Development and Application of Standard Device for Calibrating Steel Measuring Tape Based on Machine Vision

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Featured Application: A standard device of steel measuring tape based on machine vision is used for the intelligent detection of steel measuring tape, with accurate, fast, and automatic characteristics. The application of this device falls within the scope of metrology.

Abstract: Aiming to address the disadvantages of the low automation degree of the traditional steel measuring tape verification device, as well as the high labor intensity of metrologists, high time costs, and low measurement accuracy, this paper develops a new automatic steel measuring tape calibration device based on machine vision technology. In this study, the key components, such as the tape-winding mechanism, machine vision system, force measuring device, and tape-retracting device, were designed. Three different scribed line identification and location algorithms, processing the longest line, the closest to the starting line, the highest line, etc., were designed to adapt to different types of steel measuring tape. Lastly, indication error and measurement repeatability tests were carried out. The results showed that the standard device can carry out the verification and calibration of steel measuring tape, and the maximum repeatability of the indication error of the test objects was 0.025 mm, 0.038 mm, and 0.030 mm, respectively, and the indication error of each object was within the allowable error limits. The uncertainty evaluation of the indication error of each test object was 0.16 mm, 0.54 mm, 0.78 mm, which was not more than one third of the maximum permissible error value. Hence, the measuring principle, method, and procedure of the calibration device are shown to be scientific and feasible.

Keywords: metrology; steel measuring tape; calibration device; machine vision; pixel calibration; indication error calibration; scribed line recognition algorithms

1. Introduction

Steel measuring tape (SMT) is a common length measuring instrument that is used to measure commodity length and safety distances and has been listed in the catalogue of measuring instruments for compulsory verification work of the People’s Republic of China. Therefore, it is particularly important to calibrate the SMT [1]. According to the “Verification Regulation of Steel Measuring Tapes JG 4-2015”, the maximum permissible error value (MPEV) of SMT must not exceed 0.2 millimeter per meter, and the standard tape (ST) with high precision whose MPEV does not exceed 0.06 millimeter per meter is used as a measurement standard to calibrate the SMT. At the national level, NIST of the United States, PTB of Germany, and RIEM of Japan all adopt the laser interferometer method to calibrate SMT [2–4]. The laser interferometer, as the measurement standard, gives the standard value with an uncertainty of ±500 nanometer per meter. The indication error can be obtained by comparing the indication value of the SMT with the standard value [5]. Although the laser interferometer method has high precision, its cost is also
high, and thus not suitable for verifying the SMT. At present, most provincial measuring institutions in China still use the traditional method to complete the calibration process of SMT. The ST with high precision is used as the measurement standard and gives the standard value. The calibration process is to place the SMT and ST on a special calibration platform side by side. After identifying the scribed line of the SMT and ST through a reading microscope and recording the indication values of the lines, then the indication error can be calculated. It takes at least an hour for a skilled tester to calibrate an SMT with a range of 100 m. This process is characterized by low automation, low digitalization, low measuring accuracy, and high labor intensity [6,7]. To sum up, a measurement standard for calibrating SMT with low cost, high measurement accuracy, high efficiency and low labor intensity is urgently needed.

Following the development of photoelectric and image-detection vision technology, PLC and computer vision technology were introduced to the steel-tape automatic measurement system [8]. The use of machine vision technology in the automatic verification of steel tape can effectively increase efficiency and accuracy [9–11]. Grating scale measurement technology is also used in this field; Antanas et al. developed a model of the system for measuring the displacement of the tape in a raster formation device to investigate and assess the possible effects of external and internal factors on steel tape parameters [12].

Therefore, aiming to address the disadvantages of the low automation degree of the traditional steel measuring tape verification device as well as the high labor intensity of metrologists, high time costs, and low measurement accuracy, a new automatic steel measuring tape calibration device has been designed based on the research of domestic and foreign scholars. The scope of a single measurement has been broadened based on the use of the visual array image acquisition technology (currently, the upper limit of a single measurement of the common automatic detection device for SMT is 1 m, whereas the upper limit of a single measurement of the object in this paper is 5 m). In addition, the structure and working principle of key components are described in detail. Finally, a prototype has been experimentally produced, and the steel tape measure indication error and repeatability tests carried out. This study will provide a new model in the field of steel measuring tape verification.

2. Research Object

2.1. Steel Measuring Tape Calibration Device (SMTCD)

The SMTCD designed in this paper uses ST as a standard, which is mainly composed of a steel tape-winding mechanism, encoder counting mechanism, machine vision system, limit-adjusting mechanism, pressure bar mechanism, tape retracting mechanism, support bracket, granite platform, etc., as shown in Figure 1a. Figure 1b is the physical drawing of the SMTCD. The repeatability, stability, and accuracy of the device have been tested and confirmed by experts from NIM (National Institute of Metrology). The measurement accuracy reaches ±(0.02 + 2 × 10⁻⁵ L) mm (L unit: m), and the measurement range is 100 m [13].

2.2. Working Principle

From Figure 1, the machine vision system mainly refers to the eight fixed camera modules (0 m/0.5 m/1 m/2 m/2.5 m/3 m/4 m/5 m) [14]. During verification, the SMTCD adopts an industrial computer to control the fixed-position camera modules to collect and identify line pattern images of the SMT and the ST simultaneously. Within a 5 m scope, automatic measurement and data analysis can be conducted. If the steel tape exceeds 5 m, the part exceeding 5 m is driven by a stepping motor, and the SMTCD sets zero position at 5 m (and 10 m, 15 m, etc.) scribed line of steel tape measure again in combination with the counting principle of the encoder to start the next cycle of detection. Finally, the cumulative error of the values shown at each scribed line is calculated. Control principle of the SMTCD as shown in Figure 2.
In order to ensure that the rotary table is restored to its initial state to remove the steel-tape zero-installation fixture, the distance of a special reflective photoelectric sensor is established; the reflection sensors are able to determine if the rotary table is on its final lap. If it is the last lap, the rotary table stops working after the turntable is turned to a horizontal state (the rotary table position shown in Figure 3 is the horizontal state), which positioning of the new zero can be realized.

Therefore, aiming to address the disadvantages of the low automation degree of the SMT, with the low cost, high measurement accuracy, high efficiency and low cumulative error of the values shown at each scribed line, the steel-tape zero-installation fixture should be fixed on the rotary table when the winding mechanism is working, and the stepping motor drives the rotary table to rotate. As shown in Figure 3, the tape belt passes under the positioning mechanism (designed with a coded counter), the displacement of the tape belt is recorded in real time, and the rotation of the driving motor is controlled according to the current requirement, so that the accurate positioning of the new zero can be realized.

In order to ensure that the rotary table is restored to its initial state to remove the steel-tape zero-installation fixture, the distance of a special reflective photoelectric sensor is established; the reflection sensors are able to determine if the rotary table is on its final lap. If it is the last lap, the rotary table stops working after the turntable is turned to a horizontal state (the rotary table position shown in Figure 3 is the horizontal state), which conveniently and artificially removes the zero-installation fixture and steel tape.
The design of the limit mechanism and pressing mechanism ensures the straightness and parallelism of the steel tape.

### 3.2. Machine Vision System

The machine vision mechanism is shown in Figure 4. According to the working principle and in combination with the requirements for regulating the verification position, six CCD cameras with resolutions of 1944 × 2592 were arranged at each meter line with a length of 5 m, and two CCD cameras were arranged at the 0.5- and 2.5-m lines. During the operation, eight CCD cameras arranged on the verification platform took line pattern images of the standard steel tape and steel tape, in order, through high-speed image switching controlled by the computer. These were converted into digital images by a high-speed real-time image acquisition card and input into the computer for digital image processing in sequence.

As the design field of view of the CCD camera module is 33 × 44 mm, this ensures the measurement requirements of millimeter and centimeter division values and the line width error of the steel tape. The design of the limit mechanism and pressing mechanism ensures the straightness and parallelism of the steel tape.

### 3.3. Force Measuring Device

According to the “Verification Regulation of Steel Measuring Tapes JJG 4-2015”, it is necessary to stretch the tape during calibration. Different types of steel measuring tape require different tensioning force. The amount of tensioning force applied is also related to the length of the calibration platform. If the length of the calibration platform is less than 20 m, the tension force applied to the swing-type steel measuring tape is \((49 \pm 0.5)\ N\) when...
it is calibrated. If the length of the calibration platform is greater than or equal to 20 m, the tension force applied to the swing-type steel measuring tape is (98 ± 0.5) N when it is calibrated. When the measuring-depth steel tape is calibrated, different tensioning force is applied according to the mass of the metal hammer, which is (15.7 ± 0.3) N or (9.8 ± 0.3) N. Therefore, the measurement of tensioning force is very important.

Here, the force measuring device is mainly composed of two parts: the tape belt pressing mechanism and tape belt tensioning mechanism, as shown in Figure 5. Among them, the pressing mechanism is controlled by a stepping motor A to move the pressing block up and down in the z direction; the tensioning mechanism is driven by a stepping motor B to move the slide block in the x direction, and the tape belt pressing mechanism and the slide block move together in a fixed manner. Figure 5a is the nonworking state of the force measuring device, and Figure 5b is the physical figure.

Figure 5. Force measuring device: 1. Steel tape; 2. stepping motor A for pressing mechanism; 3. fixed part; 4. pressing block; 5. slide block; 6. stepping motor B for tensioning mechanism.

The working process involves the steel tape being laid flat on the granite platform, where the initial zero state is fixed. The upper computer gives instructions to the control pressing block of the tape belt pressing mechanism to move down a certain distance. The soft pressing block is pressed on the tape belt without slipping, and then the upper computer controls the slide block of the tension mechanism to move to the right, so that the tape belt is tensioned to the right to produce the required tension.

3.4. Tape Retracting Device

After verification of the steel tape, the device starts to work, which mainly consists of a servo motor, a fixed base, and a work driving arm, as shown in Figure 6. The steel tape box is fixed on the fixture. When the tape is retracted, the work driving arm drives the steel tape handle and the steel tape is wound into the tape box until the photoelectric switch is triggered and the rotary table moves to the horizontal state (mentioned in Section 3.1). The servo motor stops working and the zero fixture is manually taken out from the rotary table. Then, the last 5 m length tape belt is manually rewound.
Figure 6. Tape retracting device: 1. Servo motor for tape retracting device; 2. fixed part for motor; 3. work driving arm; 4. steel tape box; 5. adjustable fixture base; 6. head clamp; 7. fixed base; 8. tail clamp.

4. Calibration Algorithm for Pixel and Steel Tape Display Error

4.1. Pixel Calibration

For image recognition, the pixel resolution is directly related to the measurement accuracy, so pixel calibration is the first step of system calibration, as shown in Figure 7. In this design, a high-precision glass line ruler is used to calibrate pixels, and the measurement results are saved into the system. The specific calibration steps are as follows:

(1) Selection of the left scribed line and automatic recognition of the position of the cutting line (subpixel calculation), denoted as Pos_L;
(2) Selection of the right scribed line and automatic recognition of the position of the line, recorded as Pos_R;
(3) Calculate the spacing of the two lines: \( L = \text{Pos}_R - \text{Pos}_L \);
(4) The high-precision glass line ruler gives the actual measured distance \( D \) of the two-notch line or edge and the pixel resolution is \( F_{\text{pix}} = \frac{D}{L} \).

Figure 7. Pixel calibration: 1. Industrial camera (CCD camera); 2. high-precision glass line ruler.

4.2. Display Error Calibration

As the steel tape is verified by a measurement method that is compared with the standard steel tape, its indication error calibration is shown in Figure 8. The specific measurement principle is as follows:
(1) Firstly, the image recognition and measurement of the zero-scribed line distance between the steel tape and the standard steel tape is carried out under the starting camera, denoted as \( L_{\text{pos}} \);
(2) The distance between the other scribed line to be measured and the standard steel tape line under the other cameras is identified, measured, and denoted as \( R_{\text{pos}} \);
(3) The comparison reading of the scribed line can be calculated, denoted as \( L_{\text{Read}} \). \( L_{\text{Read}} = L_{\text{real}} + L_{\text{pos}} - R_{\text{pos}} + L_{\text{cail}} \), where \( L_{\text{real}} \) is the actual spacing of the standard steel tape, and \( L_{\text{cail}} \) is the modified value of the standard steel tape at the scribed line.

Then, the steel-tape indication error, denoted as \( L_{\text{Err}} \), is calculated such that \( L_{\text{Err}} = L_{\text{Work}} - L_{\text{Read}} \), where \( L_{\text{Work}} \) is the nominal value of the scribed line to be measured.

5. Different Scribed Line Recognition Algorithms

In this paper, image recognition is based on the edge detection of binary image processing [15–18]. The image is transformed into a binary graph, and then the connected domain is extracted for recognition according to the gray comparison between the scribed line and the other regions. The advantage of this method is that morphological processing can be adopted to repair the defects of binary graphs according to various defects. The edge of the binary image can be accurately located in the corresponding position of the gray image by the subpixel method.

5.1. Identification of the Longest Scribed Line

Different manufacturers and different types of steel tape have different scribed line features. For a large part of steel tape, the feature of the whole meter or whole decimeter line is the longest, as shown in Figure 9. The longest feature of the line can be used for identification and extraction. The algorithm implementation steps are as follows:

(1) Perform connected-domain clutter denoising for the segmented binary image; establish the area of interest to remain;
(2) Project the full image in the \( Y \) direction, and set one quarter of the \( Y \) height as the threshold for projection segmentation;
(3) Selection of the largest position in the projection queue and set it as \( X_{\text{pos}} \);
(4) In the segmented image of the recognition area (Figure 9c), retain the scribed line closest to \( X_{\text{pos}} \) (Figure 9d). Then, extract the boundary of the positioned notch area. Linear fitting is used to calculate the center position of the scribed line.

![Figure 8. Calibration algorithm for display error: 1. Industrial camera (CCD camera); 2. steel tape; 3. standard steel tape.](image-url)
Among the three lines, judging and locating the position of the scribed line according to the distance between one line and the zero scribed line is closest to the whole meter (Figure 10d). Then, extract the boundary of the positioned notch area. Linear fitting is used to calculate the center position of the scribed line.

5.2. Identification Closest to the Starting Line

Not all whole meter or whole decimeter lines are the longest. It is stipulated in the regulations that the length of whole decimeter lines should be different from other lines, so the whole decimeter lines should be longer or wider than other lines, as shown in Figure 10a. The whole meter or whole decimeter lines are the same. According to 5.1 the highest scribed line recognition algorithm, the whole meter line cannot be identified. However, even with this being the case, three whole decimeter lines can be segmented, as shown in Figure 10c. Among the three lines, the distance between one line and the zero scribed line is closest to the whole meter. So the whole meter line should be identified by the feedback information of the encoder combined with the ST. The new algorithm implementation steps are as follows:

1. Perform connected-domain clutter denoising for the segmented binary image; establish the area of interest to remain;
2. Project the full image in the Y direction, and set one quarter of the Y height as the threshold for projection segmentation;
3. Selection of the first three largest positions in the projection queue, and exclude the redundant half-decimeter lines (Figure 10c) according to the line length;
4. Among the three lines, judging and locating the position of the scribed line according to the distance between one line and the zero scribed line is closest to the whole meter (Figure 10d). Then, extract the boundary of the positioned notch area. Linear fitting is used to calculate the center position of the scribed line.

(c) Decimeter lines remain. (d) Line positioning image.

Figure 10. Identification closest to the starting line.

5.3. Highest Scribed Line Recognition

For the whole meter, the scribed line can be embedded with numbers, resulting in interruption of the cutting line, as shown in Figure 11a. For steel tape, the previous two algorithms cannot identify the line accurately. However, due to the whole-meter (or half-meter) line being the highest, although interrupted, this line can be identified using the highest-line information. The algorithm implementation steps are as follows:

1. Perform connected-domain clutter denoising for the segmented binary image; establish the area of interest to remain;
Performance index of the device (repeatability: 20 μm). By linear fitting, the fitting equation of value error is $y = -3E^{-6}L - 0.0018$; the indication error of the SMTCD does not exceed the maximum permissible error: ±(0.03 + 3 × $10^{-5}$) L mm (L unit: m). So, the SMTCD can carry out the verification and calibration of SMT and has a good value of popularization and application.

Figure 11. Highest scribed line recognition.

6. Repeatability Tests

SMTCD was measured with a ST and compared with the standard value (after correction). As shown in Figure 12, the average value and standard deviation (indicating repeatability) were calculated after 10 repeated measurements. Finally, the indication error of SMTCD was fitted to a linear function of L.

Figure 12. Repeatability test of SMTCD.

The repeatability test results are shown in Table 1. The maximum standard deviation of 0.014 mm (14 μm) indicates the repeatability of the SMTCD, which is better than the performance index of the device (repeatability: 20 μm). By linear fitting, the fitting equation of value error is $y = -3E^{-6}L - 0.0018$; the indication error of the SMTCD does not exceed the maximum permissible error: ±(0.03 + 3 × $10^{-5}$) L mm (L unit: m). So, the SMTCD can carry out the verification and calibration of SMT and has a good value of popularization and application.

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Table 1. Repeatability test results (unit: mm).

| Calibrated Point | Indication Error | Standard Deviation | Descr |
|------------------|------------------|--------------------|-------|
| 1000 ± 0.042     | −0.009           | 0.007              | The red marker is the corrected value of ST. |
| 2000 ± 0.167     | −0.015           | 0.010              | That is, the actual truth value of 1000 mm is 1000.042 mm, and so on. |
| 3000 ± 0.170     | 0.008            | 0.006              |       |
| 4000 ± 0.175     | −0.005           | 0.007              |       |
| 5000 ± 0.194     | −0.027           | 0.014              |       |

7. Indication Error Tests

Using the SMTCD as the standard device, a 5 m arc ruler, a 20 m measuring-depth steel tape, and a 30 m swing-type steel measuring tape were selected as the test objects, and indicating error tests were carried out 10 times. According to JJG 4-2015 Steel Measuring Tapes, the allowable error limit of ordinary steel measuring tape (II level) is “±0.3 + 2 × 10^{-4} L” mm” (L unit: m). If the nominal length of the measuring-depth steel tape does not exceed 30 m, the allowable error limit is “±2.0 mm”.

The results are shown in Figures 13–15.

![Figure 13. Indication error test of 5 m arc ruler.](image1)

![Figure 14. Indication error test of 20 m measuring-depth steel tape.](image2)
The variation trend of the indication error value of each test object is consistent, and the indication error increases with the increase in the verification points. According to the regulations' indication error requirement [19], the limits of the indication error are different for each point. The average value of 10 test results is taken as the indication error of each point and compared with the upper and lower allowable error limits. The indication error of each point is within the allowable error limits, i.e., the verification of the indication error is completed.

8. Discussion

The repeatability of all test objects increased with the increase in verification points, and the maximum repeatability of the indication errors of the 5 m arc ruler, 20 m measuring-depth steel tape, and 30 m steel tape were 0.025 mm, 0.038 mm, and 0.030 mm, respectively. According to the uncertainty evaluation method from the literature [20,21], the uncertainty evaluation of the indication error of each steel tape is shown in Table 2. The extended uncertainty \( \Delta U \) of the indication error of each test object was not more than one third of the maximum permissible error value (MPEV). The measuring principle, method, and procedure of the standard device are scientific and feasible.

| Steel Measuring Tape                  | \( s \)  | \( u_c \) | \( U \)  | MPEV |
|--------------------------------------|--------|--------|--------|------|
| 5 m arc ruler                        | 0.025  | 0.08   | 0.16   | 1.3  |
| 20 m measuring-depth steel tape      | 0.038  | 0.27   | 0.54   | 2.0  |
| 30 m swing-type steel measuring tape | 0.030  | 0.39   | 0.78   | 6.3  |

The SMTCD is an image measurement system composed of a million-level analog camera with a resolution of \( 1944 \times 2592 \), an image acquisition card, and image-processing software to achieve subpixel accuracy. At the same time, human error is reduced to achieve accurate and reliable measurement results. The SMTCD, based on the visual array image measurement technology, ensures the timely measurement of steel tape, and the verification efficiency is increased by more than 100% (the verification time of the same steel tape is reduced to more than half of the time required by manual verification in the past). Meanwhile, the SMTCD overcomes the previous need for a manual hanging weight, the need to move the reading microscope at each line for reading, the manual recording of data, and other tedious steps. Now, according to the operating procedures, the verification personnel are only required to prompt the SMTCD to automatically complete the verification work, greatly reducing the labor intensity of the verification personnel.
The device has a high degree of automation, fast detection link, high accuracy, and saves labor time and reduces labor intensity. However, there are certain disadvantages, involving the time required to install and unload the fixture before and after the verification of the steel tape. In addition, only one steel measuring tape can be calibrated at a time. Therefore, in the near future, the steel-tape automatic verification device’s performance can be further improved by the simultaneous verification of multiple stations and convenient loading and unloading.

9. Conclusions

This paper introduces a new automatic verification device for steel tape based on machine vision array in detail. An automatic winding device combined with coding technology can achieve accurate positioning. Machine vision involves image recognition, data acquisition, and processing, rather than manual readings, which are reduced in order to achieve accurate and reliable measurement results. The design of the limit mechanism and pressing mechanism ensures the straightness and parallelism of the steel tape. A double-motor control force application device uses torque to change the size of the force in the tape. When the tape is retracted, the tape-retracting device drives the steel tape handle and the steel tape is wound into the tape box until the photoelectric switch is triggered and the rotary table moves to a horizontal state. Then, the last 5 m-length tape belt is manually rewound.

In the application of machine vision measurement technology, pixel calibration is the first step of system calibration. A pixel calibration algorithm was designed in this study. At the same time, image recognition is based on the edge detection of binary image processing. In order to adapt to different manufacturers and different types of steel tape, three different scribed line identification and location algorithms, processing the longest line, the closest to the starting line, the highest line, etc., were designed.

Then the repeatability tests of the SMTCD were carried out. The indication error of the SMTCD does not exceed the maximum permissible error: \( \pm (0.03 + 3 \times 10^{-5} L) \) mm (L unit: m). According to the “Verification Regulation of Steel Measuring Tapes JJG 4-2015”, the SMTCD can carry out the verification and calibration of SMT. Lastly, the establishment of the SMTCD as the standard device involved a 5 m arc ruler, a 20 m measuring-depth steel tape, and a 30 m swing-type steel measuring tape selected as the test objects, and indication error calibration tests carried out. The results show that the extended uncertainty \( U \) of the indication error of each test object satisfies the condition of \( U \leq 1/3 \) MPEV. As such, the measuring principle, method, and procedure of the SMTCD are shown to be scientific and feasible.

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