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Abstract

A fundamental lack of research into the performance capabilities of the various sensors available to *OGP SmartScope* measurement system operators makes for a steep learning curve and increased difficulty in selecting the right sensor for the job. This research compared three typical sensors (video, touch probe, laser probe) and established a comparative performance baseline. The results indicate (with 99% confidence) significant differences within the controlled variable settings for the touch probe and video sensors – the video sensor performs best when using the ring light at 25% subject reflectivity and the larger touch probe styli outperform the smaller models. Although a single best sensor has not been identified in a global comparison, a subset of these which includes the laser, the thicker touch probe styli, and the ring light at 25% subject reflectivity, clearly outperforms the remaining devices.

Introduction

Accumold[1], a highly specialized, high-tech manufacturer of injection molded lead-frame and small- and micro-scale plastic parts, realized a need for an improved measurement system as a result of increasingly common customer demands for engineering tolerances in the micron range. As a result, Accumold used the Gage R&R test as a preliminary qualification method (Hoffa & Laux, 2007) and purchased an Optical Gaging Products (OGP) SmartScope Quest 450[2] in the Spring of 2007, and realized quickly thereafter that they were at the base of an extremely steep learning curve. With the near-total lack of statistically-based research related to the quantification of the capabilities of the different sensors available on OGP's multi-sensor systems, the need to use statistical methods to establish the performance baseline was recognized. This research fills that void.

The measurement system in this study was an Optical Gaging Products (OGP) Smartscope Quest 450, a multi-sensor system combining touch probe, laser, and video sensors. OGP of Rochester, NY, is a market leader of multi-sensor system design and manufacturing (Anonymous, 2004; Anonymous, 2005; Mason, 2008).

Review of Literature

For approximately two decades, the market of micro-manufacturing has been increasing. The expected annual growth rate of 20 percent is based on a total world market of $60 billion (NEXUS! Task Force, 2001; Spath, Fleischer, & Elsner, 2005). The leading applications are information technology, biomedical, and telecommunications industries. When manufacturing micron-level products, quality assurance is a challenge, primarily the metrology aspects (Spath, et al., 2005). As a result, expensive measuring equipment and extensively trained operators are necessary in order to measure accurately (Spath, et al., 2005). This exhaustive review of the literature has revealed no prior research in this area, underscoring the uniqueness of this study and its importance to field practitioners.

CMM Limitations

Conventional technology of coordinate measurement machines (CMMs) is based on the physical contact of part and sensor (Groff, 2008; Majlak, 2005). Very small parts are more prone to deformation or even damage due to the mechanical nature of CMM inspection (Chalmers, 2001; Doiron, Stanfield, & Everett, n.d.).

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[1]Accumold® is a registered trademark of Accumold, LLC.
[2] OGP® is a registered trademark of Optical Gaging Products, Inc. SmartScope® is a registered trademark of Quality Vision International, Inc., the parent company of Optical Gaging Products, Inc.

Throughput is an important factor in measurement systems due to increased competition (Metzger, 2008). The increased use of more stringent quality requirements has resulted in higher sample sizes of inspected parts, increasing handling and time of measurement (Chalmers, 2001; Chen, Wan, Luo, Liu, Ding, & Zhu, 2003), and CMMs are not known for speed of measurement.

Finally, contact measurement results in probe force that can result in wear of the stylus, reducing the reliability of micron level measurements (Doiron, et al., n. d.). As a result of these limitations, adoption of non-contact measurement technologies is increasing.

Non-contact Measurement Technologies

All non-contact measurement systems use some form of radiant energy to probe objects (Anonymous, 1995). Among the four major areas of non contact measurement (air gaging, capacitance, diffraction, and focus follow), light methods such as diffraction (laser, CCD) or focus follow (optical lens) are predominant (Anonymous, 1995), and these are the non-contact methods discussed in this paper.

Vision Systems

Optical lens vision systems measure the distribution of light and intensity of diffracted light upon a feature or part geometry through an optical lens. An optical system magnifies the part or feature to measure the attribute of the imaged part, and the use of multiple lenses or a zoom lens allows the measurement of a range of feature sizes, including in the Z axis (Gilman, 2004). The optics of a vision system translate the image to the metrology software for manipulation (Gilman, 2004; Groff, 2008). The ability of a vision system to magnify features much smaller than the smallest touch probe tips results in a more complete and flexible measurement system (Anonymous, 2004; Bangert, 2007; Groff, 2008). Finally, the optics of a vision system require more stringent environmental conditions than a touch probe CMM (Anonymous, 1995; Chalmers, 2001).

Lasers

A laser measuring system can measure a single point at a time or perform multi-point scans across a surface. While the laser sensor is different than an optical lens, the metrology software handles all measurement data from sensors equally (Groff, 2008). Since there is no contact between the sensor and the part, there is no sensor speed required for touching the surface with a measurement sensor. As a result, optical systems (including lasers) are faster than typical mechanical probe measurement systems, cutting costs of inspection time (Anonymous, 2007; Bangert, 2007; Flynn, 2008; Manfredi, 2007). As a result of these benefits, the use of non-contact vision measurement is increasing with approximately 40 percent of quality inspection being handled by video or laser sensors (Chalmers, 2001).

Lighting

Subject material characteristics complicate non-contact measurements. Material characteristic issues can usually be dealt with, but as materials of differing translucence, color, and reflectivity are measured, the optical capability of the sensor(s) can be altered and measurement error increased (Groff, 2008). Furthermore, visualization of part features requires magnification, necessitating light sources other than ambient light (Glowacky, 2005).

Adequate lighting is the single biggest factor in using video measurement systems (Williams, 2003). Since artificial light is required, illumination is a variable in the measurement process (Glowacky, 2005). Improvements in software, optics, and lighting are addressing illumination problems, where new algorithms improve feature detection for measurement, new optical designs improve the field view of measurement, and most importantly, lighting is becoming standardized (Williams, 2003).

Light sources are available in a variety of physical forms. Ring lights are common and designed to fit around a camera lens and provide uniform illumination (Connolly, 2002; Metzger, 2008). Ring lights are preferable to other light sources since they are constructed with single-wavelength LEDs, typically green or red, resulting in a more consistent, stable light source (Connolly, 2002; Metzger, 2008). Coaxial lights can also be LED-driven (as is the case in this study), but they differ from ring lights in that they direct their light on-axis, through the vision measurement system's lens.

Multi-sensor Measurement System Technologies

A current measurement technology trend is the combination of non-contact technologies such as laser and video and contact (touch probe) technology into a more efficient and precise multi-sensor system (Adams, 2000; Bangert, 2007; Chen, et al., 2003; Flynn, 2008; Groff, 2008; Majlak, 2005). This allows inspection operations to be calibrated to a common reference point and measurements from all available sensors to be taken in one setup (Adams, 2000; Flynn, 2008; Mason, 2008; Vince, 2005). As a result, multi-sensor systems have the flexibility to meet the changing part specifications, designs, and production rates (Flynn, 2008; Vince, 2005). Multisensor systems also result in more accurate measurement results and provide more versatility in sampling due to increased measurement speed (Metzger, 2008). This results in cost savings such as minimizing setup time, reduced part handling, less stringent part fixturing, and lower service and utility machine measurement costs (Flynn, 2008).

The introduction of multiple sensors into one platform has tradeoffs, however. The combination of technologies requires that operators have additional knowledge to understand what type of sensor to use for a specific measurement application. The setup variable differences that influence sensor performance are significant between contact and non-contact measurement. This requires in-depth operator knowledge of sensors for proficient measurement performance (Anonymous, 2007; Flynn, 2008). Since contact and non-contact measurements are suited to particular measurement applications, the knowledge of when to select a particular sensor to measure a particular dimension becomes subjective (Bangert, 2007; Chalmers, 2001).

Summary

Optical inspection is sometimes considered qualitative and somewhat subjective where the main concerns are precision and reliability of measurement results (Gilman, 2004; Wu, Xie, & Zhang, 2005). Obstacles to adopting vision inspection, including the cost of training skilled operators to accurately interpret measurements in addition to the expense of the hardware (Glowacky, 2005), are a barrier for manufacturing management (Langston, 1996). After review of contact and non-contact methods, Manfredi (2007) states that a measurement system is best configured to specific applications.

Statement of the Problem

For sound decisions regarding the proper settings for OGP SmartScope measurement system setup variables, quantitative definition of the performance differences between sensors and the performance impact of within-sensor settings is needed.
Practitioners operating OGP SmartScopes have only trial and error and the opinions of seasoned system users to guide them in the proper choice of sensor, lighting, or stylus size – three of the major variables that must be set properly in order to achieve a proper measurement. The fundamental lack of research into the impact on performance of these variables makes system operation and reliance upon measurements taken with an OGP SmartScope difficult.

Purposes of the Study

The primary purpose of this study was to establish a baseline comparison of the performance of the available sensors (video, Renishaw TP200 touch probe, and DRS-500 laser) on Accumold'S OGP Quest 450 measurement system measuring a 0.100" Mitutoyo gage block.
The secondary purpose was to provide a "cheat sheet" for practitioners to keep by their measurement systems to use as a handy guide to sensor selection (see Appendix).

Methodology

The data used in this study were gathered in January and February of 2008 at Accumold. Their system is housed in a small room erected inside a class 100,000 clean room. Temperature was held within the operating parameters of the system for the duration of the study (see Table 1 in the *Results* section).

Assumptions

This study includes the following assumptions:

1. Since answers to technical questions regarding optimal machine setup varied from expert to expert, it was assumed that other practitioners and system users were facing similar problems and would benefit greatly from research such as this.
2. The results of this study could be generalized to Z-axis measurements taken by other similarly equipped OGP SmartScope systems.

Delimitations

1. The system used for this study was a SmartScope Quest 450 multi-sensor system in the following configuration:
   a. Video sensor with grayscale sensor upgrade and green LED lighting system
   b. Renishaw TP-200 touch probe with 2 X 20mm, 1 X 20mm, 0.5 X 10mm, and 0.3 X 10mm spherical ruby styli (NOTE: the 0.5 X 10mm and 0.3 X 10mm styli were mounted on 10mm extension bars, making their effective overall length 20mm)
   c. DRS-500 laser probe
2. Other sensors are available for these systems but were not purchased by Accumold.
3. A gage block was chosen as the subject because it had a known, NIST-traceable dimension.

Color, surface texture, and reflectivity of the subject can impact the way the video sensor interprets its location; therefore, these results may not generalize to subjects of any material other than Grade 2, finished surface steel (ASTM, 2006; Mitutoyo, 2001).

Data Gathering

All measurements were made (in millimeters) on a 0.100" Mitutoyo gage block, which was wrung to a second gage block in a cross fashion. There were a total of 17 groups (see Table 1) with n = 100 (N = 1,700). Video measurements were gathered by programming one point on the lower block and one point on the 0.100" block and reporting the Z distance. Touch probe and laser measurement were programmed to measure at the same coordinates as with the video sensor. The 17 runs were randomized using Excel's *=rand( )* function in two groups – video sensor runs were treated as one group and the laser and touch probe runs were grouped together as the second, with each group randomized independently. The first group was run before the second group because the laser and touch probe programs rely on the optical programs for point placement, necessitating their being pushed to the end of the run order.

Video Sensor

There are three light source choices for measuring a Z-height with the video sensor: the SmartRing Light (SRL), ring, and coaxial lights. The SRL and ring lights are, in fact, the same device configured in two different ways – the SRL uses all available LEDs (eight concentric rings), whereas the ring light uses only the first ring of LEDs (closest to the lens) . While at first glance this may seem to be trivial and to result in little more than a change in brightness, it also offers a change in the angle of the light – using the ring light more closely approximates an on-axis light source, whereas the SRL provides more oblique light.

The owner's manual states that the optimum light setting for measuring with the video sensor is between 40% and 60% maximum reflectivity, which refers to the brightness value the system reports when the mouse pointer

Table 1. Descriptive Statistics

Sensor	(Factor 2)	Run Order	*n*	Ambient Temperature (°F)	Actual Thickness[a]	Mean Thickness	Mean - Actual	Standard Deviation	Min	Max	Range
Ring Light	25% refl.	9	100	75	2.540042	2.540153	0.000111	0.000198	2.53943	2.54060	0.00117
Ring Light	50% refl.	5	100	74	2.540036	2.539693	-0.000343	0.000156	2.53934	2.54008	0.00074
Ring Light	75% refl.	1	100	73	2.540030	2.539483	-0.000548	0.000152	2.53915	2.53986	0.00071
Ring Light	100% refl.	6	100	75	2.540042	2.539616	-0.000426	0.000128	2.53927	2.53991	0.00064
SmartRing Light	25% refl.	4	100	74	2.540036	2.539316	-0.000720	0.000132	2.53905	2.53970	0.00065
SmartRing Light	50% refl.	2	100	73	2.540030	2.539106	-0.000924	0.000128	2.53878	2.53942	0.00064
SmartRing Light	75% refl.	3	100	74	2.540036	2.539107	-0.000930	0.000123	2.53885	2.53942	0.00057
SmartRing Light	100% refl.	10	100	75	2.540042	2.539763	-0.000280	0.000138	2.53943	2.54007	0.00064
Coaxial Light	25% refl.	12	100	75	2.540042	2.538832	-0.001211	0.000375	2.53767	2.54087	0.00320
Coaxial Light	50% refl.	11	100	75	2.540042	2.538826	-0.001217	0.000226	2.53829	2.53947	0.00118
Coaxial Light	75% refl.	7	100	75	2.540042	2.538452	-0.001591	0.000190	2.53804	2.53922	0.00118
Coaxial Light	100% refl.	8	100	75	2.540042	2.538752	-0.001290	0.000180	2.53836	2.53934	0.00098
Laser	n/a	13	100	75	2.540042	2.540090	0.000047	0.000094	2.53991	2.54029	0.00038
Touch Probe	2mm stylus	16	100	75	2.540042	2.540046	0.000004	0.000115	2.53980	2.54030	0.00050
Touch Probe	1mm stylus	15	100	75	2.540042	2.540087	0.000057	0.000110	2.53990	2.54030	0.00040
Touch Probe	0.5mm stylus	17	100	73	2.540030	2.540155	0.000113	0.000107	2.53990	2.54040	0.00050
Touch Probe	0.3mm stylus	14	100	75	2.540042	2.540223	0.000181	0.000090	2.54000	2.54030	0.00030
		Mean		74.471	2.540039	2.539512	-0.000528	0.000155	2.53913	2.53997	0.00085
		Standard Deviation		0.800	0.000005	0.000580	0.000580	0.000068	0.00071	0.00048	0.00067
		Min		73	2.540030	2.538452	-0.001591	0.000090	2.53767	2.53922	0.00030
		Max		75	2.540042	2.540223	0.000181	0.000375	2.54000	2.54087	0.00320
		Range		2	0.000012	0.001771	0.001771	0.000285	0.00233	0.00165	0.00290

Note. All measurements in units of millimeters.

[a]Actual values based upon the actual value certified by Mitutoyo (NIST traceable) adjusted for ambient temperature.

is placed over the brightest pixel in the software image of the sample; 100% reflectivity would indicate that the sensor is "maxed out" by the brightness at that pixel and 0% reflectivity would indicate that no light is detected at that pixel. Alternatively, some seasoned users recommend 30-50% reflectivity, which calls the optimal value into question. For this reason, four baseline values of maximum reflectivity were examined for each lighting source – 25%, 50%, 75%, and 100%.

Renishaw TP-200 Touch Probe and DRS-500 Laser

The TP-200 touch probe body is permanently installed in the measurement head, but the system can change styli, under machine control, between the four sizes mentioned previously. It is interesting to treat the styli as factor levels because as the diameter of the ruby ball decreases, so does the shaft upon which it is mounted, and the touch-off deflection of a thinner shaft is more exaggerated than with a larger stylus. As a result, smaller styli demand gentler program control (lower velocity, higher acceleration) in order to reduce the risk of damage.

For measuring the sample with the touch probe or laser, optical focus points were first placed at the same coordinates as with the video sensor measurements; these were then used to guide the touch probe styli and the laser to these identical coordinates.

Statistical Methods

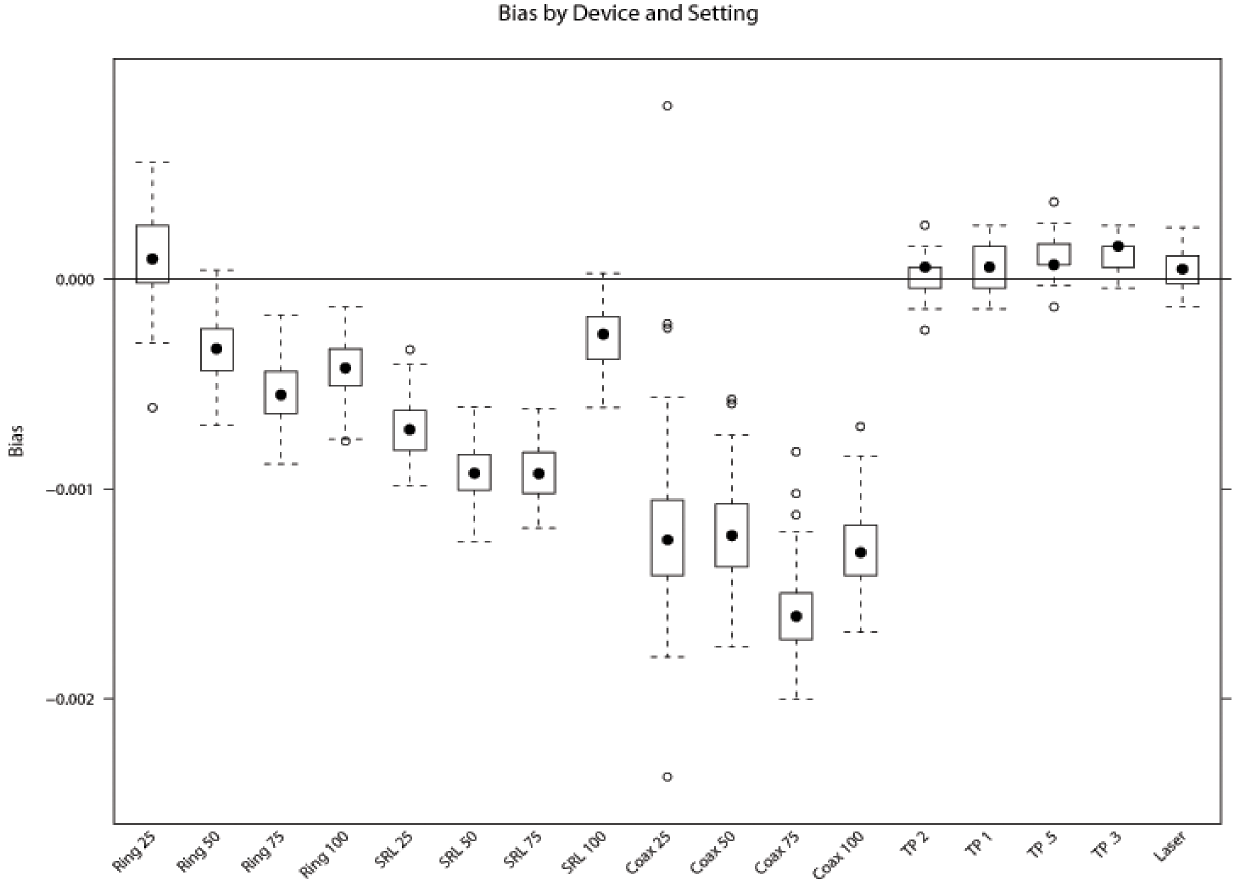
All statistical analyses were performed with R version 2.8.0 (2008) unless otherwise specified. Sensor performance can be assessed using a number of different measures. In this study, measurement bias (the difference between the measured value and the known value) was used as the primary performance metric. The impact of precision (as characterized by variance) and an overall performance measurement of mean squared error were also considered. This study examined the following:

1. Optimal setting for each device (lighting condition or probe diameter)
2. Best device in terms of both measurement bias and mean squared error
3. Characteristics common to video sensors and touch probes

Results

Descriptive statistics of the data set appear in Table 1.

Figure 1. Box plots of measurement bias for each device and setting combination. The video sensors show a tendency to underestimate while the touch point sensor and laser overestimate.



__Video Sensors – Optimal Settings__

Each light source was tested at four brightness levels (25%, 50%, 75%, and 100% reflectivity), thereby allowing the problem to be formulated as a two-way ANOVA with factors: *Brightness* and *Source* (see Table 2). Formulating the video sensor comparison as a two-way ANOVA specifically tested the null hypotheses that all interaction effects were equal (rejected; $p < 0.001$), brightness effects were equal (rejected; $p < 0.001$), and the source effects were equal (rejected; $p < 0.001$) in terms of their relationship to measurement bias. Preliminary testing revealed the presence of an interaction effect between Brightness and Source which is clearly observed in Figure 1 and Table 3. The presence of an interaction means that statistical testing with respect to either factor must be conditioned on a level of the other factor.

The overall best performing combination of source and brightness, in terms

Table 2. Two-way ANOVA Table for Lighting Source

Source	*df*	*SS*	*MS*	*F*	*p*
Source	2	0.000213	0.000107	2965.03	< 0.001
Brightness	3	0.000031	0.00001	0.00001	< 0.001
Source*Brightness	6	0.000031	0.000005	144.21	< 0.001
Error	1188	0.000043	0.000000036		
Total	1199	0.000318			

Table 3. Mean bias for each Brightness * Source interaction

	Brightness			
Source	25%	50%	75%	100%
Ring	**0.00011**[a]	**-0.00034**	**-0.00055**	-0.00043
Coaxial	-0.00121	-0.00122	-0.00159	-0.00129
SRL	-0.00072	-0.00092	-0.00093	**-0.00028**

[a] The ring light set to 25% maximum reflectivity yields the smallest bias and can therefore be declared the best light setting to use when measuring shiny steel with the video sensor.

of bias, was the ring light at 25% reflectivity. This was determined using Tukey's pairwise comparisons across every brightness and source combination ($p < 0.001$; see Table 4). The ring light was the best performer at all brightness levels with the exception of 100%, where the SRL was best ($p < 0.001$ versus each source). Examining the data across the combinations of brightness and source reveals the following:

- The ring light performed best at 25% reflectivity ($p < 0.001$).
- The SRL light performed best at 100% reflectivity ($p < 0.001$).
- Coaxial measurement bias was worst at 75%, but indistinguishable across the other lighting levels ($p < 0.001$).
- The coaxial light was the least accurate (had the largest bias) at every lighting level and was the least precise (largest variance) of all video sensor measurements.
- The largest measurement bias for each device was observed at an illumination level of 75%.

These results show the appropriate lighting level is source-specific, indicating a need for light source brightness guidelines, although there does appear to be agreement with regard to the worst lighting level and worst device.

Touch Probe – Optimal Stylus Size

Comparison amongst touch probe styli was performed in the context of a one-way ANOVA with a factor of stylus diameter (see Table 5). Formulating the touch probe sensor comparison as a one-way ANOVA specifically tested the null hypothesis that all touch probes were equal in terms of measurement bias (rejected; $p < 0.001$). Using a Bonferroni multiple comparison correction showed indicated a positive measurement bias ($p < 0.001$) for each of the styli with the exception of the thickest ($p = 0.75$), i.e. the measurement bias for the touch probe produces a tendency to overestimate (albeit by a very small amount). Table 6 shows the 2mm and 1mm styli produced the minimum bias and while they could not be differentiated from each other ($p = 0.042$), they were significantly

Table 4. Pairwise Comparisons for Light Sources

Light Source Pairing[a]	Difference	Lower Bound	Upper Bound	p[b]
Ring:1-Coaxial:1	0.0013214	0.0012336	0.0014092	< 0.001
SRL:1-Coaxial:1	0.0004906	0.0004028	0.0005784	< 0.001
Coaxial:2-Coaxial:1	**-0.0000057**	**-0.0000935**	**0.0000821**	**1.0000000**
Ring:2-Coaxial:1	0.0008676	0.0007798	0.0009554	< 0.001
SRL:2-Coaxial:1	0.0002864	0.0001986	0.0003742	< 0.001
Coaxial:3-Coaxial:1	-0.0003799	-0.0004677	-0.0002921	< 0.001
Ring:3-Coaxial:1	0.0006631	0.0005753	0.0007509	< 0.001
SRL:3-Coaxial:1	0.0002811	0.0001933	0.0003689	< 0.001
Coaxial:4-Coaxial:1	**-0.0000796**	**-0.0001674**	**0.0000082**	**0.1188280**
Ring:4-Coaxial:1	0.0007844	0.0006966	0.0008722	< 0.001
SRL:4-Coaxial:1	0.0009310	0.0008432	0.0010188	< 0.001
SRL:1-Ring:1	-0.0008308	-0.0009186	-0.0007430	< 0.001
Coaxial:2-Ring:1	-0.0013271	-0.0014149	-0.0012393	< 0.001
Ring:2-Ring:1	-0.0004538	-0.0005416	-0.0003660	< 0.001
SRL:2-Ring:1	-0.0010350	-0.0011228	-0.0009472	< 0.001
Coaxial:3-Ring:1	-0.0017013	-0.0017891	-0.0016135	< 0.001
Ring:3-Ring:1	-0.0006583	-0.0007461	-0.0005705	< 0.001
SRL:3-Ring:1	-0.0010403	-0.0011281	-0.0009525	< 0.001
Coaxial:4-Ring:1	-0.0014010	-0.0014888	-0.0013132	< 0.001
Ring:4-Ring:1	-0.0005370	-0.0006248	-0.0004492	< 0.001
SRL:4-Ring:1	-0.0003904	-0.0004782	-0.0003026	< 0.001
Coaxial:2-SRL:1	-0.0004963	-0.0005841	-0.0004085	< 0.001
Ring:2-SRL:1	0.0003770	0.0002892	0.0004648	< 0.001
SRL:2-SRL:1	-0.0002042	-0.0002920	-0.0001164	< 0.001
Coaxial:3-SRL:1	-0.0008705	-0.0009583	-0.0007827	< 0.001
Ring:3-SRL:1	0.0001725	0.0000847	0.0002603	< 0.001
SRL:3-SRL:1	-0.0002095	-0.0002973	-0.0001217	< 0.001
Coaxial:4-SRL:1	-0.0005702	-0.0006580	-0.0004824	< 0.001
Ring:4-SRL:1	0.0002938	0.0002060	0.0003816	< 0.001
SRL:4-SRL:1	0.0004404	0.0003526	0.0005282	< 0.001
Ring:2-Coaxial:2	0.0008733	0.0007855	0.0009611	< 0.001
SRL:2-Coaxial:2	0.0002921	0.0002043	0.0003799	< 0.001
Coaxial:3-Coaxial:2	-0.0003742	-0.0004620	-0.0002864	< 0.001
Ring:3-Coaxial:2	0.0006688	0.0005810	0.0007566	< 0.001
SRL:3-Coaxial:2	0.0002868	0.0001990	0.0003746	< 0.001
Coaxial:4-Coaxial:2	**-0.0000739**	**-0.0001617**	**0.0000139**	**0.2001032**
Ring:4-Coaxial:2	0.0007901	0.0007023	0.0008779	< 0.001
SRL:4-Coaxial:2	0.0009367	0.0008489	0.0010245	< 0.001
SRL:2-Ring:2	-0.0005812	-0.0006690	-0.0004934	< 0.001
Coaxial:3-Ring:2	-0.0012475	-0.0013353	-0.0011597	< 0.001
Ring:3-Ring:2	-0.0002045	-0.0002923	-0.0001167	< 0.001
SRL:3-Ring:2	-0.0005865	-0.0006743	-0.0004987	< 0.001
Coaxial:4-Ring:2	-0.0009472	-0.0010350	-0.0008594	< 0.001
Ring:4-Ring:2	**-0.0000832**	**-0.0001710**	**0.0000046**	**0.0825063**
SRL:4-Ring:2	**0.0000634**	**-0.0000244**	**0.0001512**	**0.4306840**
Coaxial:3-SRL:2	-0.0006663	-0.0007541	-0.0005785	< 0.001
Ring:3-SRL:2	0.0003767	0.0002889	0.0004645	< 0.001
SRL:3-SRL:2	**-0.0000053**	**-0.0000931**	**0.0000825**	**1.0000000**
Coaxial:4-SRL:2	-0.0003660	-0.0004538	-0.0002782	< 0.001
Ring:4-SRL:2	0.0004980	0.0004102	0.0005858	< 0.001
SRL:4-SRL:2	0.0006446	0.0005568	0.0007324	< 0.001
Ring:3-Coaxial:3	0.0010430	0.0009552	0.0011308	< 0.001
SRL:3-Coaxial:3	0.0006610	0.0005732	0.0007488	< 0.001
Coaxial:4-Coaxial:3	0.0003003	0.0002125	0.0003881	< 0.001
Ring:4-Coaxial:3	0.0011643	0.0010765	0.0012521	< 0.001
SRL:4-Coaxial:3	0.0013109	0.0012231	0.0013987	< 0.001
SRL:3-Ring:3	-0.0003820	-0.0004698	-0.0002942	< 0.001
Coaxial:4-Ring:3	-0.0007427	-0.0008305	-0.0006549	< 0.001
Ring:4-Ring:3	0.0001213	0.0000335	0.0002091	0.0004104
SRL:4-Ring:3	0.0002679	0.0001801	0.0003557	< 0.001
Coaxial:4-SRL:3	-0.0003607	-0.0004485	-0.0002729	< 0.001
Ring:4-SRL:3	0.0005033	0.0004155	0.0005911	< 0.001
SRL:4-SRL:3	0.0006499	0.0005621	0.0007377	< 0.001
Ring:4-Coaxial:4	0.0008640	0.0007762	0.0009518	< 0.001
SRL:4-Coaxial:4	0.0010106	0.0009228	0.0010984	< 0.001
SRL:4-Ring:4	0.0001466	0.0000588	0.0002344	0.0000036

Note. Insignificant comparisons are highlighted.

[a]Pairings are coded by source and brightness, where 1 = 25%, 2 = 50%, 3 = 75%, and 4 = 100%.

[b]Tested with Turkey's pairwise comparisons at $\alpha = 0.01$.

different and better than the 0.5mm and 0.3mm styli. Also see Table 1.

That the performance of the 0.3mm stylus could not be differentiated ($p = 0.9997$) from that of the 0.5mm stylus is noteworthy. The smaller of these is more expensive than the larger and more fragile – so much so that the manufacturer includes special instructions for its use and care. Since their performance is essentially identical, this should be taken as a mandate to use the smallest stylus only when absolutely necessary, such as when measuring the depth of a 0.4mm bore.

Tables 7-9 illustrate that the largest stylus has the smallest bias and decreasing size is seen to correspond with increasing bias. The *F* test for regression analysis of stylus size versus bias tested the null hypothesis that bias and stylus size were unrelated (rejected; $p < 0.001$). The regression analysis revealed an estimated slope of -0.0000769mm ($p < 0.001$) with a correlation of 0.4288, indicating a moderate inverse linear relationship between stylus size and bias. This means that for every millimeter smaller the stylus, approximately 0.0000769mm (between 0.000054mm and 0.0001mm) of bias is likely to be introduced into the measurement result. The estimated coefficient of determination indicated that 18.39% of the variability of the touch probe bias was explained by the size of the stylus.

While the results of the regression analysis may seem unimportant at first glance, it is important to remember that practitioners are often attempting to squeeze every last bit of performance out of their systems, and the knowledge that 18% of the overall variability can result from sensor selection is valuable.

Best Available Sensor

Determining the best sensor was approached from two perspectives: minimum absolute bias and minimum mean squared error. Formulating the sensor comparison as a one-way ANOVA specifically tested the hypothesis that all touch probes are equal in terms of

Table 5. One-way ANOVA Table for Touch Probe Styli and Laser

Source	*df*	*SS*	*MS*	*F*	*p*
Difference	4	0.0000012	0.000000297	27.662	< 0.001
Error	495	0.0000053	0.000000011		
Total	499	0.0000065			

Table 6. Tukey's Pairwise Comparisons of Touch Probe Styli and Laser Probe

Pairing	a - b	Lower Bound	Upper Bound	p^a
2mm-1mm	**-0.0000410**	**-0.00008894**	**0.00000694**	**0.04231**
2mm-0.5mm	-0.0001211	-0.00016900	-0.00007316	< 0.001
2mm-0.3mm	-0.0001240	-0.00017200	-0.00007606	< 0.001
2mm-Laser	**-0.0000438**	**-0.00009174**	**0.00000414**	**0.02436**
1mm-0.5mm	-0.0000801	-0.00012800	-0.00003216	< 0.001
1mm-0.3mm	-0.0000830	-0.00013100	-0.00003506	< 0.001
1mm-Laser	**-0.0000028**	**-0.00005074**	**0.00004514**	**0.99970**
0.5mm-0.3mm	**-0.0000029**	**-0.00005084**	**0.00004504**	**0.99966**
0.5mm-Laser	0.0000773	0.00002936	0.00012500	< 0.001
0.3mm-Laser	0.0000802	0.00003226	0.00012800	< 0.001

Table 7. Regression ANOVA Table for Touch Probe Styli

Source	*df*	*SS*	*MS*	*F*	*p*
Size	1	0.000001	0.00000102	89.663	< 0.001
Residuals	398	0.0000045	0.000000011		

Table 8. Regression Model Summary Table for Touch

Model	*R*	R^2	Adjusted R^2	*SE*
1	0.4288[a]	0.1839	0.1818	0.0001

[a]Predictors: (Intercept), Size

Table 9. Regression Coefficients Table for Touch Probe Styli

	Unstandardized Coefficients		Standardized Coefficient			99% CI for *B*	
Model	*B*	*SE*		*t*	*p*	Lower Bound	Upper Bound
(Intercept)	0.0001482	0.000009		15.791	< 0.001	0.000121	0.000175
Size	0.0000769	0.000008	0.4288	-9.469	< 0.001	0.000054	0.000100

measurement bias. As shown in Table 10 (constructed using Tukey's Pairwise Comparisons and SAS version 9.1 [2004]), the touch probe had the smallest bias and was the only device for which the null hypothesis of zero bias was not rejected ($p = 0.83$). Whereas Tukey's multiple comparisons was used to make pairwise comparisons among the obviously-different lighting combinations and touch probe styli, a more powerful test was required to determine the overall best sensor in terms of minimum absolute bias; Hochberg & Tamhane's (1987) tables for Hsu's Multiple Comparisons with the Best (MCB) were used. See Figure 2.

However, employing Hsu's MCB to identify the minimum bias device did not reveal a difference between the two thickest touch point probes and the laser at $\alpha = 0.01$. Therefore, although a significant difference almost certainly exists, additional data would be needed to determine that difference. The worst of the touch probe styli performed similarly to the best of the video sensors.

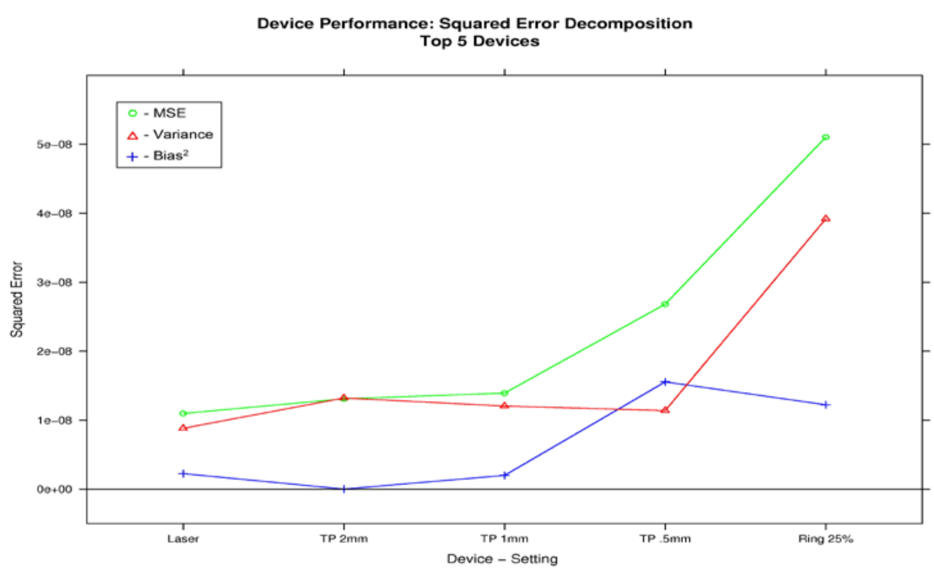
The alternative metric for measuring sensor performance was mean squared error (MSE). MSE is equal to the sum of the variance and the square of the bias, i.e. it is the expected squared distance from the true value of a new observation. When compared to a sensor that minimizes bias, the sensor minimizing MSE would produce measurements that have a smaller variance and tend to be closer to the true value. When viewed from the perspective of MSE, the laser was the best device, but this level of performance could not be distinguished from the three thickest touch probe styli or the ring light at 25% maximum reflectivity. All other devices had significantly greater mean squared error using MCB ($p < 0.05$). See Figure 2.

Table 10. Mean bias of all sensor combinations

Device	Mean Bias	Lower Bound	Upper Bound	*p*
Ring (25%)	0.000111	0.000067	0.000154	< 0.0001
Ring (50%)	-0.000343	-0.000387	-0.000300	< 0.0001
Ring (75%)	-0.000548	-0.000591	-0.000504	< 0.0001
Ring (100%)	-0.000426	-0.000470	-0.000383	< 0.0001
SRL (25%)	-0.000720	-0.000764	-0.000677	< 0.0001
SRL (50%)	-0.000924	-0.000968	-0.000881	< 0.0001
SRL (75%)	-0.000930	-0.000973	-0.000886	< 0.0001
SRL (100%)	-0.000280	-0.000323	-0.000236	< 0.0001
Coax (25%)	-0.001211	-0.001254	-0.001167	< 0.0001
Coax (50%)	-0.001216	-0.001260	-0.001173	< 0.0001
Coax (75%)	-0.001591	-0.001634	-0.001547	< 0.0001
Coax (100%)	-0.001290	-0.001334	-0.001247	< 0.0001
TP 2mm	**0.000004**	**-0.000040**	**0.000047**	**0.8301**
TP 1mm	0.000045	0.000001	0.000088	0.0085
TP 0.5mm	0.000125	0.000081	0.000168	< 0.0001
TP 0.3mm	0.000128	0.000084	0.000171	< 0.0001
Laser	0.000047	0.000004	0.000091	0.0051

[a]Tested at = 0.01; insignificant result highlighted.

Figure 2. ***Expected mean squared error (green) for the five best devices in terms of bias. Variance and bias contributions to total EMS are depicted by red and blue lines respectively.***



Implication

The implication of this research to practitioners and educators is clear: the statistically-based performance baseline for the vision, touch probe, and laser sensors of the OGP SmartScope has been established. This baseline, established by comparing the performance of these sensors on shiny steel in the Z-axis, indicates that critical dimensions should be measured, whenever possible, with the laser or touch probe. If some precision can be sacrificed for the sake of speed, the ring light with a maximum reflectivity setting of 25% is the best choice for use with the video sensor. On the other hand, the coaxial light should be avoided when possible.

Discussion and Recommendations

Many of the results in the study are confirmations of "common knowledge". For example, it is no surprise that the laser and touch probe outperform the video system. On the other hand, there are a few interesting results that contradict common perceptions. The most interesting of these are the discoveries that the video sensor performs best when set to 25% maximum reflectivity for the ring light and 100% for the SRL (within the study's delimitations). System documentation and experts alike recommend setting the maximum reflectivity to approximately 50% and state that 100% reflectivity should never be used. Similarly, it is a surprise to discover that the ring light set at 25% reflectivity actually outperforms the 0.5mm and 0.3mm touch probe styli in terms of mean bias, and performs admirably in terms of MSE when compared to the better sensors.

It should be pointed out that while these differences are statistically significant, they may not be practically so, depending on the application. For example, the difference between the ring light at 25% and the SRL at 25% is statistically significant ($p < 0.001$), but the actual difference in means is a mere 0.837 microns (0.0008369mm). A difference this small can likely be disregarded as unimportant for applications with engineering tolerances larger than nine microns.

In order to verify or refute these findings, this research should be repeated in other locations and with OGP measurement systems of differing sizes, configurations, and installed options. Future studies will be required in order to examine the sensors' performance on different materials (specifically, materials of different colors, translucence, and reflectivity) and in the XY plane.

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APPENDIX: PRACTITIONERS' "CHEAT SHEET"

This figure displays the best-to-worst range of sensors in terms of Mean Square Error (MSE; combined bias and variance). Light sources are included in the figure only at their optimal settings. These values reflect the performance of an OGP Smart-Scope Quest 450 measuring in the Z-axis with a shiny steel subject (gage block).

Tear this sheet out and place it in a convenient location for use as a quick reference.