ILLUSTRATING PRINCIPLES OF PRECISION ENGINEERING THROUGH DESIGN AND DEVELOPMENT OF A DISPLACEMENT GAUGE FOR MEASURING MACHINES

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ABSTRACT
The paper presents a project-based course on Precision Engineering. During the course, the students have lectures and five labs in the beginning five weeks of the course, during which time they also choose a project from a set of proposals to illustrate the principles of precision engineering they are learning. Teams of 3–4 students are formed and preliminary design is carried out during this first half of the course. During the second half, they carry out the design to provide a working prototype and finally they give a final presentation. The collection of the proposals is performed with the support of internal (i.e. researchers) and external customers. The supporters are asked to suggest a high-compliance, high-sensitivity displacement gauge for measuring for example the deviation from straightness of a straight edge or deviations from roundness of a sphere or cylinder. The probe must have low force, sensitivity much smaller than typical 5 μm of a Coordinate Measuring Machine, it must be compatible with commercial A/D converters and standard electronics, and it has to be realized by a combination of mechanical amplification and using technology that lends itself to trouble-shooting by technical assistants of a variety of backgrounds. The paper illustrates the design and the development of one of the proposed projects, by discussing the design issues, the prototype manufacturing, and the testing phase. The paper then discusses how the project-based approach can strengthen and make more effective the description of physical principles behind precision engineering (flexure design, tolerance design, thermal stability, accuracy of transducers and measurement devices, etc.) and their relationship with mechanical design, part manufacturing, and assembly. It is also a very effective way of illustrating how many engineering design problems are tightly related with mechanical stiffness, how stiffness is rooted in the design engineering specifications, and how design principles like kinematic constraint impact the product conformance with requirements and specifications.

NOMENCLATURE
CCD  Charge-Coupled Device
CMM  Coordinate Measuring Machine

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INTRODUCTION

Advances in engineering are often enabled by more accurate control of measurement and manufacturing tolerances. At the Stanford University, the course ME-324 – Precision Engineering covers concepts and technology that enable precision, such that the ratio of overall dimensions to uncertainty of measurement is large relative to normal engineering practice. Typical application areas include: scientific instrumentation for applied physics, diamond turning equipment, integrated circuit manufacturing equipment, and manufacturing metrology systems. Within the ME-324 course, application experience is provided through the team-based design and manufacture of precision engineering projects emphasizing principles of precision engineering.

The subject for the team-based design and manufacturing project usually changes every year, and each year more than one subject are usually developed by 3–4 teams. Inspirations for the projects arise from real-word applications: a “customer” suggest an application and sets the requirements, then he follows the prototype development meeting the students roughly once every two weeks. The customers are usually academic or industrial researchers, this ensuring a broad spectrum of different, and meaningful, applications.

The present paper describes the subject, the organization, the development, and the outcomes of the team-based project carried out during Spring 2011. In this case, the teachers decided to opt for a single project subject that was suggested by the teachers themselves—which had not happened during previous years, when customers were external persons—and which was actually a follow-up of one of the past year projects.

The first section will provide a more detailed description about the course organization, the time allocation, and the available resources. The second section will present the subject of team-based projects, which is a high-accuracy displacement gauge. Here will be listed the different initial solutions evaluated by the students, and the theory of operation of the selected cases will be described. The detailed design and manufacturing of the prototypes—including performance discussion—will be expressed in the third section, while the last two sections will respectively describe the project outcomes from a teaching point of view, and analyze the possibility of porting this course—and especially its experimental part—elsewhere.

COURSE ORGANIZATION

The course named Precision Engineering (code ME-324) is a 10 weeks, 40 hours course offered primarily to graduate students of Mechanical Engineering at the Stanford University. It is a course aimed at illustrating in a coherent and organic fashion the multidisciplinary knowledge base that enables the design and realization of precision devices. As such, the theoretical lessons cover metrology, kinematics, structural dynamics, optics, automatic controls, materials properties and selection, manufacturing processes, all exposed as enabling technologies for the precision engineer. Course literature (books and papers) is reported in the References section [1, 2, 3, 4, 5, 6, 7].

Beside the classroom lessons, students are presented with laboratory trainings and experiences (about 8 hours), and they also have to carry on the team-based project that is the matter of the present paper. Table 1 synthetically reports the course content organization.

At the end of the course, the teams are expected to present their work to a jury made of professors and researchers as well as of external experts and potential customers of the developed devices.

While designing and developing their projects, the students have access to the facilities available at the Stanford Product Re-

### Table 1: Course Syllabus

<table>
<thead>
<tr>
<th>Week</th>
<th>Labs</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Safety training</td>
<td>Principles of PE. Thermal effects on machines and meas.</td>
</tr>
<tr>
<td>2</td>
<td>Flexures lab</td>
<td>Trad/la gauging. Kinematic design and flexures.</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>Reversal. CMM operation.</td>
</tr>
<tr>
<td>4</td>
<td>CMM &amp; traditional gauging</td>
<td>Materials for PE. Bearings for PE.</td>
</tr>
<tr>
<td>5</td>
<td>Laser Interferometer</td>
<td>LI demonstration. CMM algorithms.</td>
</tr>
<tr>
<td>6</td>
<td>—</td>
<td>Vibration isolation. Automatic controls.</td>
</tr>
<tr>
<td>7</td>
<td>—</td>
<td>Optical alignments.</td>
</tr>
<tr>
<td>8</td>
<td>—</td>
<td>Grinding &amp; Lapping.</td>
</tr>
<tr>
<td>9</td>
<td>—</td>
<td>Diamond Turning Machines. Project development.</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
<td>Final presentation rehearsals. Project development.</td>
</tr>
</tbody>
</table>
alization Laboratory. In particular, they have access to machining tools (lathes and milling machines, both manual and CNC), measurement tools (standard gauges and calipers, manual CMM), electronic breadbording tools, and standard designing and prototyping softwares (CAD/solid modelers, Matlab, LabVIEW).

The literature reports scarce examples of this kind of highly interdisciplinary laboratory courses, and they are mainly found in the field of mechatronics courses [8, 9, 10], although usually more aimed at the illustration of design principles than at the development of real, state-of-the-art systems as in the case presented here.

CASE STUDY: HIGH-PRECISION DISPLACEMENT GAUGE

As mentioned above, the subject of the projects here presented is a high-precision displacement gauge, which is a follow-up of one of last year projects. Last year, in fact, one of the students team successfully developed a highly repeatable vertical spindle for roundness measurements, as shown in Fig. 1. The spindle itself was originally intended to be used together with an LVDT displacement gauge. The available Pretec LVDT, though, proved to be not suitable for the application in terms of ease of operation, robustness, contact force, and repeatability. In particular, the contact force was too high, actually exceeding the elastic limit of the aluminum alloy under measurement, and scratching its surface as a result. Needless to say, this invalidated the use of the LVDT and provided the idea of developing a new displacement gauge with the main requirements of high repeatability, low stiffness, and low contact force.

For this reason, the students have proposed displacement gauges to be used with the existing spindle, thus realizing a roundness measuring machine, or mounted on the x way of a lathe in order to measure the roundness of spindle rotation. The displacement gauges are aimed at having measurement accuracy laying somewhere in the range between that ensured by typical coordinate measurement machines, down to the ~5 nm accuracy provided by state-of-the-art roundness measurement systems.

The requirements for the new displacement gauge have been set as follows:
A) 5 nm << accuracy << 5 µm
B) contact force should be ~50 mN and low stiffness
C) thermal stability for the time needed to scan at least two rotations of the workpiece on the spindle, i.e. about 5 mins.
D) ease of operation
E) maintainability
F) robustness

In particular, it is worth noting that requirement B is set in conformity to international metrology good practice, after the observation that the repeatability of measurements taken with high-resolution displacement gauges is limited by the deformation associated with the Hertzian contact between displacement gauge and workpiece. This deformation mainly depends on nominal load and on local curvatures, so that a nominal load of about ~50 mN can ensure an associated displacement range in the order of 50 nm in most operating conditions, thus not affecting the overall repeatability. In fact, by recalling the sphere-on-sphere Hertzian contact solution [11]:

\[ d = \left( \frac{9F^2}{16RE^*} \right)^{1/3} \]

where
\[ \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \]
and
\[ E^* = \frac{1}{E_1} + \frac{1}{E_2} \]

one can see from the chart in Fig. 2 that the ~50 mN criterium actually satisfies the repeatability requirement, giving a contact displacement of about ~50 nm for a probe radius of 2 mm.

Requirements D to F relate to the fact that the displacement gauge will be a real laboratory device that will be used during the following years both for teaching and research. As such, it is important that the probe will be easy and flexible to use (in terms of mechanical and software/electronic interfaces), and that wear effect and misusage effects will be easily repaired (for example by using standard components for probe tip, or by making fragile components like flexure hinges easy to replace).
At the week 4, the students get a document stating the requisites outlined above and also reporting a selection of possible designs, with the recommendation that these designs are only meant as source of inspiration and that they would rather have to find their own solutions. These possible designs are in the form of rough sketches (see for example Fig. 3) and short descriptions, and suggest different ways to achieve displacement amplification (by optical or mechanical amplification) and to perform the displacement detection (by means of a PSD, a linear CCD, or an LVDT).

Finally, the budget allocated for each project is usually around $300. Devices or systems of general usage, like A/D converters, data-loggers, and such, can have a separate —and usually larger— budget.

**TABLE 2: DISPLACEMENT MEASUREMENTS: C = CONTACT, N = NON-CONTACT**

<table>
<thead>
<tr>
<th>Type</th>
<th>Repeatability</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>C: LVDT</td>
<td>0.5 µm</td>
<td>mid-high</td>
</tr>
<tr>
<td>C: Optical encoders</td>
<td>0.5 µm</td>
<td>low-mid</td>
</tr>
<tr>
<td>C: Fiber-optic strain gauge</td>
<td>0.1 µm</td>
<td>high</td>
</tr>
<tr>
<td>C: Resitive gauge</td>
<td>1 µm</td>
<td>low</td>
</tr>
<tr>
<td>C: Mech. resonators (AFM)</td>
<td>10 nm</td>
<td>mid-high</td>
</tr>
<tr>
<td>N: Laser Interferometers</td>
<td>50 nm</td>
<td>high</td>
</tr>
<tr>
<td>N: Laser-doppler vibrometers</td>
<td>5 nm</td>
<td>high</td>
</tr>
<tr>
<td>N: Laser triangulation gauge</td>
<td>0.5 µm</td>
<td>mid</td>
</tr>
<tr>
<td>N: Ultrasound sonar</td>
<td>1 mm</td>
<td>low</td>
</tr>
<tr>
<td>N: Capacitive sensor</td>
<td>0.1 µm</td>
<td>low-high</td>
</tr>
<tr>
<td>N: Eddy-current sensor</td>
<td>10 µm</td>
<td>low</td>
</tr>
</tbody>
</table>
used as precision instruments) as a factor in selecting this concept.

The general concept for this solution can be described as in Fig. 4, when a laser beam illuminates a linear CCD sensor, the position of the centroid $x_g$ of the laser image can be calculated with subpixel accuracy as by the formula [18]:

$$x_g = \frac{\sum_{i=0}^{N-1} i \bar{\delta} x I_i}{\sum_{i=0}^{N-1} I_i}$$

(2)

where $N$ is the number of pixels along the CCD, $\bar{\delta} x$ is the average pixel width, and $I_i$ is the light intensity as measured by the $i$-th pixel. The displacement gauge tip can thus cause translation or rotation of the laser beam (possibly exploiting optical lever-age) and the laser image centroid position can then be used as a detector for the probe tip motion. Note that from Eq. 2 it appears evident that the spatial resolution in the determination of $x_g$ depends in higher $i$ pixels, such that a pixel on the far right side of the sensor has a significant weight on $x_g$ even when not illuminated, but only giving a dark noise value. For this reason, a threshold filtering can be applied that brings to 0 intensity values smaller than the maximum dark noise level. In this case, assuming a beam width of 1.5 mm, the position resolution can be estimated as the effect of the variation of the rightmost pixel within the beam width $w$:

$$\delta x_g \approx \frac{w}{n}$$

(3)

where $n$ is the number of gray levels for each pixel after A/D conversion.

It should be also noted that, although better signal analysis algorithms could be adopted to improve repeatability of $x_g$ measurement (see for example those proposed by Liu et al. [19]), the Authors wanted to keep the system simple enough for the students to be able to successfully design, realize, and —more importantly— understand the precision system as a whole around this concept. In fact, particular care has been taken to guide the students in avoiding the application of signal processing and statistical techniques to the CCD-collected data, in order to have them deal with a deterministic system as much as possible: even if this choice could arguably limit the effectiveness of the data processing system (and of the measurement system as a whole), this actually can make it easier to relate design choices and their effects on precision.

Although the concept of linear CCD for laser laser triangulation is not new, it should be noted that the one presented here has some novelty to it. In fact, existing commercial gauges based on laser triangulation (e.g. Keyence products) usually are non-contact systems, and thus have to deal with general reflecting and non-reflecting surfaces. Consequently, they have a lens that focuses on the CCD the image of the laser beam diffracted by the surface under measure. This introduces uncertainties like surface and lens stability. Conversely, the concept adopted by the students uses a high quality mirror surface moved by a contact probe to steer the laser beam by reflection directly on the linear CCD, thus avoiding the need of lenses, simplifying the optical path, and making it more deterministic.

At this point it is clear that, since both groups have cho-

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**TABLE 3: CONCEPTS SELECTION, GROUP 1**

<table>
<thead>
<tr>
<th></th>
<th>CCD</th>
<th>LI</th>
<th>PSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resol. (m)</td>
<td>$10^{-8}$..$10^{-9}$</td>
<td>$10^{-9}$..$10^{-10}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Size (mm)</td>
<td>300</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Usability</td>
<td>easy</td>
<td>difficult</td>
<td>medium</td>
</tr>
<tr>
<td>Expanse of proj.</td>
<td>mechanical + algorithmic</td>
<td>mechanical only</td>
<td>mechanical + elect.+alg.</td>
</tr>
<tr>
<td>Range (mm)</td>
<td>1</td>
<td>$\gg 1$</td>
<td>1</td>
</tr>
<tr>
<td>Learning</td>
<td>large</td>
<td>med</td>
<td>med</td>
</tr>
<tr>
<td>Systems needed</td>
<td>1-CCD, laser, optics</td>
<td>optics</td>
<td>A/D conv. PSD</td>
</tr>
<tr>
<td>Confidence</td>
<td>med</td>
<td>high</td>
<td>med</td>
</tr>
<tr>
<td>Enthusiasm</td>
<td>high</td>
<td>low</td>
<td>med</td>
</tr>
</tbody>
</table>
As soon as the groups selected the concepts, they immediately started the design phase. Within each group, tasks of procurement, drawing/solid modeling, simulation, and manufacturing were spontaneously assigned to different members on the basis of their particular expertise.

The two prototypes have been developed as shown in Figs. 8 and 6. Both designs share the same detection principle based on a linear CCD illuminated by a laser beam, as discussed above. Apart from this common denominator, though, they are different both in the mechanical part (flexure) and in the optical path geometry. In the first case, in fact, the whole device occupies an elongated box with the laser source and the linear CCD on one side, and the probe/mobile mirror assembly and the secondary mirror assembly on the other side. In this case, the probe tip motion is transferred into a roto-translation of the laser mirror thanks to a rotational double hinge as for the solid model reported in Fig. 5 right.

During the design phase, both groups had to take care of the following issues:
- kinematic design
- stiffness
- measurement gain
- material selection
- subsystems selection and characterization

Regarding the kinematic design, both prototypes were designed by exploiting kinematic mounts on the base frame for all the subsystems (flexure, mirrors, laser source, and CCD). In some case the three-V mount was chosen, on some other the 3-2-1 DoF mount (Kelvin mount [2]) was implemented (this was the case of secondary adjustable mirror in group 1 prototype). Kinematic mounts work together with the high conductivity aluminum alloy to minimize thermal gradients and structural distortions.

The design of the flexure element proven a demanding study for the groups components. In particular, they had the opportunity to have an immediate feeling on the effects of design parameters and of manufacturing capabilities on the flexure stiffness, which—as above explained—is a key specification on the final product and which is consequently affected by trade offs on other factors (e.g. robustness, dynamic range, vibration isolation) that can be tricky to optimize. Nominal stiffness values for the two designs are reported in Tab. 5 which also reports the respective measurement gains. It is interesting to note that the two different design choices resulted in rather complementary...
performances in terms of stiffness and gain. It is also interesting to remark how the rotational flexure hinge shown in Fig. 5 has been implemented in a rather innovative way: while this design is usually realized by two separate plates with through holes screwed together, in this case it has been designed (and later on manufactured) from a single piece of aluminum with four tapped holes machined on the two opposite sides by means of a flat head drill. This design —although trickier to manufacture due to the counter-side operations— has the advantage of eliminating the joint between the two flexures, thus reducing potential hysteresis and nonlinear behaviors.

Selection, procurement, and characterization of the linear CCD has also been performed in this design phase. Both groups selected the same Mightex’s TCE-1304-U linear CCD camera. It is an enclosed camera, based on a single-line, CCD chip with USB2.0 (480 Mb/s) interface. It has 3648 pixels measuring 8 μm × 200 μm, with a 16-bit A/D converter, an electronic shutter allowing exposure times ranging from 0.1 ms to 6,500 ms, and a frame rate up to 138 scans/s. Mightex also provides LabVIEW drivers for the camera, thus allowing rapid development of measurement processing software. Note that, after Eq. 3, the nominal sensor resolution in terms of centroid position results to be:

$$\delta x_g \approx \frac{1500 \mu m}{65536} \approx 22 \text{nm} \quad (4)$$

Preliminary testing on the camera pointed out a dark noise level of about 1000/65536 (about 1.5%). This value resulted to be rather constant even on long time acquisitions (3000 s) as reported in Fig. 7: the chart shows the average intensity of all pixels when the CCD is kept carefully protected from any visible light source at a constant temperature of 20 ± 0.1 °C collecting one frame per second. The standard deviation of this average dark current noise resulted to be 50/65536.

Realization
The manufacturing and assembly of components took about two weeks and was directly performed by the students, thanks to their prior education in manufacturing and machine tool usage, and thanks to the availability of machine tools and manufacturing facilities and materials available at the Stanford’s Product Realization Lab.

In parallel to these shop activities, one or two students per group were carrying on the development of custom acquisition software, mainly written in LabVIEW. With some minor differences, in both cases the resulting software is able to capture camera frames (with user selectable exposure and frame rate), threshold the pixel intensities to reduce the effect of dark noise (threshold level is also user selectable), calculate the centroid position as for Eq. 2, and save the data on a plain text file for further analysis.

As soon as the prototypes have been assembled, a calibration procedure was performed. Each group detailed a calibration protocol defining both the calibration set-up and the cali-

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**TABLE 5: NOMINAL STIFFNESS AND GAIN**

<table>
<thead>
<tr>
<th>Group</th>
<th>Stiffness (mN/mm)</th>
<th>Gain (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Fig. 8)</td>
<td>300</td>
<td>26</td>
</tr>
<tr>
<td>2 (Fig. 6)</td>
<td>400</td>
<td>52</td>
</tr>
</tbody>
</table>

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http://www.mightexsystems.com

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FIGURE 6: CAD MODEL OF PROTOTYPE FROM GROUP 2

FIGURE 7: DARK CURRENT NOISE ESTIMATION (RELATIVE TO THE A/D CONVERSION LEVELS) FOR MIGHTEX LINEAR CCD CAMERA
bration methodology. The resulting protocols were quite similar, and generally consisting in the set-up of the displacement sensor against the surface of a target prismatic block that is mounted on a linear micrometric stage. The laser interferometer available at the PRL is then aimed at the cube corner reflector mounted on the same target block and aligned so that the laser line results as coincident as possible with the line of action of the displacement probe, thus minimizing Abbé’s offset. A calibration curve is then constructed by taking measurements on 50 points along the gauges ranges in random order, in a temperature controlled metrology room. An example calibration curve is reported in Fig. 10. The calibration factor is calculated from the least-squares linear fit of points in Fig. 10, and subsequently applied for the identification of device performances as reported in the following sections.

As defined by group 2, the calibration protocol can be outlined as follows.

**Setup (see Fig. 9)**

1. Set up the Linear Displacement Device to be calibrated on a reference structure.
2. Also mount a linear stage with resolution offering fine adjustment over the range the instrument operates. This linear stage must be positioned so that it actuates the measurement probe of the Linear Displacement Device in the correct orientation.
3. Set up a Laser Interferometer (LI) with the axis of the laser beam, through the interferometer, going to the cube corner all in line with the translational motion of the probe time of the Linear Displacement Device. This assures that there is no Abbe offset in the calibration. The cube corner should be mounted rigidly to the linear stage.

**Measurement**

1. Collect several data points of the form (Calculated Laser Source Interferometer Cube corner Linear stage Reference frame Displacement Gauge)

**Testing**

The calibration set-up allowed estimation of gain and stability of the two prototypes as reported in Tab. 6. The *measurement gain* was calculated as the slope of the best fit line in the calibration curve, and resulted close enough to the nominal values (see Tab. 5). The *static stability* was determined as a maximum measurement variation with the probe in contact with a stable, stiff surface (a gauge block) over a 120 s period, taking a sample point per second. This is of course the lower limit to the measurement repeatability, as the latter is affected by additional factors such as the linear stage repeatability.

The *repeatability* was calculated using a different setup: the
The stylus of the measurement system was set to slide along the surface of a Johansson block (by means of a linear stage) for a length of 1500 \( \mu \text{m} \), taking one measurement every 100 \( \mu \text{m} \) and repeating the same scan six times along the same surface patch. The least-square fits of the resulting data were used to compare the residuals for the six scans and calculating the repeatability as the average range of residuals at each stage position, as shown in Fig. 11. The repeatability of both prototypes was estimated — as reported in Tab. 6 — as generally better than 0.06 \( \mu \text{m} \), thus satisfying the requisite A.

### TABLE 6: PERFORMANCES OF PROTOTYPES

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement gain</td>
<td>20.1</td>
<td>57.1</td>
</tr>
<tr>
<td>Static stability</td>
<td>0.02 ( \mu \text{m} )</td>
<td>0.07 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Range</td>
<td>1200 ( \mu \text{m} )</td>
<td>500 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.06 ( \mu \text{m} )</td>
<td>0.02 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>

### TEACHING RESULTS

Developing a measurement system is often an highly interdisciplinary task. As such, students had the opportunity to experience how this reflects in design trade-offs. In particular, they encountered the hardest difficulties in the flexure design (where the trade-offs between stiffness, measurement range, linearity, and robustness have to be addressed), miniaturization (where the limit is set by the available manufacturing systems), and integration (where the software interfacing with hardware devices and performing the required data processing had to be quickly developed and verified). While miniaturization could not be addressed (and in fact the resulting prototypes are relatively bulky), the lack of experience in flexure design and in software development have been overcome by tutoring the students during the laboratory activity, which resulted in additional one hour per week for the course coach.

In general, the laboratory experience above described is the last example of a rather long tradition of project based learning, which the Design Group in Mechanical Engineering is heavily invested on. The Authors believe that their students benefit from the integration of design and hardware creation. They also believe that hands-on experience combined with engineering analysis, teamwork, and design thinking produces exceptionally effective engineering designers. This kind of laboratory based courses aims for our students to graduate confident and joyous in their ability to create physical devices. A further, higher level aim is to develop a sense of adventure and entrepreneurship in Stanford graduates. The Stanford Product Realization Lab—in which the presented activity has been conducted— currently supports 34 Mechanical Engineering project based courses. The PRL is a place that enables the implementation of student ideas rather than offering training in the use of machine tools. In this way the PRL has become an extension of our project based courses. Relative to the ME-324 - Precision Engineering course, project based learning is a very effective means to teach the principles of precision engineering. The validation for this education process comes from the comments we receive from alumni years after their graduation.

“The PRL develops a wonderful sense of adventure and entrepreneurship.” Peter Francis, President and CEO of J.M. Huber

“The lessons that really stuck were the ones about having an open mind, and not letting daunting tasks stop you from trying.” Adam Grosser, Partner, Foundation Capital

“That is what the PRL did for me. It gave me a chance to take the theories and concepts I learned in textbooks and internalize them by testing them myself.” Dana Ung, Partner, Zao Creative Technologies

“And perhaps the greatest gift of the PRL is still with me, the sense of wonder, magic, and beauty in creating things.” Kevin Fine, Tesla Motors

### CONCLUSION

The paper presents two designs and development of high-precision displacement gauges that have been carried out as a laboratory activity within a mechanical engineering course. The rather ambitious aim was to build a system having a repeatability
significantly better than that of common CMMs, and it has been addressed by the students by exploiting mechanical and optical leverages coupled with CCD-based laser triangulation system in an original way. Both the final prototypes developed by the two work groups proven a satisfactory performance, at such an extent to result appealing even for research activities.

From a teaching point of view, the laboratory activity was generally evaluated by the students as demanding —especially for the broad amount of different knowledge fields involved—but also stimulating, motivating and insightful, providing them with a better understanding about the relationships between the abstract, often unrelated, concepts learned during their previous career on a learning-by-doing basis.

Despite the satisfying technical and teaching outcomes, as for all such kind of laboratory-based experiences, the portability of the experience described is limited firstly by the available resources, and secondly by the students curricula. About the resources, replication of this experience—or of a similar one—in different universities requires the availability of a well equipped mechanical shop allowing the students to manufacture prototypes made of custom components (flexures, housings, shaped blocks, joints). This also requires a significative budget dedicated to the acquisition of raw materials, standard components, and devices. For the cases presented here, both the groups spent a little less than $1000. About the students curricula, the students groups must include members with expertise or formation in fields of mechanics, optics, mechanical design, kinematic/dynamic modeling, and to a lesser extent electronics, programming, and signal acquisition and processing.

REFERENCES