscilloscope with 8-bits accuracy and the DMM with 6.5-bits accuracy are in the top of the internal trace chain. First, these two instruments are calibrated by external standard instruments (such as oscilloscope calibrator), and then other instruments (such as AWG) with lower accuracy are calibrated by these two instruments. So a trace chain is achieved by combining internal instruments and external instruments to realize the traceability of all instruments of ATE. As both

oscilloscope and AD channel are measurement instruments, AD channel trace to oscilloscope using DA channel as a mediator.

### A. Dependency matrix

Table 1. A list of calibration operation.

Calibration point	$CP_1$		$CP_2$		$CP_3$		$CP_4$				
calibration	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_8$	$C_9$	$C_{10}$	$C_{11}$
parameter	$S_1$	$S_2$	$S_3$	$S_4$	$S_5$	$S_6$	$S_4$	$S_7$	$S_8$	$S_4$	$S_8$

First, according to the calibration specification, we list the calibration points and corresponding parameters, shown in Table 1, and then we construct the multi-signal flow graph for the trace chain of ATE, shown in Fig.2. The output voltage and frequency of D/A channel of 13-bits resolution are respectively traced to DMM and oscilloscope; the calibration instrument of DC gain and offset of AWG is DMM NI PXI-4070, and that of output frequency of AWG is RF signal analyzer NI PXI-5660. For the convenience of observation and analysis of waveform, AWG is also connected to the oscilloscope Tek DPO3054B to establish measurement chain. In Fig.2,  $O_i$  is the instrument or model of ATE;  $CP_i$  is the calibration point in the trace chain;  $C_i$  is the calibration operation;  $O_i(G)$  is the fault of instrument ;  $O_i(S_j)$  is the OT parameter  $S_j$  of instrument  $O_i$ ;  $S_i$  is parameter to be detected, specific as follows:

$S_1$  is static amplitude parameters, including linearity, calculus linear, error limit, dc gain and error, dc offset and error, random noise.

$S_2$  is dynamic amplitude parameter, including ac gain and error, SNR, analog bandwidth and frequency response,

Table 2. Dependency matrix of calibration and OT conclusion.

	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_8$	$C_9$	$C_{10}$	$C_{11}$
$O_3(G)$	1	1	1	0	0	0	0	1	0	0	1
$O_3(S_1)$	1	0	0	0	0	0	0	1	0	0	1
$O_3(S_2)$	0	1	0	0	0	0	0	1	0	0	1
$O_3(S_3)$	0	0	1	0	0	0	0	1	0	0	1
$O_5(G)$	0	0	0	1	1	1	1	0	0	1	0
$O_5(S_4)$	0	0	0	1	0	0	1	0	0	1	0
$O_5(S_5)$	0	0	0	0	1	0	0	0	0	0	0
$O_5(S_6)$	0	0	0	0	0	1	0	0	0	0	0
$O_6(G)$	0	0	0	0	0	0	1	1	1	0	0
$O_6(S_4)$	0	0	0	0	0	0	1	0	0	0	0
$O_6(S_7)$	0	0	0	0	0	0	0	1	0	0	0

$O_6(S_8)$	0	0	0	0	0	0	0	0	0	1	0	0
$O_8(S_4)$	0	0	0	0	0	0	0	0	0	0	1	0
$O_8(S_8)$	0	0	0	0	0	0	0	0	0	0	0	1

etc.

$S_3$  is time scale parameter, including sampling rate (real-time, equivalent), time-based errors, etc.

$S_4$ ,  $S_5$  and  $S_6$  are respectively voltage, current and resistance.

$S_7$  is waveform parameters, including the type of waveform, frequency range and resolution, etc.

$S_8$  is frequency parameter.

According to the multi-signal flow graphs, we can obtain the OC matrix to describe the relationship between calibration and OT conclusion, as is shown in Table 2.

### B. Calibration strategy

Table 3.  $W_{OTD}$  and  $W_{OTL}$  of each column of OC matrix.

	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_8$	$C_9$	$C_{10}$	$C_{11}$
$W_{OTD}$	2	2	2	2	2	2	4	6	2	3	5
$W_{OTL}$	24	24	24	24	24	24	40	48	24	33	45

First,  $W_{OTD}$  and  $W_{OTL}$  of each column of OC matrix are respectively calculated by equation (1) and (4), as is shown in Table 3, from which we can see that  $C_8$  has the maximal  $W_{OTD}$  and  $W_{OTL}$ , so  $C_8$  is the first calibration to be done.

Having obtained the first calibration  $C_8$ , we separately use “0” and “1” corresponding rows to form  $OC_1^0$  and  $OC_1^1$ , as is shown in Table 4. After that, both  $W_{OTD}$  of each column of  $OC_1^0$  and  $W_{OTL}$  of each column of  $OC_1^1$  are calculated. From Table 4 we can see that  $C_7$  and  $C_{10}$  have the same  $W_{OTD}$ , here  $C_{10}$  will be the second calibration to detect OT, for it is easier to perform. Whereas  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_{11}$  have the same  $W_{OTL}$ ,  $C_1$  will be the second calibration to locate OT. Above procedure should be repeated until it is a single OT conclusion or pass state at the end of the branch.

The CST of ATE is shown in Figure 3. Through query and traverse of the CST, metrologist can detect and locate ATE OT conclusion easily, so as to complete calibration work efficiently.

### C. Result analyses

On the one hand, both  $W_{OTD}$  and  $W_{OTL}$  of calibration operation  $C_8$  in the forth calibration point  $CP_4$  (the calibration for AWG) of multi-signal graph are the maximal value among all calibration operations, so  $C_8$  is used as the first calibration; on the other hand, from the

trace chain of ATE we can see that ensuring the accuracy of the oscilloscope is the premise of AWG calibration, once there is a OT conclusion in the oscilloscope, it cannot be used for the calibration of the AWG, therefore,

Table 4.  $W_{OTD}$  and  $W_{OTL}$  of each column of OC matrix.

		$OC_1^0$									
		$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_9$	$C_{10}$	$C_{11}$
$O_5(G)$	0	0	0	1	1	1	1	0	1	0	
$O_5(S_4)$	0	0	0	1	0	0	1	0	1	0	
$O_5(S_5)$	0	0	0	0	1	0	0	0	0	0	
$O_5(S_6)$	0	0	0	0	0	1	0	0	0	0	
$O_6(S_4)$	0	0	0	0	0	0	1	0	0	0	
$O_6(S_8)$	0	0	0	0	0	0	0	1	0	0	
$O_8(S_4)$	0	0	0	0	0	0	0	0	1	0	
$O_8(S_8)$	0	0	0	0	0	0	0	0	0	1	
$W_{OTD}$	0	0	0	2	2	2	3	1	3	1	

		$OC_1^1$									
$O_3(G)$	1	1	1	0	0	0	0	0	0	0	1
$O_3(S_1)$	1	0	0	0	0	0	0	0	0	0	1
$O_3(S_2)$	0	1	0	0	0	0	0	0	0	0	1
$O_3(S_3)$	0	0	1	0	0	0	0	0	0	0	1
$O_6(G)$	0	0	0	0	0	0	1	1	0	0	
$O_6(S_7)$	0	0	0	0	0	0	0	0	0	0	
$W_{OTL}$	8	8	8	0	0	0	7	7	0	8	

the AWG should be calibrated first. The calibration strategy based on dependency matrix is consistent with practical calibration work, which show that the defined  $W_{OTD}$  and  $W_{OTL}$  are significant.

Let  $p$  the number of branches,  $K_i$  is the step number of the  $i$ -th branch, the average calibration operation number of ATE can be calculated:

$$N_D = \frac{1}{p} \sum_{i=1}^p K_i \quad (7)$$

$$= \frac{1}{15} (7 \times 2 + 6 + 5 + 4 \times 7 + 3 \times 4) = 4.33$$

The average calibration operation number of designed calibration strategy for ATE is 4.33, as for the normal calibration scheme, there are total eleven items of four instruments in this ATE to be calibrated, obviously, the workload is much bigger ; in addition, we can see from Figure 2 that through seven calibration operations ( $C_8$ ,

$C_{10}$ ,  $C_5$ ,  $C_6$ ,  $C_7$ ,  $C_9$ ,  $C_{11}$ ) in sequence, we can determine whether ATE is in tolerance or not. Generally speaking, ATE is in tolerance most of the time, hence, we can draw conclusion that ATE is in tolerance by this

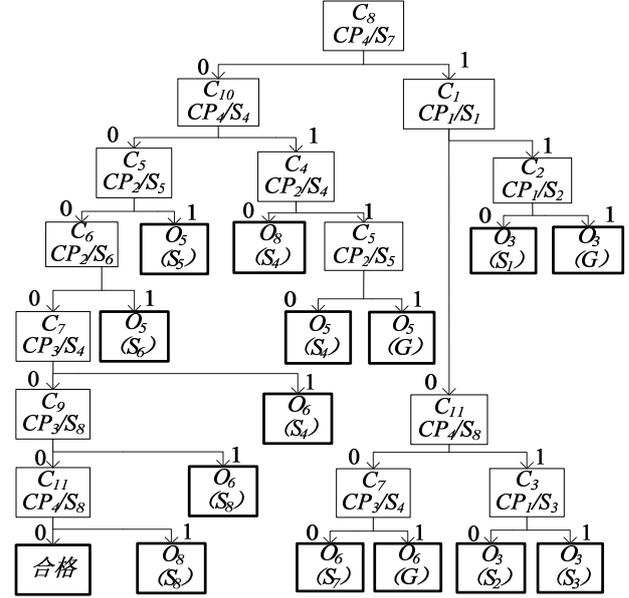


Fig. 3. Calibration strategy tree.

group of calibration operations in regular ATE calibration work, without the need of calibration for all parameters of all instruments and obviously improve the efficiency of the calibration work.

#### IV. CONCLUSIONS

Calibration strategy is helpful to reduce the error of ATE in use as much as possible and to maintain the minimum cost of calibration. A design approach of ATE calibration strategy based on dependency matrix is introduced in detail in this paper. Take an ATE as an example, the detailed process is illustrated and the results are analyzed to show its significance. This calibration strategy has the characteristic of adaptive, for the next calibration operation is decided by previous calibration result, and the design approach has nothing to do with the type of the calibrated ATE, it is applicable to all kinds of ATE.

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