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Design of Fixtures for Calibration of Thread Wires and Gaging Balls on Horizontal 1-D Measuring Machines

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Abstract

The universal 1-D measuring machine is used in many laboratories to calibrate ring gages, plug gages, threaded plugs, and other similar equipment. Horizontal measuring machines are more common than vertical machines- small gaging balls or small thread wires can fall off the machine. We discuss the functional requirements for calibrating small spheres and cylinders. We review the kinematic principles in design of precision machines. The fundamental kinematic principles in a precision fixture or precision machine are to restrain only the degrees of freedom necessary to prevent unwanted motion, and not to overconstrain the part- which would lead to distortion. There are additional kinematic requirements: the moving gaging probe and the need to establish a zero reference if you are taking direct reading measurements as opposed to a comparison measurement. Additional functional requirements and constraints include operator ergonomics and cost of fabrication of the fixtures. We apply these principles to the design of fixtures to help calibrate small gaging balls and thread wires. We present the design and fabrication of the fixtures, and also the test and qualification of the fixtures in a calibration environment.

1. Introduction

1.1 Principles of Kinematic Design

Kinematic fixturing enables high repeatability in the positioning of rigid bodies. As a result, principles of kinematic design are applied to precision machine tools, clamps, bearings, and in the measurement of dimensional standards. Examples of kinematic coupling can be found in systems as simple as a three-legged stool or as complex as the National Ignition Facility (NIF). For instance, in the NIF, positioning of optics [1] and placement of deuterium-tritium fuel spheres [2] utilize principles of kinematic constraint to eliminate unwanted motion and enhance repeatability in positioning, and in turn, reproducibility of the overall experiment.

Any unconstrained rigid body has six degrees of freedom: three in translation and three in rotation (refer to Figure 1). When a sphere is brought into contact with a plane, one translational, and no rotational, degrees of freedom are constrained A properly constrained body will only have three translational and three rotational constraints [3]. A system with fewer contacts is said to be underconstrained, and with more contacts is said to be overconstrained. A fixture which underconstrains or overconstrains a rigid body may lead to additional positioning uncertainty, as no manufacturing or fabrication process can produce fixture features that are exact. Essentially, in the absence of gross geometric errors, a properly designed kinematic fixture enables consistent positioning in spite of imperfections inherent with any manufacturing process. The classic example of a perfectly constrained kinematic fixture is that of the three V-groove Kelvin clamp [4], shown in Figure 2. Note that a normal force, F_n, is required to provide "force closure" [5]. In many instances this normal force is simply gravity.

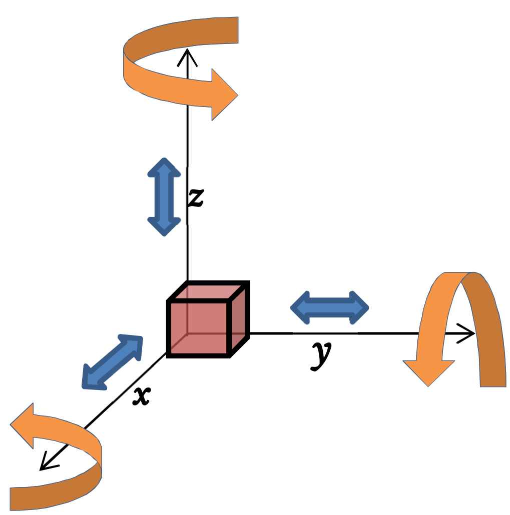

Figure 1: Any Unconstrained Rigid Body Has Six Degrees of Freedom. Three in rotation, and three in translation, as expressed in Cartesian coordinates.

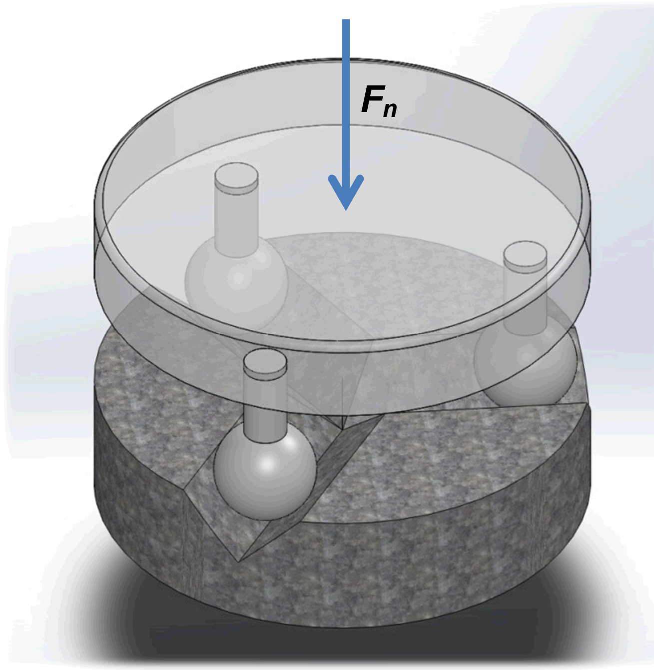

Figure 2: Type II Kelvin Clamp. Note that exactly six points of contact (two in each V-groove) are made between the objects, resulting in constraint of all six degrees of freedom. Another Kelvin clamp design (Type I) consists of three spheres against a flat, a V-groove, and a tetrahedral hole.

In practice, bodies are not perfectly rigid and will deform, i.e. idealized point contact is not possible. Therefore, stiffness of contact points is relevant to kinematic coupling. Elastic constraint is another means of fixturing objects when proper kinematic coupling is not possible, but is less desirable as it requires large forces to achieve repeatable positioning and can lead to undesirable deformation in the object of interest. Real fixtures may also deviate from kinematic principles for practical reasons- cost, fabrication difficulty, or the need for greater configuration flexibility. For example, a tetrahedral hole provides kinematic constraint for a sphere, but is rather difficult to machine. A conical or cylindrical cavity is the typical alternative. If the rim of the cavity were perfectly circular (as well as the sphere), this would not present an issue. However, wobble and other factors when drilling the hole result in an oblong shape, which will affect positioning. Therefore, while proper kinematic fixturing is not always practical, the inherent limitations of alternative approaches should be considered.

1.2 Recommended Measurement Practices for Thread Wires and Gage Balls

Thread wires are utilized to measure the pitch diameter of external threads, whereas gage balls are used to master external measurement machines. Thread wires are made from alloy tool steel, whereas gage balls are typically made from alloy tool steel, tungsten carbide, ruby, or other materials with a high bulk modulus of elasticity and low coefficient of thermal expansion (CTE). Detailed requirements for thread wires and gage balls can be found in ASME B89.1.17-2001 [6].

While the standard recommends measuring thread wires in the deformed state, NIST provides values for master wires based on undeformed measurements. For measurements of both thread wires and gage balls in the deformed state, the applied force must be known, and then a correction for deformation must be calculated to obtain a zero-force value. Recommended force values and guidance on deformation corrections are provided in ASME B89.1.17-2001.

Thread wires may be measured with two flat parallel anvils, or, preferably, using a fixed master cylinder and a moveable flat carbide anvil. The master cylinder is oriented perpendicular to the thread wire, creating a point contact. Gage balls should be measured using two flat parallel anvils. Out-of-parallelism of the anvils can lead to error in the measurement due to different positioning of a master and unknown. This error can be reduced with proper fixturing. Uncertainty also results from temperature fluctuations which cause differential thermal expansion (even with low CTE materials). Therefore, temperature control and equilibration during measurements are crucial, requiring stability better than ±0.25 °C for the best dimensional accuracy.

1.3 The Universal Length Measurement System

The Length-Mass-Force (LMF) Project of the Primary Standards Laboratory (PSL) has traditionally utilized a vertical length measurement setup, shown in Figure 3, for the calibration of thread wire and gage ball sets. While the setup provides good repeatability (±50 nm typical), repeatable positioning is challenging with the potential risk of dropping thread wires or gage balls. With the smallest gage balls, loss is likely if dropped. Placement of smaller gage balls and thread wires can be especially cumbersome.

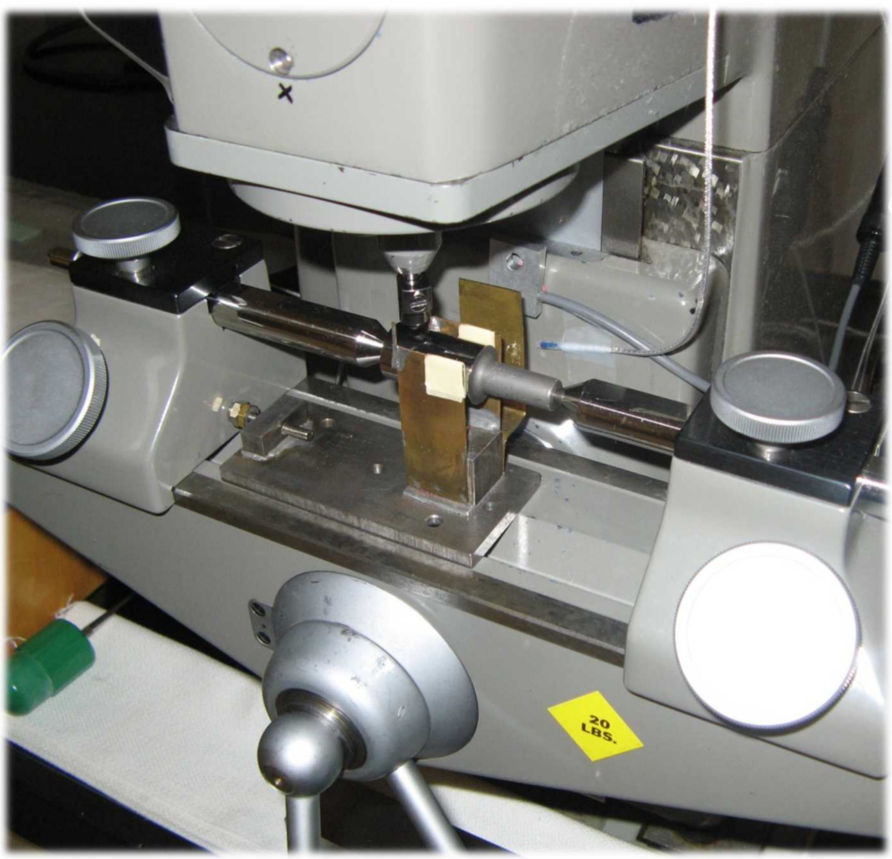

Figure 3: Vertical Length Measurement System.

A horizontal universal length measurement system (Pratt & Whitney LABMASTER Model 175[*]) was acquired to calibrate thread wires and gage balls, though the system is optimized for plug gages, ring gages, thread gages, and micrometers. The system is shown in Figure 4 with the standard diameter (0.375” or 9.52 mm) probes equipped. Selected parameters of the system (from the manufacturer) are listed in Table 1. Various accessories, including small diameter (0.100” or 2.54 mm) probes were purchased separately for the system. While optional accessories included V-grooves and other fixtures, none appeared well-suited for our specific needs with thread wires and gage balls. This study presents the design and fabrication of fixtures for the placement of a wide size range of thread wires and gage balls on a horizontal universal length measurement machine. Use of rapid prototyping is explored for such fixtures to substantially reduce cost and improve turnaround time. Lastly, a testing and qualification plan for use of the horizontal universal measurement machine as a direct-reading system for thread wires and gage balls is outlined.

Figure 4: Photograph of the Horizontal Measurement System. The standard diameter parallel anvils are shown. Note that two dial indicators were added by the authors to provide immediate feedback when changing table position.

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[*] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the authors, Sandia National Laboratories, or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

Table 1: Selected Manufacturer's Specifications of the Horizontal Universal Measurement Machine. *Adapted from Ref. [7]*.

PARAMETER	VALUE
Instrument Uncertainty (*k*=2)	0.05 + 0.5L/1000 µm
Repeatability (*k*=2)	±0.04 µm
Resolution	0.0025 µm
Measurement Range	0 mm to 330 mm
Direct Reading Range	178 mm
Contact Force	0.56 N to 11.12 N

2. Design and Fabrication of Custom Fixtures

2.1 Functional Requirements

Fixture design centered around the fundamental requirement of positioning both inch and metric series thread wires and gage balls for measurement on the horizontal length measurement system. A complete inch series thread wire set has 34 thread wires ranging from 80 pitch to 4 pitch (approximately 0.00723" to 0.144", whereas a metric set has 30 wires ranging from 0.2 pitch to 10 pitch (approximately 0.116 mm to 5.78 mm). A full inch series gage ball set has 31 balls ranging from 1/16" to 1", whereas a metric set has 25 balls from 1 mm to 25 mm in diameter.

A list of more specific functional requirements was created following the brainstorming of numerous fixture concepts (14 unique ideas were conceived for the gage balls alone). The functional requirements for the gage ball fixture were that it provide:

(1) Access to both sides of the gage ball.
(2) Proper kinematic fixturing.
(3) Ease of use for the metrologist.
(4) Ability to reposition during measurements.
(5) Does not physically damage the gage ball.
(6) Limited need for manipulation during placement and operation.
(7) Minimum effects from temperature changes.
(8) Prevention for the dropping and/or loss of the gage ball.
(9) A minimum number of fixture or probe changes over a complete set.

The fixture concepts were ranked based on the functional requirements. Also considered were cost and manufacturing of the fixtures when choosing the final designs. Ultimately, several gage ball fixture designs were chosen for solid modeling, including using parallel rolls against a flat surface, several variations of a V-groove, and ball-in-cup type holders. For the thread wires, it was anticipated that the final fixture would be some variation of a transverse V-groove. The final fixture designs, along with trays for holding gage balls and thread wires to be measured, are highlighted in the next section.

2.2 Solid Modeling of Fixtures with Computer-Aided Design (CAD) Software

The highest-ranking conceptual designs were modeled using SolidWorks 2014 CAD software. Solid modeling with collision detection enabled the ability to simulate different probe and gage ball/thread wire sizes in the fixture designs. Using these simulations, refinements were made and final models were selected. In addition to fixtures, trays for holding the thread wires and gage balls were also designed.

Thread Wire Fixture and Tray

The final thread wire fixture, capable of properly positioning the entire size range of both inch series and metric series thread wires, is shown in Figure 5. The measurement configuration relies on a 3/4" master cylinder positioned vertically in the fixture. The thread wire, positioned horizontally, self-locates to the appropriate height on the master cylinder. The standard diameter probes contact the back of the master cylinder and the other side of the thread wire. The appropriate measurement is achieved by zeroing the probes against the cylinder at the same height. While ridges, as opposed to inclined flats, would provide the proper kinematics (point instead of line contact) they would not be practical. Though the wire rotation about its axis is not constrained, it is unlikely due to friction. A glass microscope slide, placed in the slot, prevents longitudinal translation, thereby enabling repeatable positioning of the center of the thread wire. Glass microscope slides also provide a cost-effective alternative for creating bearing surfaces that are smooth to 50 nm or better on the inclined flats, enhancing repeatability.

A model of the entire thread wire setup, including the custom-designed tray, is shown in Figure 6. Staging of thread wires to be measured on the same table improves thermal equilibration for diameter measurements. Thread wires are handled using tweezers, to prevent the transfer of oils and contaminants and also to maintain thermal stability.

Gage Ball Fixtures and Tray

Ultimately, it was determined that a single fixture for gage balls was not feasible due to the wide size range encountered in a typical set. For small gage balls (5 mm and smaller), a ball lens holder constructed of 6061-T6 aluminum (Newport Optics) and intended for optical setups was found to provide adequate positioning for measurement with the small diameter probes. Though the conical holder deviates from proper kinematics, it offered a practical and cost-effective solution. A tray for positioning and catching gage balls was designed for the ball lens holder. Both are shown in Figure 7.

For larger gage balls (>5 mm diameter), a 90° groove fixture was designed for use with the small and large diameter probes. A groove made by the intersection of two planes at right angles is optimum from a kinematic standpoint [1]. As with the thread wire fixture, microscope slides placed on the bearing surfaces provide smooth and stiff contact points for gage balls, improving repeatability of the measurements. The simple groove design is shown in Figure 8.

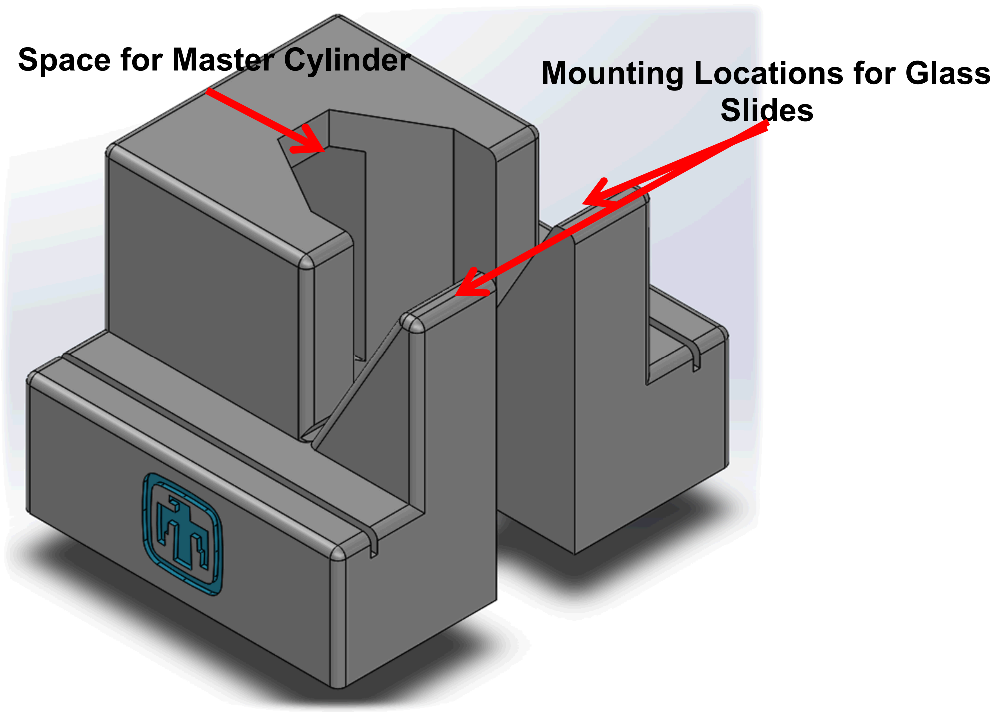

Figure 5: Thread Wire Fixture. Fixture is capable of positioning thread wires ranging from 0.1 mm to 6mm in size for horizontal measurement with the standard diameter (0.375”) parallel anvils. The master cylinder and glass microscope slides are not shown.

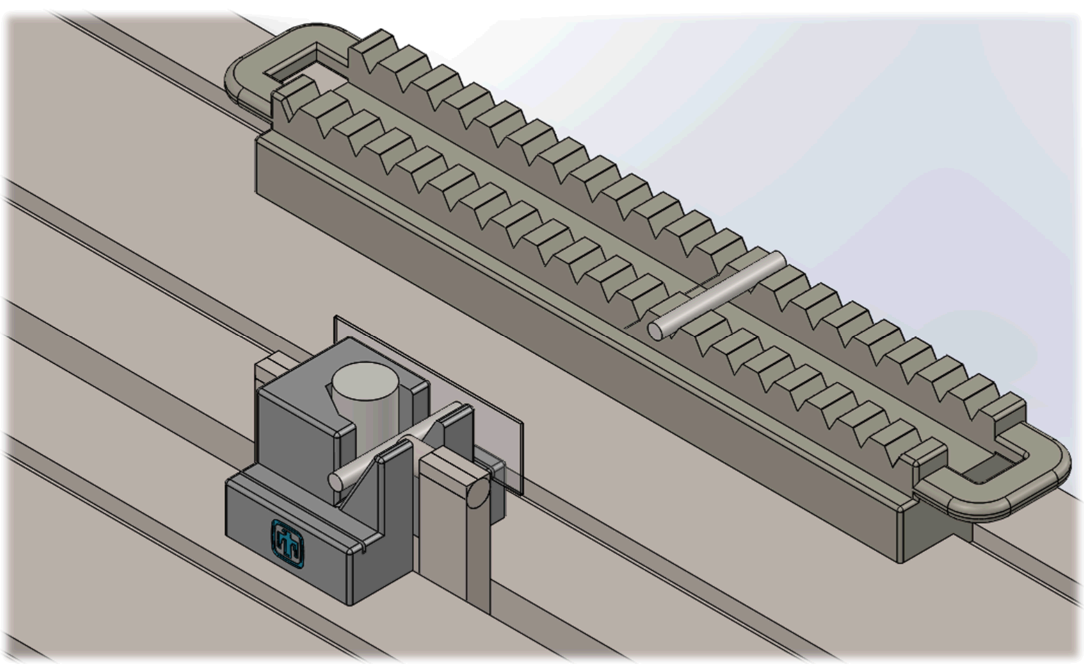

Figure 6: Envisioned Setup for the Measurement of Thread Wires.

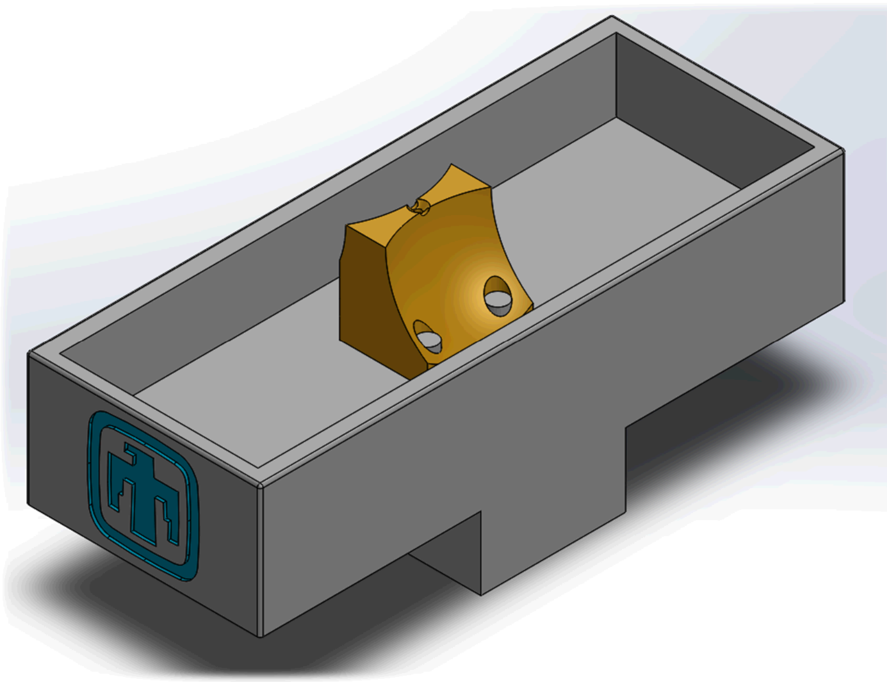

Figure 7: Spherical Ball Lens Holder in Custom Catch Tray Adapted for Measurement of Gage Balls from 1 mm to 5 mm.

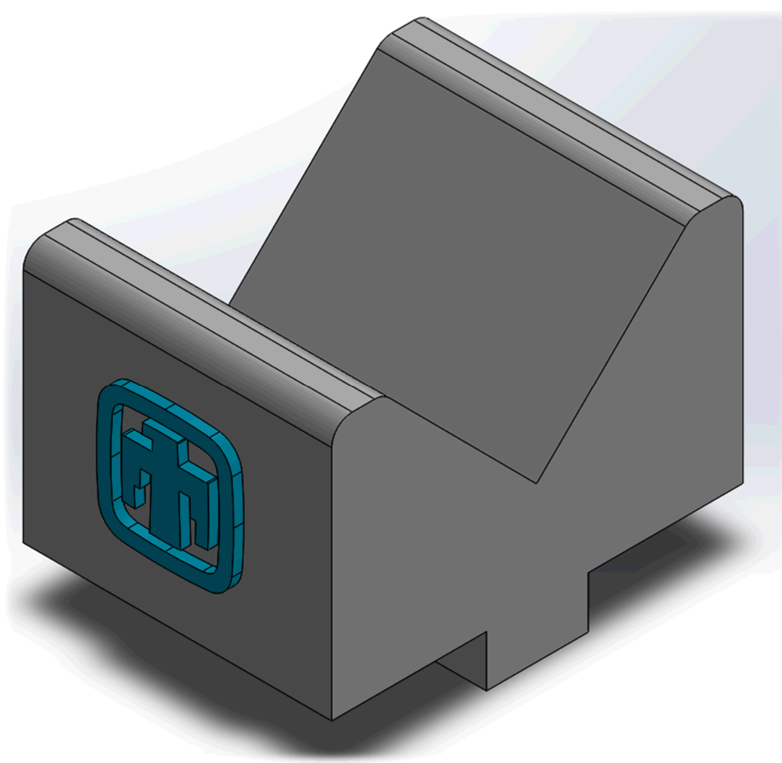

Figure 8: Simple Groove Fixture for Measuring Gage Balls Larger than 5 mm in Diameter.

2.3 Development Using Rapid Prototyping

Initially, 6061 aluminum was considered to be the optimum material from which to construct the fixtures. 6061 has a very high thermal conductivity (about 167 W/m-K for the T6 temper at room temperature), which would improve thermal communication with the table and reduce stabilization time. In this approach, fixtures would have been fabricated using computer numerical control (CNC) machining.

However, rapid prototyping using thermoplastics offers the ability to test fixture designs at up to $1/10^{th}$ the cost of traditional manufacturing methods with metals. The use of glass microscope slides reduces concerns of contact point stiffness. While thermal communication with the table is far less effective (typical thermal conductivity of about 0.2 W/m-K), the use of fans to provide consistent convection heat transfer should mitigate this effect. Ultimately, all fixtures and trays (with the exception of the purchased ball lens holders) were constructed in VeroBlackPlus RGD875, an acrylic-based plastic feed used in 3D printers. The fixtures and trays were built on a Stratasys Objet500 Connex 3D printer, with turnaround time for all parts being less than one day. A photograph of the fixtures and trays, shortly after removal from the 3D printer, are shown in Figure 9.

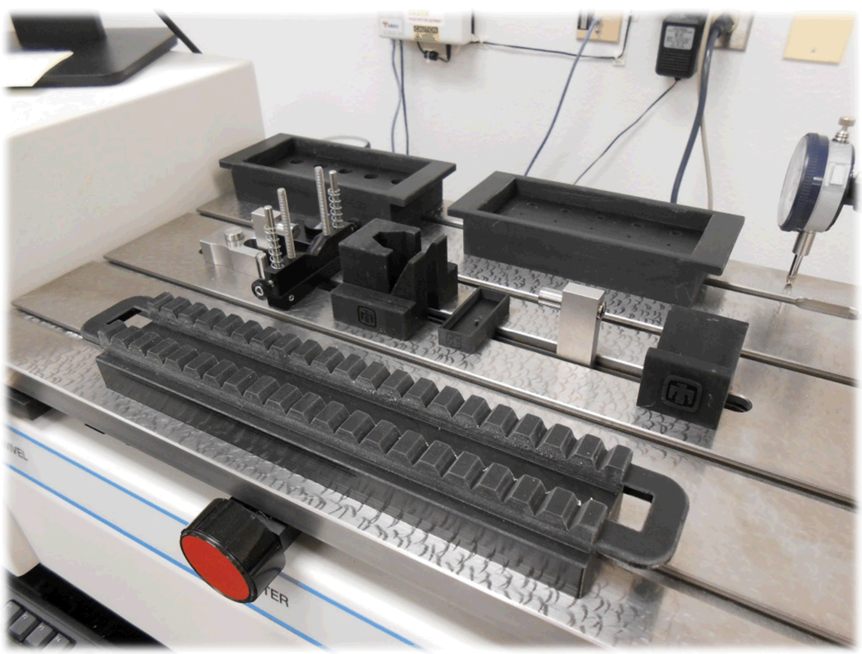

Figure 9: Fixtures and Trays Created *via* Rapid Prototyping.

2.4 Vacuum Handling System

Transfer and positioning of gage balls has traditionally been performed with tweezers. For the smallest gage balls (diameters of 5 mm and smaller), this process can be rather cumbersome for the metrologist, requiring patience and care to avoid dropping and losing the gage ball during transfer. Incorporation of a vacuum handling system was proposed to facilitate transfer and positioning of small gage balls. Assuming a vacuum supply pressure of 50 kPa and that the suction area would at most cover half the gage ball diameter, the following force balance results:

$$\frac{4}{3}\rho\pi r^3 g \leq P_{suction}\pi\left(\frac{1}{8}r\right)^2$$

where ρ is the material density of the gage ball, r is the radius of the gage ball, and $P_{suction}$ is the net suction pressure. The force balance is plotted for alloy steel and tungsten carbide gage balls in Figure 10. As seen in the figure, the force balance predicts that a vacuum handling system operating at 50 kPa would be able to hold up to a 9 mm steel gage ball. An off-the-shelf system (Edmund Optics), designed for the handling of optical lenses and wafers, was acquired for the purpose of transferring gage balls. Testing indicated that the system was sufficient for holding alloy steel gage balls up to 9 mm in diameter.

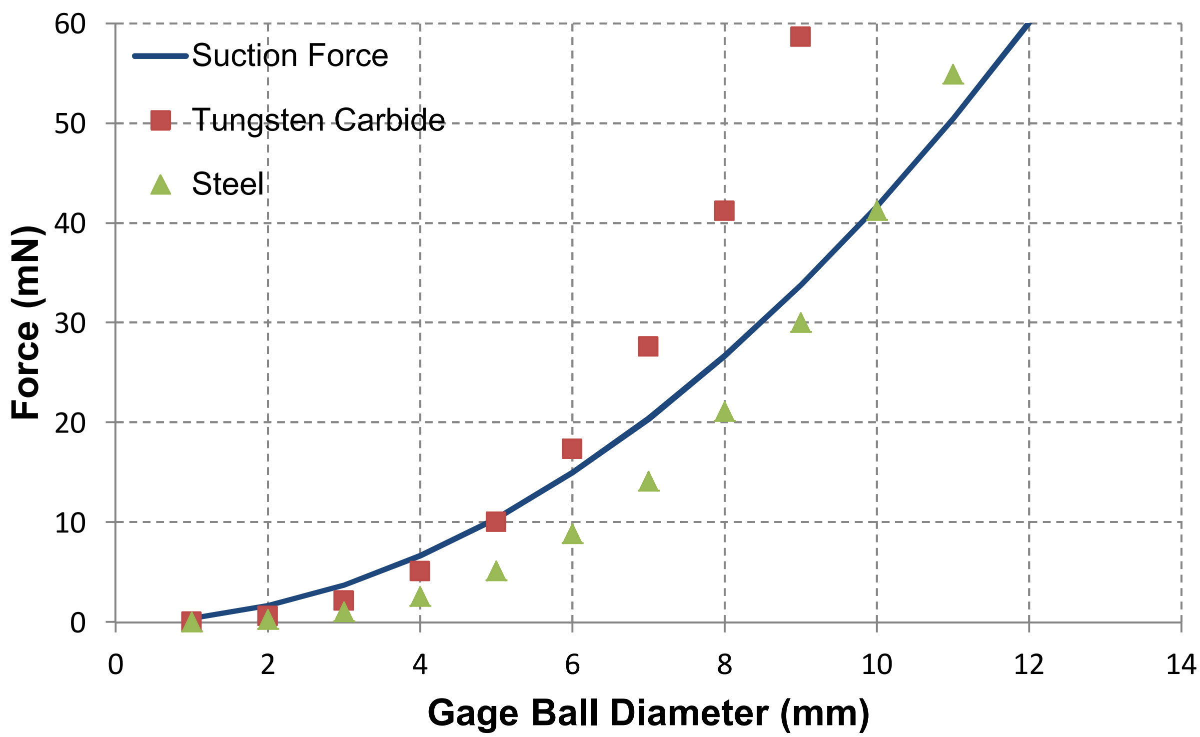

Figure 10: Force Balance for a Vacuum Handling System Lifting a Gage Ball.

3. Qualification and Test Plan

The horizontal measurement machine was originally intended for use as a comparison system, where every gage ball or thread wire in a set must be directly compared to a corresponding master. However, excellent linearity of the system over a wide measurement range may enable use as a direct system, where a minimum of two measurement points (zero and a master corresponding to the maximum size in the set) could be used to establish reference values. More likely, three reference points will be used to better establish linearity over the necessary measurement range for a complete set, i.e., a zero and master thread wires/gauge balls corresponding to the minimum and maximum size in the set to be measured. One possible procedure is outlined below:

- Measure and set zero.
- Measure check standard.
- Measure unknown.
- Correct for deformation and thermal expansion.

An uncertainty budget must also be drafted for the system and direct measurement approach. The ISO Guide to the Expression of Uncertainty in Measurement [8] should be followed when determining and reporting sources of uncertainty in the measurement of thread wires and gage balls. Typical sources of uncertainty for thread wire measurements are discussed in reference [6]. Sources of measurement uncertainty are similar for gage balls. These sources of uncertainty are summarized in Table 2.

Table 2: Typical Sources of Uncertainty for the Measurment of Gage Balls and Thread Wires. ***Adapted from Ref. [6].***

Type A	Type B
Repeatability (determined from series of measurements of a single thread wire or gage ball)	**Certified uncertainty of master** **Scale error** **Force setting** **Coefficient of thermal expansion** **Temperature deviation between part and master** **Parallelism of anvils** **Instrument linearity over span**

The linearity over the range must be accounted for if the system is to be used for direct measurements. It can be estimated by measuring a complete master set, and reporting the maximum deviation of the measured value from linear for the measurement range of interest. Alternatively, the uncertainty associated with a linear fit based upon the reference master values can be calculated.

Accounting for the uncertainty of a general fitted function, *y(x)*, when both data points x_i and y_i have non-negligible uncertainties is quite complicated and not definitive. In the case of a linear fitted function of the form $y=mx+b$, where x is the measured value, and y is the true value from the calibrated master, the following equation may be used to express the equivalent uncertainty in y_i [9]:

$$\sigma_{\mathrm{y_i,eq}} = \sqrt{\sigma_{\mathrm{y_i}}^2 + \left(\mathrm{m}\sigma_{\mathrm{x_i}}\right)^2}$$

If the uncertainties in x, or in y, are not all equal, then the equivalent error will be different for each point along the curve. The uncertainty in the slope and intercept of the linear calibration curve can then be determined by:

$$\sigma_{\mathrm{m}} = \sigma_{\mathrm{y_i,eq}} \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i^2}}{\mathrm{N}\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i^2} - \left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i}\right)^2}}$$

$$\sigma_{\mathrm{b}} = \sigma_{\mathrm{y_i,eq}} \sqrt{\frac{\mathrm{N}}{\mathrm{N}\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i^2} - \left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i}\right)^2}}$$

where N is the number of calibration points from which the linear curve is fitted. The 95% confidence bands for the straight line are then defined by:

$$\mathrm{y(x)} = (\mathrm{m} \pm \varepsilon_{\mathrm{m}})\mathrm{x} + (\mathrm{b} \pm \varepsilon_{\mathrm{b}})$$

where $\varepsilon=1.96\sigma$. The uncertainty due to nonlinearity over the measurement range can be taken as the deviation between the linear fit (including uncertainty of the fit) and a line with $m=1$ and $b=0$ at the point of interest.

Measurements will first be performed on unfixtured gage blocks to assess the feasibility of performing direct measurements. Qualification will then be performed on thread wires and gage balls to determine repeatability attainable with the rapid-prototyped fixtures.

4. Conclusion

Principles of kinematic design enable highly repeatable positioning without requiring overly precise manufacturing tolerances. We have presented the design of custom fixtures to enhance repeatability and practicality of calibrating thread wires and gage balls on a horizontal universal length measurement system. Fixtures were rapid-prototyped using 3D printing technology to reduce cost and improve turnaround time.

As of writing the extended abstract, hardware has been fabricated, but qualification testing has not yet begun. Future work includes qualification of the horizontal length measurement machine for use as a direct (instead of comparison) system and quantitatively assessing the best achievable repeatability of thread wires and gage balls using this setup.

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