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Development of a novel system for linear displacement sensor calibration

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Abstract

This paper presents the development of semi-autonomous metrological devices, capable of calibrating variety of linear displacement sensors, like Linear Variable Differential Transformers (LVDT), string potentiometers, laser displacement sensors and other. Data acquisition equipment that could be used for measuring objects of various shapes and sizes are already available; however, devices specifically tailored for the calibration of displacement sensors are not currently offered. Advantages of this new technology, that we are investigating and developing, include reduction of time, costs and human resources required to perform calibration. In addition to that, the advantages of an affordable calibration device will allow calibrations to be carried out internally, as opposed to outsourcing to dedicated facilities. The scope of the project encompasses research into the device's compliance with ISO/IEC 17025 to obtain NATA accreditation, research into design, and selection of material and manufacturing processes to ensure an acceptable measurement of uncertainty is achievable across all varieties of linear displacement sensors. The sensors are used to measure suspension displacement, steered angle and various other geometries on vehicles and test equipment. Outcomes of this research project offer experimental evidence that proves the feasibility of developing and manufacturing devices that produce an acceptable uncertainty that meets testing standards requirements at a fraction of the cost of comparable measuring devices.

Keywords: Calibration; metrology; test equipment; linear displacement; sensors

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1. Introduction

Dimensional metrology has many devices and apparatuses for the measurement of all types of geometrical shapes however; there is no device specifically designed for the calibration of linear displacement sensors. Calibration of an instrument is the process of configuration that provides measured numerical values according to accepted standards and ranges. The use of laser interferometers for high accuracy dimensional measurements has proven to be an effective method of obtaining highly accurate calibration results [1], [2]. These methods, while highly accurate, are not easily implemented in real world situations because of specialist techniques required as well as high calibration cost of the laser interferometer devices.

An interesting approach is the use of ironless inductive position sensor (I2PS). It is a novel device that measures high-precision linear position without being affected by radiation and external magnetic fields which is relevant for Defence applications. They are built on the basis of the linear variable differential transformer (LVDT) [3]. LVDT sensors are used in various mechatronics devices, hydraulic and pneumatic, for the measurements of mechanical quantities including force, pressure or displacements. This sensor has two magnetic coupled coils through the common core. Reluctance of the magnetic circuit is the function of the core position, i.e. displacement. LVDT's give good accuracy of 0.1% error, with low cost. These systems may use complex analog electronics, hard to adjust and calibrate, but there are digital solutions as well [4].

Data Acquisition and Analysis Laboratory (DAAL) at Land Engineering Agency's Accredited Test Services Monegeetta uses a range of linear displacement sensors during testing. Testing conducted at DAAL is predominantly carried out with NATA accreditation for most procedures. DAAL previously held NATA accreditation for the calibration of linear variable differential transformers, at an uncertainty of 0.2% of reading or 0.06 mm (whichever is the greater) from 0.1 mm to 300 mm. Displacement measurements are extremely important and could be conducted using various systems. DAAL now uses linear displacement sensors including LVDT's, String potentiometers and laser displacement sensors which are calibrated at regular intervals to meet compliance with DAAL's testing requirements.

Apart from mechanical string potentiometers, there are also complementary metal-oxide semiconductor (CMOS) digital potentiometers, or resistive digital-to-analog converters. They are important components for various mixed-signal circuits and electronic systems [5]. Laser displacement sensors are very popular because of their reliability, rigidness and contactless operation. They consist of light emitters, like laser diodes and light detectors. They are smart electronic devices that include microcontrollers and neural networks [6].

Calibration device previously used by DAAL was a Schaevitz CAL-1212 Calibrator. The Schaevitz CAL-1212 Calibrator does not have adequate range to calibrate the string potentiometers used in DAAL and does not have the capability to adapt jigs or fixtures to accommodate LVDT, string potentiometers and laser displacement sensors. All calibrations are now outsourced to external companies. The current calibrators of the string potentiometers give a measurement uncertainty of 0.220 mm for calibration Research budget was allocated for this project with an expected measurement uncertainty of less than 0.22 mm.

A measurement device more readily available with lower accuracy may be more suited for the application of sensor calibration. Comparison of various automated systems and robotics indicates a system of low complexity is feasible for this application [7], [8]. It would be possible to automate a system that is linear in motion and constrained to a single axis.

2. Preliminary research

A market research activity was carried out to determine what commercial calibration devices are available and the capability of these items. The devices researched were the Labconcept Nano, Pratt and Whitney laser Measuring Machines and Trimos V9. Further research into the National Measurement Institute's (NMI) capabilities and approaches to displacement metrology were explored.

The NMI's geometry measuring equipment and the current geometry measuring devices, available on the market, highlighted some consistency in design features. The main consistencies between all devices are:

- A linear guideway to maintain alignment;
- A displacement measuring device (normally a laser interferometer);

- A lead screw to provide axial displacement (CNC or manual control);
- Temperature sampling; and
- Dedicated workbenches with integrated PC software.

By using these basic design features and adapting componentry to suit the required budget, a preliminary uncertainty budget with a 95% confidence interval was developed using known values from reputable component manufacturers. Reasonably expected values taken from previous calibration reports can be seen in Table 1, where: U_i = Uncertainty estimate, k_i = Reducing factor, $u(x_i)$ = Standard uncertainty, c_i = Conversion factor, v_i = Degrees of freedom, u_c = Combined standard uncertainty, V_{eff} = Effective degrees of freedom, k = Coverage factor, U_{95} = Expanded uncertainty.

Table 1. Preliminary uncertainty budget

Component	Units	Distribution	U_i	k_i	$u(x_i)$	c_i	$\lvert c_i.u(x_i)\rvert$	v_i
Linear Scale	mm	Normal	0.0070	2.04	0.003431	1	0.00343	30
Parallelism	mm	Normal	0.0500	2.04	0.024510	1	0.02451	30
Digital Read Out Resolution	mm	Rectangular	0.005	2.04	0.002449	1	0.002449	90
Linear Guide Misalignment	mm	Rectangular	0.0127	3.18	0.003994	1	0.00399	3
						u_c	0.025	
						v_{eff}	33.2	
						k	2.04	
						U_{95}	0.05 mm	

The dominant components of uncertainty are depicted in the graph shown in Fig. 1.

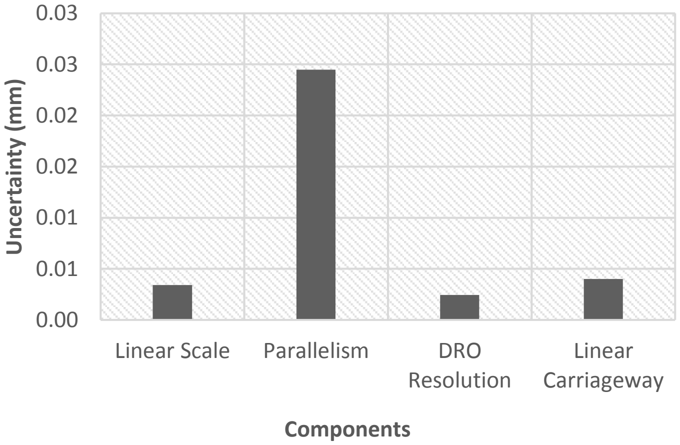


Fig. 1. Comparison of uncertainty components.

It can be seen from this comparison that parallelism between the linear guide and the measuring device are the largest contributors of uncertainty to the system. Parallelism misalignment is caused by the measuring device and the carriageway not being parallel which causes an error in measurement. To mitigate this issue, it is proposed that the components that can contribute to parallelism misalignment will be corrected using a coordinate measuring machine.

Compliance with AS ISO/IEC 17025:2018 requires development of quality procedures and documents aligned with Accredited Test Services Certification to AS/NZS ISO 9001:2016 Quality Management Systems –

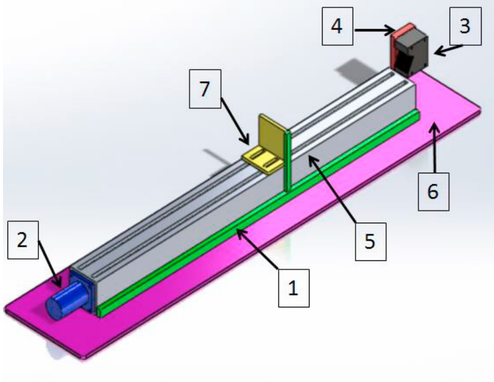
Requirements.

3. System description

New, comprehensive measurement system integrates mechanical, electrical computer and software subsystems. The primary components for this system are:

- Mechanical
    - Linear carriageway, Base plate, Sensor jigs, Sensor-carriageway interface
- Electrical
    - Linear scale (for this novel approach a linear scale was selected as the measuring device), Digital multi-meter, Stepper motor, Power supply
- Hardware
    - NI DAQmx
- Software
    - LabVIEW software will be utilized for interface a digital multi-meter, linear scale, stepper motor driver and compiling data in a .xls or .csv file will be utilized

A carriageway on a leadscrew, driven by a stepper motor, will provide axial displacement for the sensors. The various sensors will require specific jigs to constrain the sensors axially and to prevent parallelism errors. Parallelism errors can be further mitigated by using a laser alignment device, to align the jig placeholder and the sensor-carriageway interface, prior to commencing each calibration procedure. The attachment of the sensor to the calibration system, power-up and the reset, are the initial actions required from the operator. After this, setup system operation is autonomous.



Component	Number	Colour
Linear scale	1	Green
Stepper motor	2	Blue
Laser sensor	3	Black
Jig placeholder	4	Red
Carriageway	5	Grey
Baseplate	6	Pink
Sensor-carriageway interface	7	Yellow

Fig. 2. System configuration

New calibration system's components are shown in Fig. 2. System is further connected to PC, digital multi-meter and power supply, which is not shown in this figure.

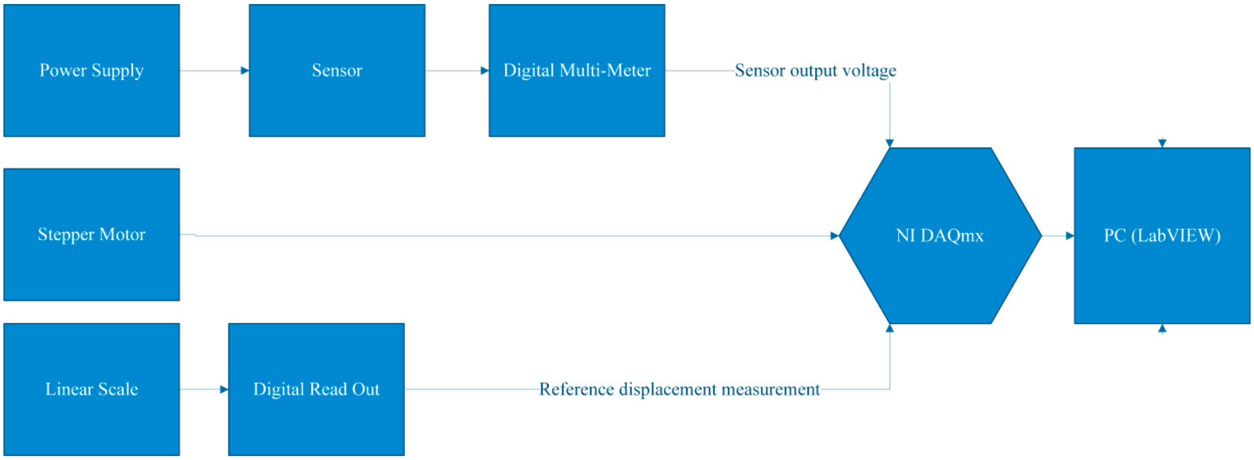


Fig. 3. Sensor and hardware configuration

Fig. 3 shows the hardware and sensor configuration of the system. System software is being written in LabVIEW and an executable version will be loaded on to dedicated PC. A NI DAQmx will be used to connect the stepper motor, digital multi-meter and the digital read out with the LabVIEW vi. National Instruments hardware and software platforms are widely used for data acquisition, calibration and control [9], [10].

A LabVIEW program called *System.vi* is used to execute the system starting with the front panel designed to configure the calibration parameters. LabVIEW vi will then execute the calibration driving the stepper motor to the first calibration interval. LabVIEW vi via the DAQmx hardware will access the digital multi-meter and digital readout values and compile these into an array to be outputted into a text file or spreadsheet format. LabVIEW stores the data in file paths defined by the user, and specific to each sensor. This segment of the LabVIEW code is shown in the Fig. 4.

Fig. 5 shows the whole logic process for the main LabVIEW vi to execute a calibration. Once all iterations of the calibration measurement procedure have been completed, LabVIEW compiles the data from the linear scale output and the digital multi-meter readings to create a plot and scatter graph of the data points. Application then analyzes the coefficient of determination to define the linearity of the measurements. When the sensor is calibrated, software saves and compiles the data into a report for the user.

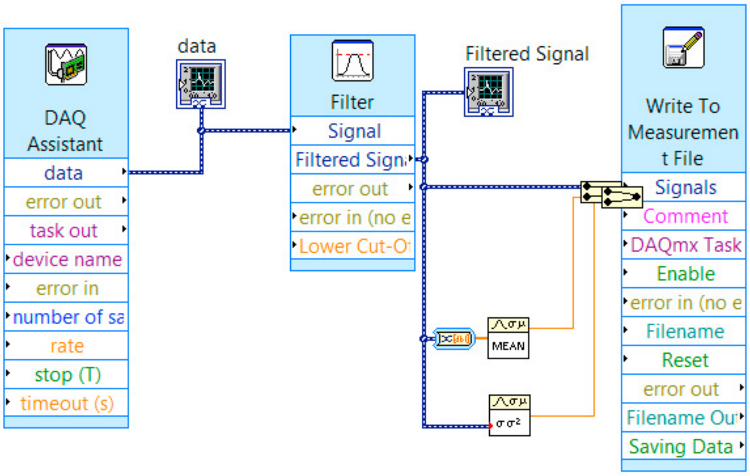


Fig. 4. One segment of the control program used to save measurement data

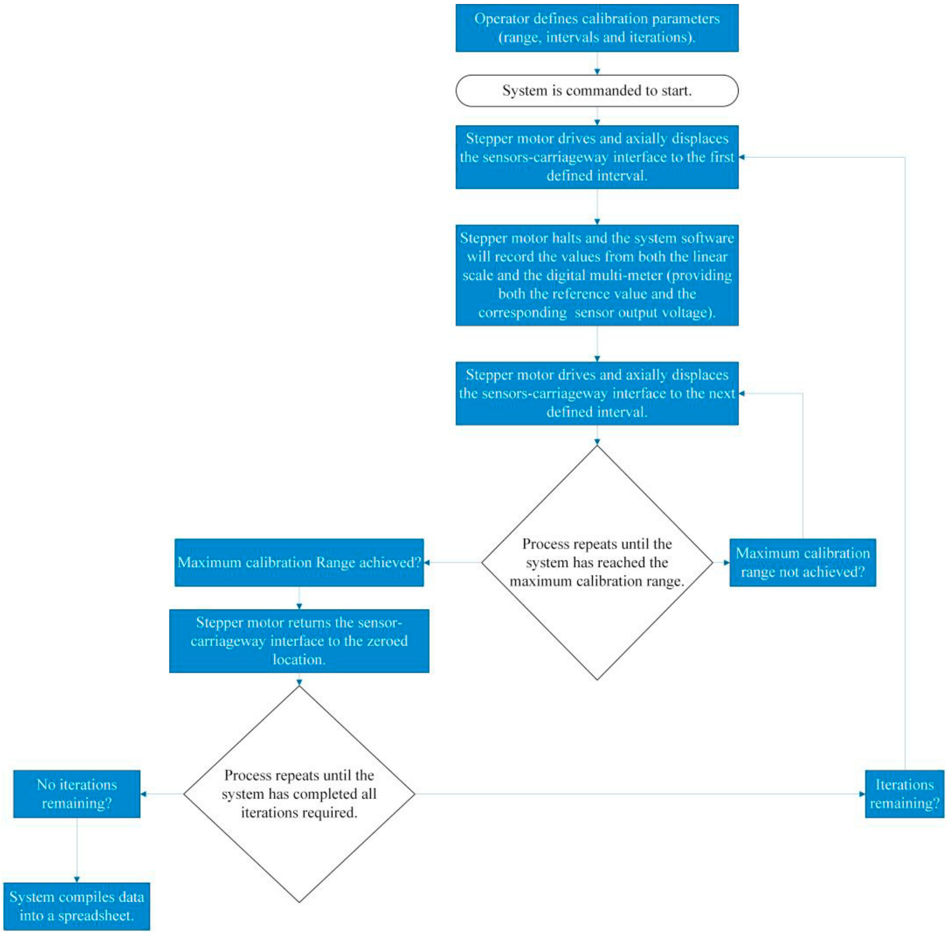


Fig. 5. Flowchart shows system functionality

4. Feasibility

The requirements for parallelism misalignment adjustment and the general system layout will not require manufacturing tolerance outside of normal engineering practices. The device will be used within a laboratory with a tightly temperature-controlled environment and as such, temperature sampling is unnecessary.

To determine the uncertainty of the device, calibration is required. A preliminary calibration was conducted on the linear scale. With the linear scale's digital read out displaying 100.01 mm, three measurements were taken.

The sample mean ($\bar{x}$) was established using Eq. 1:

$$\bar{x} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{1}$$

The sample standard deviation (s) was determined by Eq. 2:

$$s = \sqrt{\frac{\sum_{j=1}^{n} (x_j - \bar{x})^2}{n-1}} \tag{2}$$

The experimental standard deviation of the mean (ESDM) ($s_{\bar{x}}$) was determined using Eq. 3:

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} = u_A \tag{3}$$

The results of the preliminary calibration fell within the acceptable uncertainty range for this project.

5. Conclusion

A novel system has been proposed to give calibration facilities the ability to calibrate displacement sensors internally with minimal resources. The completion of the feasibility study and the preliminary uncertainty budget compiled in this report, makes it technically feasible for this device to achieve its expected calibration uncertainties. Further development of the system is required to adapt fail safe calibration procedures for all sensor types and to ensure the entire systems compliance with AS ISO/IEC 17025:2018.

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