A Precision 2-D Laser Scanner for Measurement of Thermal Shift in Superconducting Devices

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Abstract

A novel method developed at Argonne National Laboratory for laser scanning two-dimensional (2D) profiles has been applied to a new instrument, the Cryoscanner, for measurement of cold mass thermal shift within the cryostat vessels of superconducting (SC) devices for particle accelerators. This paper presents the hardware, controls and data acquisition / processing methods utilized for the Cryoscanner, as well as the measurement results for the first deployment of the instrument to measure thermal shift within the APS Helical Superconducting Undulator (HSCU), commissioned in 2018. Recent progress toward improving the internal laser targets for the Cryoscanner will also be presented.

BACKGROUND

Basic 2D Scanning

The 2D laser scanning method described here was developed to address metrology issues encountered at the Advanced Photon Source (APS), an accelerator based x-ray source located at Argonne National Laboratory, and is utilized in several applications.[1, 2, 3]

The scanning devices are relatively low-cost and simple in design; they consist of a charge-coupled device (CCD) based laser displacement sensor (LDS) mounted to a linear translation stage. The system translates the LDS in a programmed move-stop-read routine, records the LDS displacement measurements (X), and the LDS positions along the translation (Y), and combines them to produce 2-D coordinates (X, Y). Resolution of <5 µm has been achieved using these systems. 3D coordinates are generated by entering a constant Z value, or by adding a second translation axis to enable 3D raster scanning capability.[3] Data acquisition is electronic; measurement information is processed using coordinate metrology software and spreadsheets.

CRYOSCANNER

As SC accelerator technology evolves, accurately characterizing and controlling thermal shifts in these devices is becoming more important. Techniques to minimize or cancel out this motion, to reduce uncertainty in corrections and to develop better methods of acquiring thermal shift measurements are key to keeping this technology moving forward.[4]

The Cryoscanner is a new compact, portable coordinate measurement instrument designed to ascertain thermal shift in SC devices for particle accelerators. The system externally measures relative change in the position of cold mass components inside a cryostat vacuum vessel through glass viewports. 2D coordinates are acquired from several instrument locations, providing enough information to quantify change in component position in up to six degrees of freedom (DOF). Note that the Cryoscanner is not an absolute measurement device. Rather, the instrument quantifies displacement of the internal cold mass of SC devices with respect to the cryostat vessel from a pre-aligned baseline position, under different thermal and vacuum conditions. Separate, external laser tracker measurements record the 3D coordinates of each instrument and target location with respect to the vessel. The laser tracker also records any changes in the cylindrical cryostat vessel shape, as well as any changes in the Cryoscanner positions, due to vacuum differential pressure forces. During data processing we reduce and transform the 2-D scans to fit the actual 3-D positions with respect to the cryostat vessel, referenced to the recorded baseline measurements of the scanner targets. An image of the Cryoscanner device is depicted in figure 1.

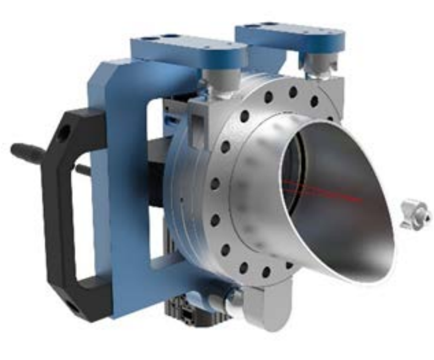

Figure 1: Photorealistic rendering of the Cryoscanner, a precision 2D laser scanner for measurement of thermal shift in superconducting devices.

Figure 2: CCD Laser Displacement Sensor

CCD Laser Displacement Sensor

The Cryoscanner employs a Keyence LK-G 152 LDS. LDS's project a laser on to any surface, and an integrated linear CCD detects change in the position of the projected laser spot to register displacement. Depicted in figure 2 is an image of a LDS. The LK-G series sensors measure one-dimensional displacement at various ranges and resolutions, from 10 mm; +/-1 mm at 0.01μm resolution, to 500 mm; +500 mm / – 250 mm at 2.0 μm resolution, and have a sampling rate of 50 kHz. The sensors measure either diffuse or specular surface reflectivity and are capable of measuring through transparent media such as glass, as well as surface measurement of transparent objects. LDS units provide displacement information, not absolute measurement. The diagram in Figure 3 illustrates the LDS basic measurement principle.

Orientation of the LDS with respect to the direction of translation is crucial to producing accurate scans. The LDS registers displacement as the image of the laser spot moves along its linear CCD axis. Translation parallel to the plane defined by the LDS projected laser and linear CCD axis produces errors, because the CCD is physically moving in the same direction as its pickup axis. Observations revealed considerable measurement noise in this orientation. Furthermore, the return signal was lost when the laser projection passed over steps in a profile. The direction of LDS translation must therefore be perpendicular to the plane defined by the LDS projected laser and linear CCD axis. The histograms in figure 4 show the distribution of point-to-point displacements across >35,000 samples, and compare measurement quality for parallel versus perpendicular orientations of the LDS with respect to the translation direction.[1]

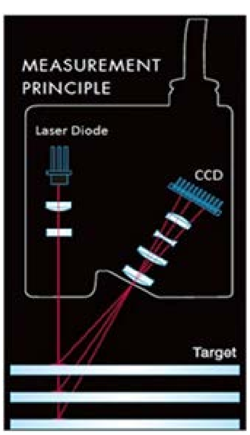

Figure 3: Diagram of the LDS basic measurement principle

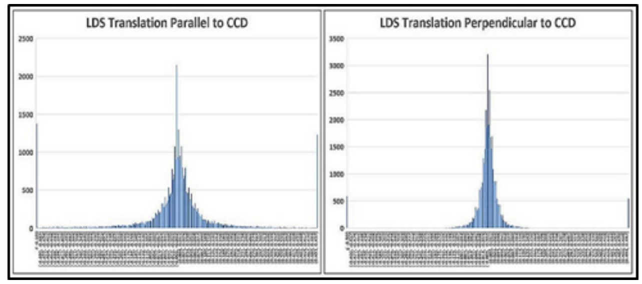

Figure 4: Comparison of the distribution of point-to-point displacement for parallel versus perpendicular LDS orientation to the translation direction across >35,000 samples.[1]

Translation Stage

The Cryoscanner utilizes a motorized Pi MICOS translation stage equipped with precision encoders to record the vertical position of the LDS. Straightness of the linear translation directly affects the transverse accuracy of the device, and is specified at <10 μm per meter over the length of travel. The unidirectional linear encoder repeatability specification is <1 μm. The LDS is translated in only one direction during measurement to avoid backlash error and ensure repeatability. The vertical coordinate component is recorded in even steps, determined by the translation step distance specified by the operator, typically every 100 μm.

Kinematic Couple

A kinematic couple is a deterministic, highly repeatable positioning system that exactly constrains six DOF without over-constraint. A Kelvin-type kinematic couple interfaces the Cryoscanner instrument and the cryostat vessel to provide repeatability for measurement at multiple locations. The kinematic couple design relies on a simple modification of a standard 6” diameter con-flat vacuum flange. Using a locating fixture, two small stainless steel “dog ears” and a flat rest are tack welded to each flange that will accept the instrument. Fastened to the “dog ears” are two truncated spherical elements. The Cryoscanner frame is equipped with a trihedral (cone), a vee-block and a sphere. The trihedral and vee-block constrain five DOF in a hinge arrangement across the two top spheres under a gravity preload. The sphere contacting the flat rest at the bottom constrains the sixth DOF, preloaded via the moment created by the hinge arrangement. Figure 5 shows an image of the con-flat flange modifications. Figure 6 shows a photograph of the Cryoscanner instrument coupled to a cryostat.

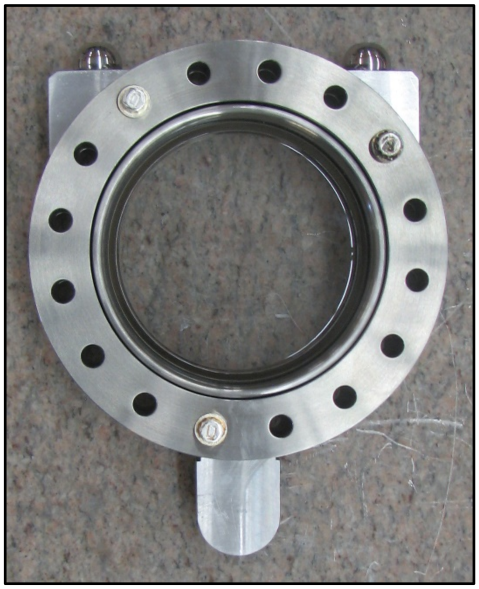

Figure 5: Vacuum flange with kinematic element modifications and viewport attached

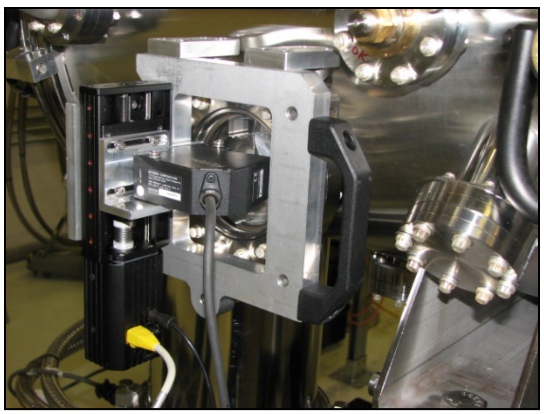

Figure 6: Photograph of the *Cryoscanner* instrument coupled to a cryostat vessel

Vacuum Viewports

The initial assumption when considering optical measurement through a transparent medium is that the surface quality and parallelism of the glass is of critical importance. While this is true for optical measurements in most cases, the Cryoscanner design takes a different approach to dealing with refraction effects. The kinematic couple precisely locates the instrument in the same position with respect to each viewport for every measurement set. Refraction effects are a constant for all measurement sets. A comparison between measurements taken through a precision, coplanar optical flat versus a low-cost borosilicate vacuum viewport showed virtually no difference in scan quality. The use of borosilicate windows resulted in a lower overall cost for the system, as expensive, optical grade windows are not necessary. Distortion of the viewports due to vacuum differential pressure forces was a concern; however, the effect is negligible, as shown below:

The following equation solves for Δx, deflection at the center of a circular window under a pressure differential (Roark, 1975).[6]

$$\Delta x = 0.0117(1-\upsilon^2)\ \Delta P\ D^4 / E_G\, t_w^3$$

The transmitted wave-front optical path difference (*OPD*) for a rim-mounted window when deflected by a pressure differential is given by this equation (Sparks and Cottis, 1973 according to Vukabratovich, 1992) [7]

$$OPD = 0.00889(n\text{-}1)\ \Delta P^2 D^6 / E_G^2\, t_w^5$$

Where υ is the Poisson ratio for the glass, D is the window diameter, ΔP is the pressure differential, E_G is the Young's modulus for the glass, t_w is the window thickness, and n is the refractive index. Calculations for the borosilicate glass viewport show that the Δx is 4.8 µm, and the *OPD* is 6Å, indicating that effects from vacuum pressure differential forces are indeed negligible.[8]

Targets

The choice of target material and surface finish makes a significant difference in the quality of data collected with the Cryoscanner. The first targets we tried were simple vee-grooves machined into aluminum plate. Although the surface appeared smooth to the eye, magnification revealed a very rough finish that produced noise in the measurements. To enhance scan quality, we tried a precision-ground stainless steel vee-block target, and observed improved results. We contacted the maker of the vee-blocks to find out if other finishes were available to optimize the scan quality. Two surface finishes were suggested; a satin titanium (Ti) surface and a lapped finish on a monolithic stainless steel (SS) vee-block. The satin Ti finish produced superior results; however, scan quality of the lapped SS vee-block proved to be adequate at a lower cost and shorter lead-time, and was specified for the APS Helical Superconducting Undulator (HSCU). Table 1 shows a comparison of the results obtained with different target finishes.

New custom targets with the satin Ti finish and a larger included angle are specified for the APS Upgrade SCU's, currently in the design phase. Increasing the vee-block angle from 90º to 120º reduces the angle of incidence between the LDS laser and the vee-block surface, improving the diffuse laser spot image at the LDS CCD. Results show <5 µm agreement with known displacements applied in a test platform, further described below in the recent progress segment. The new satin Ti target mounted to the test platform is shown in figure 7.

Target Finish	Line Fit Deviation (rms)	Maximum Deviation
Machined Aluminum	>25 µm	>50 µm
Lapped Stainless Steel	<10 µm	<20 µm
Satin Titanium	<5 µm	<10 µm

Table 1: Line fit results for various target surface finishes

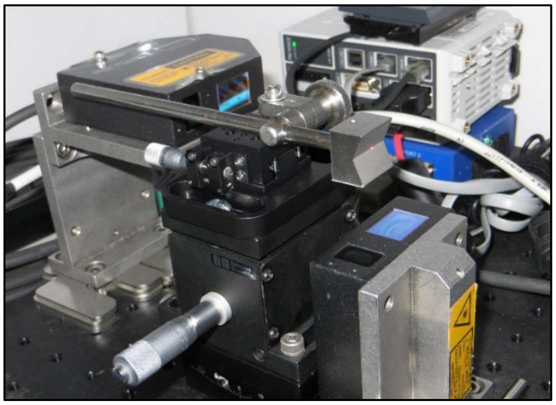

Figure 7: Image of the 120^{o} satin Titanium Cryoscanner target set up on the test platform. The LDS laser spot is visible at the target center.

Controls and Data Acquisition

Various software tools are available to create applications for scanner control and acquisition of coordinate measurement data, including open source tools such as Experimental Physics and Industrial Control System (EPICS), as well as commercially available systems engineering software such as Laboratory Virtual Instrument Engineering Workbench (LabVIEW).

Keyence LK-Navigator software provides control for the LDS's. Data acquisition is also possible using the software. The first 2-D scanner we built used LK Navigator to synchronously record measurement data from two LDS heads.[2] The program has a wide range of settings to apply to the system, including sampling rate, synchronization, tolerance, damping, and trigger settings, for a variety of different measurement applications.

The Cryoscanner utilizes EPICS, a freely available set of Open Source software tools, libraries and applications developed to create distributed soft real-time control systems for scientific instruments such as particle accelerators, telescopes and other large experiments. Original development of EPICS was a collaboration between Argonne and Los Alamos National Laboratories, and it is in use at many large scientific facilities throughout the world.[4] Capable of running large facilities, EPICS is also scalable and adaptable for creation of automated control and data acquisition programs for smaller systems.

A custom EPICS application provides control and data acquisition capabilities for the Cryoscanner. The application runs on a Windows laptop, using a single computer as both an I/O controller and graphical user interface. The software controls both the motorized translation stage and LDS through a single USB connection, and records measurement data into a binary file, later converted to an ASCII file containing the measured coordinates. The program allows various settings, including start and stop positions of the translation, measurement spacing and settlement time. It also features real-time plotting of the scan data. Figure 8 shows a screen capture of the EPICS control and data acquisition interface, including a 2-D real-time plot of a vee-block target profile.

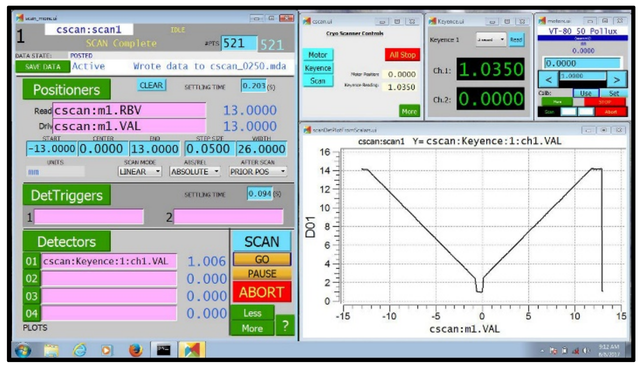

Figure 8: Screen capture of the EPICS control and data acquisition interface, including a 2-D real-time plot of a vee-block target profile

Measurement & Data Processing

Coordinate metrology software provides a detailed analysis tool for the Cryoscanner measurements. Measurement data is processed using Spatial Analyzer software to perform geometric fitting and statistical analysis. Further analysis is performed using spreadsheets.

The 2D scans measured by the Cryoscanner system are reduced to single, discreet coordinate points to determine displacement. Each scan collects about 200 coordinate points across the face of the vee-block target. In the raw coordinate data, the Y values are recorded based on the translation steps set by the operator (typically every 100 µm), and are the same for all sets. The X ordinate is a variable measured by the LDS. The Z coordinate is a constant, hand-entered by the operator based on the instrument location when coupled to the cryostat vessel. The 3D ASCII coordinate files generated by the Cryoscanner are imported directly into Spatial Analyzer for processing. A best-fit line is constructed through the coordinate points for each face. A single discreet point is then constructed at the intersection of the 2 lines. As Y is recorded as an even step for each vertical position in the raw coordinate data, the 2D position of the constructed point is a function of the X ordinate. An image of lines and points constructed from coordinates collected using the *Cryoscanner* is shown in figure 9.

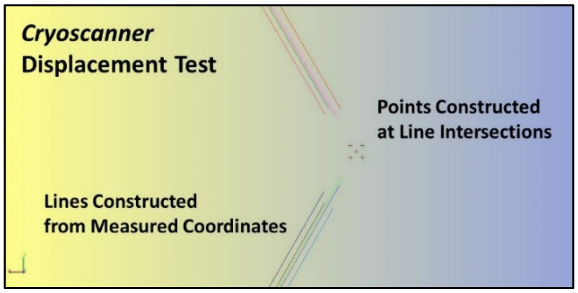

Figure 9: Graphic image of lines and points constructed from coordinates collected using the *Cryoscanner*

Helical Superconducting Undulator

The first SC device to be characterized using the new portable Cryoscanner was the Helical Superconducting Undulator (HSCU), a helically wound SC magnetic device that imparts circular polarization by oscillating an accelerated electron beam to produce intense X-ray energy. Pictured in figure 10 is a photo-realistic rendering of the HSCU cryostat vessel.

We adapted the HSCU cryostat vessel to accept the Cryoscanner instrument at four measurement positions, as described earlier in the kinematic couples section. Tests of the first Cryoscanner prototype, performed in spring 2017, indicated there were problems that needed to be resolved, including the target finish and LDS orientation issues described earlier, as well as LDS measurement range issues and unanticipated design interferences.

Figure 10: Photo-realistic rendering of the Helical Superconducting Undulator (HSCU) cryostat vessel

The initial scan data was very noisy, with random variations > 0.5 mm. The first solution attempted was to alter the target surface finish, and although we observed improvement, there was still substantial noise in the scans. We later realized that the LDS translation orientation was parallel to the plane defined by the LDS projected laser and linear CCD axis, resulting in the CCD physically moving in the same direction as its pickup axis. Changing the orientation of the LDS to set the translation perpendicular to the linear CCD axis solved the noise problem, and resulted in very clean scans. Analysis confirmed a statistically significant effect on measurement quality, as shown earlier in the figure 2 histograms.[1] In addition, the original range specified for the LDS, 500 mm; +500 mm / - 250 mm, was troublesome due to the target distance falling at the extreme end of the LDS measurement range. Narrow, slotted laser path apertures in the thermal shield produced interference in the long-range LDS laser signal.

We modified the system in June 2017, and observed improved results. The problems were solved by employing a shorter range LDS, 150 mm; +/- 40mm, and adding invar extensions to the targets, placing them just inside of the thermal shield aperture. The shorter range LDS also has a lower profile laser path, resulting in a better fit with the 89 mm (3.5”) diameter glass viewport.

The modified instrument was utilized for measurement of the cold mass within the HSCU cryostat during test cool-downs to ascertain the magnitude of displacement due to thermal shift. The scanner recorded 2-D profiles from four known positions to quantify thermal shift of the cold mass with respect to the cryostat vessel in five degrees of freedom: horizontal (X), vertical (Y), pitch, roll and yaw. Although it is possible to ascertain longitudinal (Z) shift with custom targeting, this spatial component is the least relevant to the performance of the HSCU, and is not considered. Warm alignment corrections were applied based on the Cryoscanner thermal shift measurements, and were verified in subsequent cool downs. The instrument was also employed to verify the HSCU cold mass position after transport and installation in the APS storage ring. The HSCU cold mass thermal shift results are presented in table 2, and a measurement quality analysis result is shown in table 3.

Ordinate	Initial W [mm]	W to C [mm]	C to W [mm]	W to C [mm]	C to W [mm]	W to C [mm]	Final C [mm]
	19-Oct	27-Oct	27-Nov	1-Dec	12-Dec	9-Jan	
X US	0	-0.059	0.059	-0.059	0.094	-0.082	**-0.047**
X DS	0	-0.065	0.065	-0.086	0.120	-0.109	**-0.075**
Y US	-0.075	0.100	-0.100	0.093	-0.097	0.150	**0.071**
Y DS	-0.075	0.164	-0.164	0.160	-0.183	0.174	**0.077**

Table 2: HSCU cold mass thermal shift results over three cool down cycles

	RMS Standard Deviation [mm]		Standard Uncertainty [mm]	
	X [mm]	Y [mm]	X [mm]	Y [mm]
Overall	0.005	0.006	0.0005	0.0006
A only	0.003	0.006	0.0007	0.0011
B only	0.005	0.007	0.0011	0.0015
C only	0.007	0.008	0.0015	0.0016
D only	0.004	0.004	0.0008	0.0008

Table 3: Cryoscanner measurement quality for HSCU measurements over 96 individual scans.

Recent Progress

Recently we performed tests to determine measurement quality for a modified satin Ti target design, described earlier. On a test platform, shown in figure 10, we apply several precise 2D displacements in X and Y to the target position within a 1 mm^2 area for comparison against values measured using the Cryoscanner. The maximum observed displacement from thermal shift in the HSCU device was <200 μm. Displacements are applied using two Keyence LK-G37 LDS's with 0.05 μm resolution as a reference. Metrics analysed include fit statistics for lines constructed through the measured coordinates, point to point distance comparisons and best-fit transformations for all points in a measurement set. Line fits through 70 to 80 points consistently have a maximum deviation of <10 μm, and an RMS standard deviation of <5 μm, and point to point distances are in agreement to <5 μm. A least squares best fit result comparing ten precisely applied 2D displacements in X and Y to coordinates measured by the Cryoscanner shown in table 4. Analysis of the measurement sets indicate the device is capable of repeatable, reproducible 2-D coordinate measurement at a resolution of <5 μm RMS.

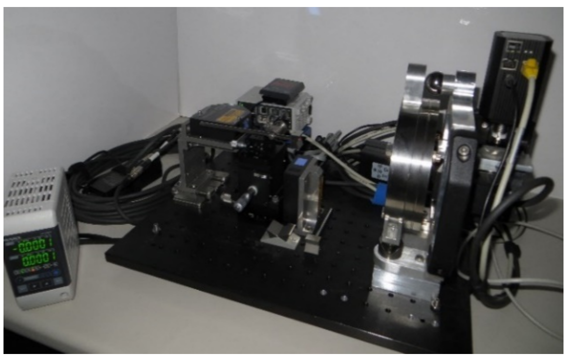

Figure 10: Cryoscanner test platform; instrument mounted in an inverted orientation

Least Squares Best Fit				
Results	**X [mm]**	**Y [mm]**	**Z [mm]**	**Mag.**
Count	10	10	10	10
Max Error	0.0038	0.0055	0	0.0067
RMS Error	0.0019	0.0028	0	0.0034
StdDev Error	0.0020	0.0030	0	0.0036
Unknowns	6			
Equations	30			
Point	**dX [mm]**	**dY [mm]**	**dZ [mm]**	**dMag**
1	0.0009	-0.0018	0	0.0020
2	-0.0038	-0.0055	0	0.0067
3	-0.0020	0.0007	0	0.0021
4	0.0002	0.0008	0	0.0008
5	0.0011	-0.0004	0	0.0012
6	0.0026	-0.0038	0	0.0046
7	0.0015	0.0044	0	0.0046
8	0.0013	0.0032	0	0.0035
9	-0.0020	0.0014	0	0.0024
10	0.0002	0.0010	0	0.0010

Table 4: Least squares best fit result comparing ten precisely applied 2D displacements in X and Y to coordinates measured by the Cryoscanner

Advances have also been made to streamline data collection and post-processing. These include the capability to enter a Z coordinate constant and to change the X direction sense (+ or -) of the LDS output within the EPICS interface. Also, a filter application was developed that re-orders the ASCII output to simplify formatting of the files for use in Spatial Analyzer. Significant time savings have been realized as a result of the improvements.

CONCLUSION

A new method for ascertaining displacements in SC devices due to thermal shift has been successfully implemented at Argonne National Laboratory. The HSCU is only the first SC device to employ this instrument. We plan to use the portable Cryoscanner to ascertain thermal shifts in future SC devices, refining and improving the technique as we gain experience.

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The diagram in figure 1 appears courtesy of the Keyence Corporation of America, Itasca, Illinois, 60143

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