

A method to calibrate steel length measuring tapes by mechanical comparison

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Abstract— This paper describes a mechanical method for calibration of steel length measuring tapes with a hook or hook-ring and lengths up to 10 m. A reference and a test tape are laid horizontally by a series of horizontal supporters. In the measuring process the reference standard tape is moved with respect to the test tape by rotating a micrometer head. This movement is measured by a digital dial gauge. The tension weights are used to stretch out the tapes up to appropriate tensions. The tapes are properly clamped at the other end of the system against the pulling force of tension weights. The coincidence of scale marks is done by viewing the image of a CCTV camera which is coupled with a monitor. The temperature of the two tapes is measured to account the temperature effect. The deviation in length from the zero of the test tape is measured by considering temperature correction and sag correction. The performance of the system was checked with a pre-calibrated steel tape and results from the system are in agreement with the calibration certificate of the test tape. A method to estimate the combined uncertainty of the deviation in length calculated by the proposed method is also presented.

Keywords—Measuring Tapes, Calibration, Mechanical Comparison

I. INTRODUCTION

Many types of measuring tapes are used by industrialists, contractors, surveyors, and others for building layouts, measurement of land areas, the establishment of land boundaries, and similar other purposes. Inaccuracies in such measurements can cause misalignments, boundary controversy, and other problems. From an industrial perspective, the accuracy of the measuring tapes plays a vital role in the production of good quality products. In industrial perspective it is very important to carry out the measurements acceptable to international standards for a better market for their products. Therefore the demand and the necessity for the calibration of measuring tapes are rapidly increasing. Still, very few facilities are available in Sri Lanka to calibrate measuring tapes for the range of more than 2 m in accordance with international standards. System operates in some calibration Laboratories are suitable to calibrate measuring tapes only

up to 2 m. However, these systems can be used for longer tapes also by repeating the measurement several times which causes sources of errors. The test tape is not stretched to the recommended force at once and alignment errors are possible when repeating the measurement for various lengths of the tape.

Therefore, the main objective of this project is to fabricate a tape calibration bench that operates with a mechanical comparison method and introduce a mechanical calibration method to further solve the existing gaps in the calibration of length measuring tapes. In the method proposed, the calibration of the unknown tape (test tape) is performed by a mechanical comparison method respective to a calibrated steel tape (reference standard tape). The deviation of length at the particular length of the test tape is determined in comparison with the corresponding length of the reference standard tape.

II. MATERIALS AND METHOD

The system is constructed based on wall mount architecture. A vertical Stainless Steel (SS) wall is constructed on a series of parallel L Irons fixed to the cement floor by anchor bolts. This SS wall extends to more than 10 m lengths. The L Irons are partially covered by a SS sheet (SS wall), and the parts of the system are fixed to this artificial wall. The system mainly consists of several major parts listed below.

- 1) The Measuring head
- 2) Tape supporting system
- 3) Tape tensioning system
- 4) Scale markings localization system
- 5) Tape clamping system
- 6) Temperature monitoring system

A. The Measuring head

We aim to measure the deviations of scale marks of the test tape with respect to the corresponding scale marks of

the reference tape by one to one comparison. In this method, the reference tape is moved while the test tape is unmoved towards the coincidence of corresponding scale marks of test and reference tapes. Therefore the measuring head is designed to accommodate this basic principle of coincidence of scale marks. The schematic diagram of the measuring head is given in Figure. 1.

This part consists of a micrometer head, a dial gauge and a clamp for the reference tape as illustrated in the Figure.1. The spindle of the micrometer is in contact with a horizontally movable steel rod which is going through a steel barrel. This rod is in contact with plunger of the dial gauge. When the fast drive of the micrometer head rotates, the spindle horizontally pushes the rod and presses the plunger. Since the clamp of the reference tape is fixed to this rod, the reference tape moves with rotating the fast drive of the micrometer. This movement of the reference tape is measured by indication of the dial gauge.

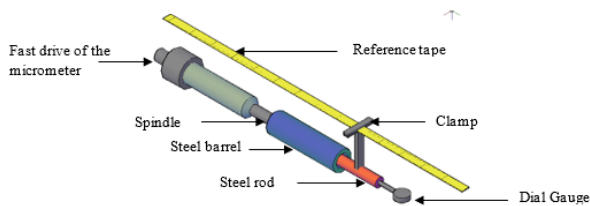


Figure 1: Diagrammatic representation of the perspective view of the measuring head.

B. Tape supporting system

The second part includes a set of supporting arms which are located at 1m distance apart. The perspective view of this part is given in the Figure. 2. To reduce the friction between the tapes and supporting arms, steel rods are made in round shape. These supporting arms are free to move through a horizontal channel along the total length of the bench and can be fixed to the system at any point along the channel. This steel channel is fixed to the SS wall. The height of the arms is also free to adjust through rotating the height adjustment nuts.

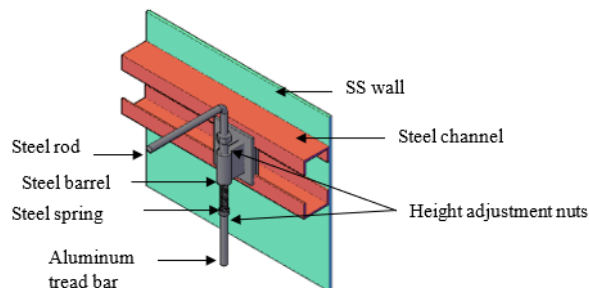


Figure 2: Diagrammatic representation of perspective view of a supporting arm.

C. Tape tensioning system

This part is for stretching out the tapes up to appropriate tensions (United States.USATF.2015) so that they are straight

enough without sagging and bending on the supporting arms. The tensions, at which steel tapes are to be calibrated, expressed in terms of load in kilograms. For the tapes with ribbon length less than 10 m, the tension load is 2 kg and for ribbon length 10 m through 30 m, the load is 5 kg (National Institute for standard and Technology.(2014).SOP No.11). The tensions were applied to the tapes by connecting two hanging weights at the end of the two tapes. These connections are made with steel wires which are going around friction less pulleys. In the design, these two pulleys are made so that they are free to move in 3 directions to align horizontally and vertically two tapes each other. An illustration of front view of the tape tensioning system with pulleys is given in Figure.3.

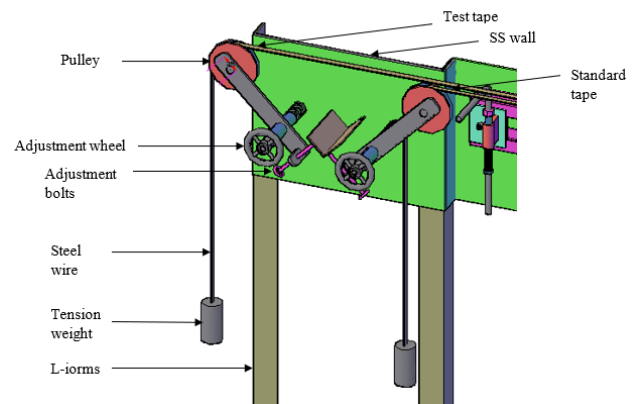


Figure 3: Diagrammatic representation of front view of the tape tensioning system. By rotating the adjustment wheels and adjustment bolts the alignment of two tapes can be adjusted.

D. Scale markings localization system

For coincidence the corresponding scale marks on the test tape and reference tape it is required a clear vision of scale marks. The coincidence of scale marks is made by rotating the micrometer attached to the measuring head which is located at one end of the system. A Closed-Circuit Television (CCTV) camera is used to fulfill these two requirements. The image of the camera is sent to an LCD display. In this method the CCTV camera is focused on to a particular scale mark and the image of the scale mark is viewed on the display. Therefore coincidence of scale marks is possible by viewing them on the LCD from one end of the system. This CCTV camera is free to move along the 10 m distance throughout an aluminum channel which is fixed to the SS wall. An image of the scale mark viewing system is given in Figure. 4.

E. Tape clamping system

The tapes are clamped by tightening the tapes in between two steel plates. The clamping system for the test tape is given in Figure .5. The system is designed so that the test tape is free to adjust in three directions at the measuring end. Both the test and reference tape is free to adjust in three directions at the other end by means of the tape tensioning system.

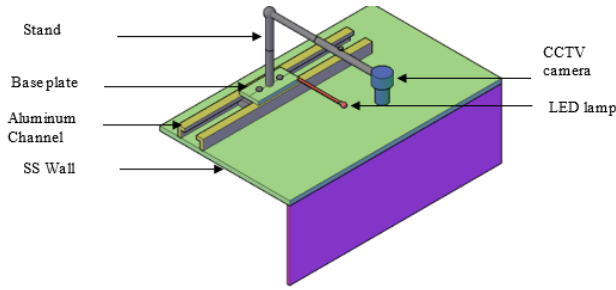


Figure 4: Diagrammatic representation of the perspective view of the scale marks localization system. The horizontal and vertical position of the camera can be adjusted by means of adjustment nuts and adjustment bolts respectively. The camera stand is attached to a base plate which is free to move along the aluminum channel. This aluminum channel is fixed to the top of the SS wall.

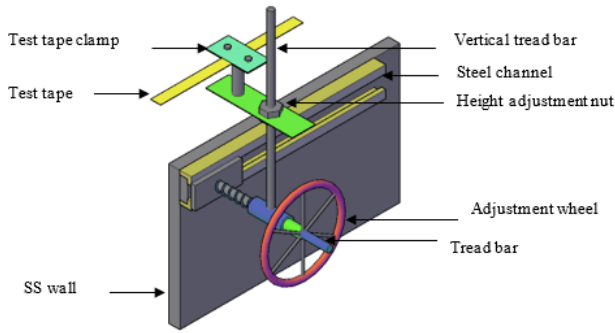


Figure 5: Diagrammatic representation of the front view of the clamp for the test tape.

F. Temperature monitoring system

A calibrated digital thermometer with two typed K surface thermocouples is used to measure the temperature on the tapes. The averaged temperature is used in the calculation of the temperature effect (United States.USATF.2015 United States. Air Force Academy.2008). A variation in length is introduced due to the temperature variation of the tape and this variation depends on the material that, the tape is made from. The difference in that variation in the length of the two tapes is defined as the overall temperature correction. This overall temperature correction is defined in terms of the difference in average temperatures of two tapes and the difference in thermal expansion coefficients of materials of two tapes. The system is installed in a room where the temperature and humidity are controlled at 20 ± 1 °C and 50 ± 10 % levels respectively. The room temperature and humidity are recorded by a mechanical thermo-hygrograph.

G. Procedure of taking measurement.

Since the system operates on a mechanical comparison method, the reference tape is moved while the test tape is fixed to coincide with relevant scale marks. This movement is given by rotating the micrometer head. Due to this rotation of the micrometer, the spindle of the micrometer pushes the probe of the dial gauge at an equal distance and the dial gauge reads the quantity of the movement. At First, the CCTV camera head is moved and focused on the zero lines and moved the reference tape with respect to the test tape so

that coincides two zero lines of the two tapes. In most of the test tapes, there is no dedicated zero line is marked and the outer edge of the hook or hook ring is used as the zero line. Since there is a dedicated zero line for the standard tape and the zero line of the standard tape is movable by rotating the micrometer head, the zero line of the standard tape coincides with the outer edge of the hook or hook ring of the test tape. This is possible with greater accuracy since the coincidence is performed on the zoomed image on the computer screen. Once the coincidence is completed, then the display value on the dial gauge is tared. The deviations in length at other scale marks of the test tape are measured with respect to the zero setting. The camera head is moved to the next measurement location. The reference tape is moved to coincide the scale mark of the test tape with the relevant scale mark of the reference tape. The magnitude of the movement is given by the reading of the dial gauge. This indicates the deviation in length of the test tape respective to the reference tape at that particular length. The corrections relevant to the temperature deviations and sagging of the tapes between supporters are also quantified and algebraically added to the dial gauge reading to compensate for those effects (United States.USATF.2015 , United States. Air Force Academy.2008 Van Hagen, J.L.).

III. CALCULATION

A. Horizontal straight-line distance

The horizontal straight-line distance from zero of the test tape, L can be written

$$L = L_S + d + \Delta K + \Delta C \quad (1)$$

Where:

- L_S = Corresponding distance of the reference standard tape obtained from certificate.
- d = The measured deviation
- ΔK = Overall temperature correction, given by the difference in temperature between two tapes and difference in thermal expansion coefficient between two materials in which the tapes are made (United States. Air Force Academy.2008).

This temperature correction is given by the equation

$$\Delta K = L_n [\bar{\alpha} \Delta t + \Delta \alpha \cdot \delta t] \quad (2)$$

Where:

- L_n = Nominal length of tape interval under test
- (α) = Average value of the linear thermal expansion coefficients of two tapes.
- Δt = Temperature difference between two tapes.
- $\Delta \alpha$ = Difference in expansion coefficients of two tapes
- t = Drift in average temperature of two tapes from 20 °C

For the simplicity it is assumed that temperature difference between two tapes is zero, i.e $\Delta t=0$ °C and equation 2 becomes

$$\Delta K = L_n[\Delta\alpha.\delta t] \quad (3)$$

$$\Delta K = L_n[(T - 20)(\alpha_S - \alpha_X)] \quad (4)$$

Where:

- α_S = Linear expansion coefficient of reference standard tape
 α_X = Linear expansion coefficient of test tape
 T = The average measured temperature of two tapes during the calibration

ΔC = Overall sag correction. In this method, the tapes are calibrated when they are supported at equidistant points by horizontal supporters. Therefore the weight of the tapes affects their length. The ‘‘sag’’ causes the horizontal length to be shorter than when the tape is supported throughout its length. Here, the difference in sag correction between test tape and the standard tape is defined as the overall sag correction and is given by,

$$\Delta C = C_x - C_s \quad (5)$$

Where:

- C_x = Sag correction of the test tape
 C_s = Sag correction of the reference standard tape.

Sag correction of a given tape is given by (United States. Air Force Academy.2008 Van Hagen, J.L.)

$$C = \frac{L_n}{24} \left(\frac{wd}{P} \right)^2 \quad (6)$$

Where:

- L_n = Nominal length of the tape section
 w = Weight of the tape per unit length
 d = Distance between two successive supporters (1m)
 P = Tension of the tape in kg

The overall sag correction, ΔC is given by

$$\Delta C = \frac{L_n^3}{24N^2} \left(\left(\frac{w_x}{P_x} \right)^2 - \left(\frac{w_S}{P_S} \right)^2 \right) \quad (7)$$

where:

- N = Number of equidistance suspensions
 w_S = Average weight per unit length of the standard tape ribbon
 w_X = Average weight per unit length of the test tape ribbon
 P_S = Tension applied to standard tape in kg
 P_X = Tension applied to test tape in kg

Weight per unit length (w) can be calculated using equation given below (Van Hagen, J.L.).

$$w = \frac{w_1 - w_c - w_L}{L_T + L_B} \quad (8)$$

Where:

- L_T = Graduated length of the tape.
 L_B = Length without graduations.
 w_1 = Total weight of the tape
 w_c = Weight of the case
 w_L = Weight of the loop

B. Uncertainty Calculation

The mathematical model for the straight line distance is given in equation (1). Then the corresponding combined standard uncertainty, $U_c(y)$ can be written in the following format (International Bureau of weights and measures.2008).

$$U_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x} \right)^2 U^2(x_i) \quad (9)$$

$$U_c^2(L) = \left(\frac{\partial L}{\partial L_s} \right)^2 U^2(L_s) + \left(\frac{\partial L}{\partial d} \right)^2 U^2(d) + \left(\frac{\partial L}{\partial \Delta K} \right)^2 U^2(\Delta K) + \left(\frac{\partial L}{\partial \Delta C} \right)^2 U^2(\Delta C) \quad (10)$$

Here;

$$\frac{\partial L}{\partial L_s} = 1$$

$$\frac{\partial L}{\partial d} = 1$$

$$\frac{\partial L}{\partial \Delta K} = 1$$

$$\frac{\partial L}{\partial \Delta C} = 1$$

$U(L_s)$ = Uncertainty of the length of the reference standard tape, given on the calibration certificate.

$U(d)$ = Uncertainty of measured length deviation. This consists of calibration uncertainty of dial gauge, resolution of dial gauge, vertical and horizontal parallelism of two tapes and coincidence uncertainty. Therefore $U(d)$ can be written as International Bureau of weights and measures.(2008)

$$U^2(d) = U_{cal.g}^2 + U_{res.g}^2 + U_{H.para}^2 + U_{V.Para}^2 + U_{coinc}^2 \quad (12)$$

$U(\Delta K)$: Uncertainty associated with temperature effect, which can be written as

$$U^2(\Delta K) = \left(\frac{\partial \Delta K}{\partial \bar{\alpha}}\right)^2 U^2(\bar{\alpha}) + \left(\frac{\partial \Delta K}{\partial \Delta t}\right)^2 U^2(\Delta t) + \left(\frac{\partial \Delta K}{\partial \Delta \alpha}\right)^2 U^2(\Delta \alpha) + \left(\frac{\partial \Delta K}{\partial \delta t}\right)^2 U^2(\delta t) + \left(\frac{\partial \Delta K}{\partial L_n}\right)^2 U^2(L_n) \quad (13)$$

$$U^2(\Delta K) \approx \left(\frac{\partial \Delta K}{\partial \Delta t}\right)^2 U^2(\Delta t) = \bar{\alpha}^2 L_n^2 U^2(\Delta t) \quad (14)$$

Here, other terms have been neglected as they are infinitesimal. Though it is assumed that the temperature difference between tapes is zero, the uncertainty of that difference is important in uncertainty evaluation.

$$\Delta t = t_s - t_x \quad (15)$$

Where:

t_s = Average temperature on reference tape
 t_x = Average temperature on test tape

$$U^2(\Delta t) = U^2(t_s) + U^2(t_x) \quad (16)$$

$$U^2(t_s) = U_{cal.t}^2 + U_{res.t}^2 + U_{scatter}^2 \quad (17)$$

Where:

$U_{cal.t}$ = Calibration uncertainty of the thermometer
 $U_{res.t}$ = Uncertainty from resolution of thermometer
 $U_{scatter}$ = Uncertainty from scatter
 $U(\Delta C)$ = The uncertainty associated with sag correction can be written From equation (5)

$$U^2(\Delta C) = U^2(C_s) + U^2(C_x) \quad (18)$$

From equation (6), $U^2(C_s)$ can be written as

$$U^2(C_s) = \left(\frac{\partial C_s}{\partial L_n}\right)^2 U^2(L_n) + \left(\frac{\partial C_s}{\partial w_s}\right)^2 U^2(w_s) + \left(\frac{\partial C_s}{\partial p_s}\right)^2 U^2(p_s) \quad (19)$$

$$\frac{\partial C_s}{\partial L_n} = \frac{C_s}{L_n}$$

$$\frac{\partial C_s}{\partial w_s} = \frac{2C_s}{w_s} \quad (20)$$

$$\frac{\partial C_s}{\partial p_s} = \frac{-2C_s}{p_s}$$

$$U^2(C_s) \approx \left(\frac{\partial C_s}{\partial w_s}\right)^2 U^2(w_s) \quad (21)$$

Here, it is assumed that other two components are very small and can be neglected. From equation (8), $U^2(w_s)$

$$U^2(w_s) = \left(\frac{\partial w}{\partial w_1}\right)^2 U^2(w_1) + \left(\frac{\partial w}{\partial w_c}\right)^2 U^2(w_c) + \left(\frac{\partial w}{\partial w_L}\right)^2 U^2(w_L) + \left(\frac{\partial w}{\partial L_T}\right)^2 U^2(L_T) + \left(\frac{\partial w}{\partial L_B}\right)^2 U^2(L_B) \quad (22)$$

$$\frac{\partial w}{\partial w_1} = \frac{1}{L_T + L_B}$$

$$\frac{\partial w}{\partial w_c} = \frac{-1}{L_T + L_B}$$

$$\frac{\partial w}{\partial w_L} = \frac{-1}{L_T + L_B} \quad (23)$$

$$\frac{\partial w}{\partial L_T} = \frac{-w}{L_T + L_B} \approx 0$$

$$\frac{\partial w}{\partial L_B} = \frac{-w}{L_T + L_B} \approx 0$$

Then the equation (22) simplify to

$$U^2(w_s) = \left(\frac{\partial w}{\partial w_1}\right)^2 U^2(w_1) + \left(\frac{\partial w}{\partial w_c}\right)^2 U^2(w_c) + \left(\frac{\partial w}{\partial w_L}\right)^2 U^2(w_L) \quad (24)$$

Here, $U(w_1)$, $U(w_c)$ and $U(w_L)$ are the uncertainties related to the weight measurements and consist of balance calibration and resolution uncertainties. $L_T + L_B$ is the total length of the test tape.

IV. RESULTS

Performance of the system was checked with a pre-calibrated steel tape. The measurement was repeated five times and the results are given in Figure (6). The black color line indicates the results obtained from the calibration certificate of the test tape (reference curve). The other five color lines indicate the results obtained from the system for 5 repeated test cycles at 1 m steps. Those lines lie very closely with the calibration results of the test tape for lengths up to 5 m. However, the results show slight deviations from the calibration curve of the test tape at longer lengths. The given expanded uncertainty with confidence level $k=2$ of values indicated on the reference line was 0.3 mm and the estimated expanded uncertainty with the same confidence level of values obtained from the system was 0.5 mm. The table.1 indicates the values of deviation in distance and expanded uncertainty of the reference curve and the test run curves.

Table I: Comparison of values of deviation in the distance of the reference curve with its expanded uncertainty and values in deviation in the distance of test runs with the calculated expanded uncertainty. The values are in mm.

Nominal distance	Deviation of reference curve	Exp. Uncertainty $k = 2$	Deviation of test run					Exp. Uncertainty $k = 2$
			Run-1	Run-2	Run-3	Run-4	Run-5	
1000	0.1	0.3	0.00	0.00	0.09	0.18	0.15	0.5
2000	0.1		0.00	0.00	0.00	0.04	0.05	
3000	0.2		0.22	0.41	0.31	0.04	0.07	
4000	0.3		0.36	0.33	0.34	0.15	0.07	
5000	0.3		0.33	0.36	0.27	0.23	0.22	
6000	0.3		0.41	0.64	0.52	0.51	0.45	
7000	0.4		0.16	0.16	0.35	0.27	0.70	
8000	0.4		0.22	0.16	0.31	0.25	0.58	
9000	0.4		0.42	0.39	0.49	0.63	0.58	
10000	0.4		0.72	0.66	0.57	0.60	0.64	

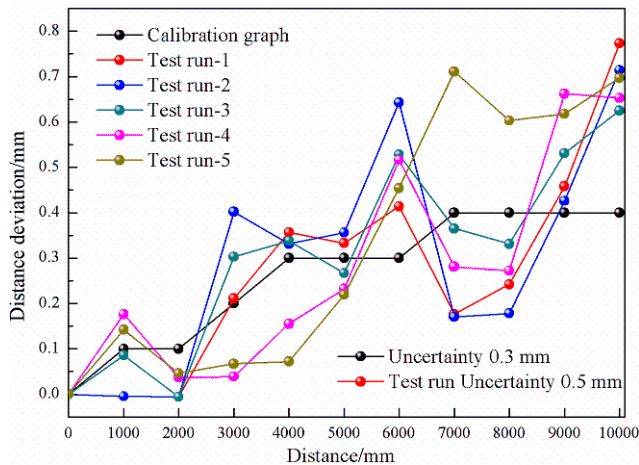


Figure 6: Results of the calibration performed by the system for a pre-calibrated steel tape. The Black color line is the calibration curve as given in the calibration certificate of the tape. Other lines are based on results obtained by the system at repeated calibration cycles. Lines are just a guide to the eye.

V. CONCLUSION

A system to calibrate steel measuring tapes up to 10 m was successfully constructed and a method to calibrate steel measuring tapes was subsequently proposed. The system was constructed on an artificial steel wall following the wall mount architecture. The system includes several components namely a measuring head, a tape supporting system, a tape tensioning system, a scale markings viewing system, a tape clamping system, and a temperature monitoring system. The system follows a mechanical comparison technique and corresponding scale marks on the test tapes are coincided by moving a reference standard tape respective to the test tape. This movement is given by rotating the fast drive of a micrometer and the movement is measured by a dial gauge. Both the reference and test tape are horizontally supported by a series of supporting arms which are placed at a 1 m distance apart from beginning to end of the system. The tape tensioning system provides the ability to tension the tapes up to the required standard tensions. The system is having the flexibility to change the tensioning weight as per the range of the test tapes. A CCTV camera and a computer display are used to obtain a zoomed image of scale marks. In order

to account for the temperature variation of the laboratory from the reference temperature, a temperature monitoring system is coupled with the two tapes. The system enables measurement the deviations in length from zero, and this deviation is corrected for temperature variation of the room from reference temperature and sagging of tapes between supporting arms. The accuracy of the system and the method were tested with a calibrated steel tape and it was found that the results from the system are in agreement with its calibration certificate.

VI. ACKNOWLEDGEMENT

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