OPTICAL INSPECTION OF SRF CAVITIES AT FERMILAB

E. Toropov*, D. A. Sergatskov#, FNAL, Batavia, IL 60510, U.S.A.

Abstract

The production of a SRF cavity includes a string of multiple treatments at different facilities before the cavity can be RF-tested in a cryogenic system. Many of the processing steps change the cavity surface and affect the RF performance of the cavity. Interjection of optical inspections between these steps provides us with an instant feedback on the processes involved as well as gives us new insight on the mechanisms responsible for forming surface abnormalities. The major drawback of inclusion of frequent optical inspections is the increased amount of time and labour in the cavity production cycle. An optical inspection of equatorial and iris welds of a 1.3GHz TESLA-shape cavity produces about two thousand pictures. We developed an automated procedure where a computer takes over the most of the routine operations including adjusting the camera focus. With that automation, the inspection currently takes about three hours and little operator time. We will describe the developed system including the focusing algorithm and discuss ways to further optimize the procedure.

INTRODUCTION

The technology of manufacturing SRF is steadily improving. However, cavities often do not achieve the performance goals due to the quality of the inner surface. An optical inspection system developed by Kyoto University collaboration allows us to obtain high-resolution images of inner surface of SRF cavities [1].

The system was originally designed to closely inspect a certain area of interest on the surface. In order to make a full inspection of a cavity, an operator must perform operations of switching between cells, changing rotation angle, and adjusting the focus. Special software was designed to take over these operations.

The main problem of developing an automated system is creating a mechanism that would keep the surface in focus. This includes three independent components: an algorithm for performing autofocusing, a method to apply it efficiently, and a way to check/correct mistakes of autofocus.

Optical inspection has to deal with problems such as long inspection time, low image quality, and necessity for calibrations. Inspection time depends on the mechanical design of the system, the camera speed, and the camera field of view. The indicator of image quality is image resolution. It is determined by two factors – the camera and the optics resolution. Finally, differences in outer diameters of equators and tuning of cavity length make it necessary to employ calibration prior to inspection.

*etoropov@fnal.gov
#das@fnal.gov

MECHANICAL SETUP

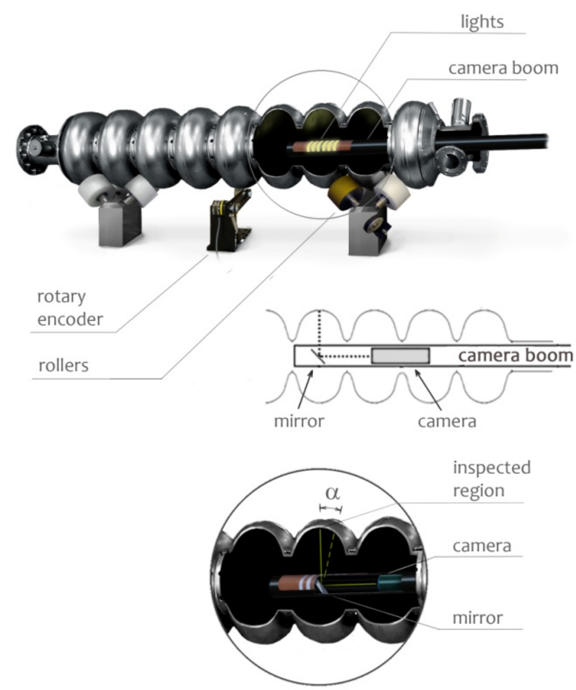

Figure 1: Optical inspection stand.

Fermilab has two optical inspection systems, which are referred to as the production and R&D systems. The production system is used to inspect bare 1.3 GHz cavities while R&D system was designed to inspect dressed and 650 MHz cavities.

The optical inspection system is used to study the inner surface of a SRF cavity with an optical camera. A system consists of a base, a camera boom – a plastic tube with a camera inside, four motors, a rotary encoder, and a computer. The boom can move along a cavity (see Fig.1.)

The first motor moves a cavity along the stand, thus changing the inspected cell. The second motor changes the angle of rotation – this is accomplished by either rotating a cavity (production system) or by rotating the camera boom (R&D system).

Fig.1 depicts the inner design of the boom. The camera has a constant focal length but it can focus on the surface by moving along the boom by the third motor. The mirror tilt is changed by the fourth motor. The lights installed on the boom are controlled by separate control electronics.

INSPECTION SEQUENCE

A typical optical inspection of a 9-cell cavity includes inspecting all the equators and irises welds and heat-affected zones. At first, equators are inspected, after that – irises.

The cavity position is first set at a certain cell and at the rotation angle equal zero (see Fig.2.) Depending on a system (production or R&D) a different number of pictures is taken at different mirror tilts to cover the whole heat-affected zone. After that the rotation angle is incremented. The procedure repeats until the whole circumference is covered. The next cell is then inspected.

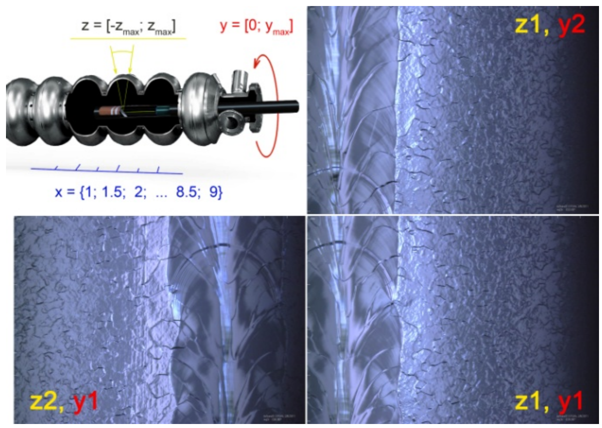

Figure 2: Inspection images samples.

The overlap between images is approximately 30%. Images from the production system have the resolution of 20 um and field of view of 13x9 mm. The depth of field (focal depth) is 0.2 mm.

AUTOFOCUS

The distance from the camera to the cavity surface changes during inspection. The most significant reasons are imprecise horizontal cavity positioning and the bent shape of cavities. That makes it necessary for the system to be able to perform automatic focusing, which will be referred to as autofocus.

Mechanism

For computer focusing is a process of maximizing some sharpness metrics. Sharpness metrics is the function of distance to the object, it reaches maximum at the camera focal length (see Fig.3.) There are several sharpness metrics, see [2] for examples. Different metrics perform best in different cases. Each of them has parameters to define.

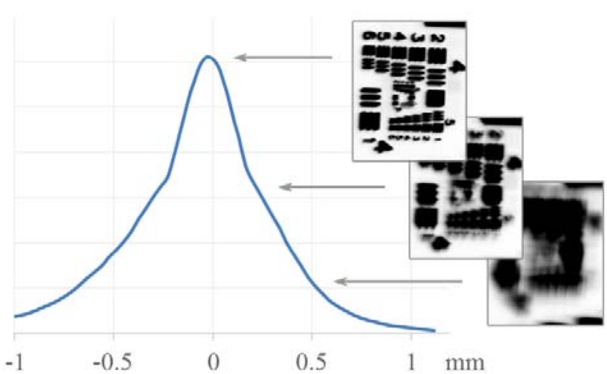

Figure 3: Sharpness metrics vs. camera-object distance.

After extensive research we found that the "local variance" metrics gives most satisfactory results on the maximum number of sample measurements [3]:

$$F_{Local\ variance} = \frac{1}{Height \cdot Width} \sum_x \sum_y \left| i(x,y) - \mu_r(x,y) \right|$$

$$\text{for } \left| i(x,y) - \mu_r(x,y) \right| > \theta$$

where $i(x,y)$ – intensity of pixel (x,y);

θ – threshold parameter;

$\mu_r(x,y)$ – mean intensity in the square region with the center in (x,y) and with the side $2r+1$.

A metrics needs not to be calculated for a whole image. In fact, it may be advantageous to apply the autofocus algorithm to a region of interest in the image – ROI. For a small depth of field different parts of the image are in focus at different camera-object distances. Hence, it is necessary to choose what image part to focus on. The method to choose it must fulfill two requirements – (1) the selected part should have the largest number of details and, at the same time, (2) brighter regions are preferable.

We chose ROI as a rectangle of a preset fraction of an entire image. Its position in the image is selected in such a way that the rectangle has the maximum value of $M/\sqrt{I}$, where M is the metrics calculated for the rectangle and I is the overall intensity of light collected from it.

The last component of autofocus is an algorithm of reaching the peak of the chosen metrics [4], [5]. Algorithms differ by quality, robustness, and time of execution. The most important requirement is robustness to noise, different lightning conditions, etc. Execution time is also important since autofocus has to be performed several hundred times during an inspection.

The algorithm that we use is based on the assumption that sharpness function can be fitted with Gaussian:

$$Gaussian(x) = y_0 \times \frac{1}{2\pi\,\sigma} \exp\left(-\frac{(x - x_0)}{2\sigma^2} \right)$$

The algorithm takes several metrics samples from both sides of the peak and then fits those values with Gaussian. The maximum of the gauss function is regarded as the focal distance (see Fig.4.)

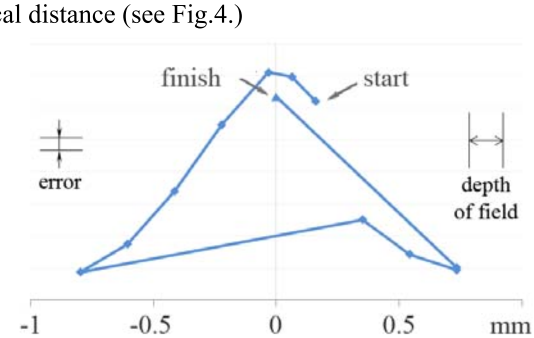

Figure 4: Algorithm to find metrics peak.

The algorithm also includes optimization for different initial conditions. For example, if three first taken values suggest that the image was initially in focus then the autofocus algorithm stops.

To summarize, when autofocus is performed, first, ROI is chosen, then the camera-object distance changes according to the algorithm described above. On every step the sharpness metrics is applied to the ROI of the image. Finally the decision is made on what distance is most close to the focal distance.

Applying Autofocus

The task of autofocus is to keep the camera-object distance within the camera depth of field from the focal distance. Fig.5 depicts the focal distances for the bottom and top sides of one of the equators. The difference in plot shapes is due to variations of surface shape.

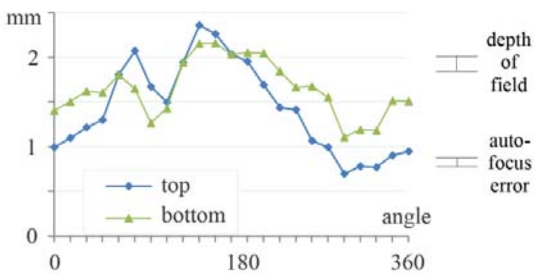

Figure 5: Focal distances of two sides of equator for 360°.

As one can see from the figure, autofocus procedure has to be performed a number of times. However, it is possible to reduce this number if we assume that the focal distance changes gradually. In this case it is possible to interpolate values between autofocus-measured focal distances. We make the linear interpolation using two points for a series of points between them (see Fig.6.)

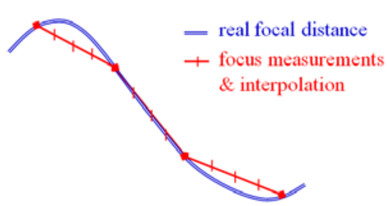

Figure 6: Interpolating focal distances.

In the production system we make 14 autofocus runs and interpolate 9 values between each pair of them – one for an image. Thus there are 130 images per equator.

Managing Outliers

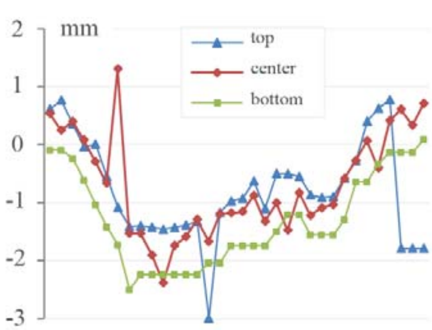

Figure 7: Outliers example for R&D system.
R&D system takes three images per angle (top/center/bottom).

The autofocus may give a wrong result or fail to converge, especially when a surface image lacks details. Fig.7 shows a real example of several autofocus mistakes. In this case all the interpolated values before and after the outlier are incorrect. Hence, the algorithm must include a check for outliers. If an outlier is found, the program substitutes it with a previously acquired focus value.

There can be different approaches to track down outliers. One approach is based on the fact that focal distance changes gradually and uses historical information to check if there is a sudden leap on the last autofocus run. A Kalman filter is ideal for this purpose. It uses all the previously collected values from the same equator side to predict a new value (points on a same curve on Fig.5). If this predicted value is too far from the autofocus-measured value an outlier is detected.

Another approach is to compare acquired values from different equator sides. Autofocus is performed for equator top and bottom sides. These values are then compared (in Fig.5 points on two curves at a same angle). If the difference is greater than a certain value, then there is an outlier.

In our design a value is regarded as an outlier if it is considered to be an outlier by any of these criteria.

RESULTS

The full inspection of the equators and irises on the production system currently takes 3 hours. ~2500 images are taken, autofocus runs ~250 times. For every rotation angle two images of equator are taken – 'top' and 'bottom'. The switch between two is performed via tilting mirror, not sliding a cavity. In this case, there are smaller mechanical vibrations and the surface plane is close to normal to the camera.

Time Consumption

Table 1: Two Fermilab systems with 1.3 GHz cavities.

Optical inspection system	Production	R&D
Rotating element	cavity	camera boom
Image resolution, µm* (naked eye – 100 typically)	20	10
Field of view, mm	12.8 x 9.1	7.5 x 5.7
Camera sensor pixels	1400 x 1000	3488 x 2616
# of images for 9-cell cavity	2460	5560
Time consumption, hrs	3	9
Motors	1	1.5
Focusing	1.5	2.5
Camera buffer reading	~0	3
Mechanical relaxation	0.5	2

* measured with 1951 USAF chart.

In the table above you can see the inspection time for 1.3 GHz 9-cell cavities for the production and R&D systems in Fermilab. The following are the reasons of longer inspection time of the R&D system:

1. The camera used in the R&D system is slow ArtCam 900MI. It is a high resolution USB camera that requires 0.9 sec. to transfer its buffer.
2. The narrower camera field of view enhances the image resolution but also greatly increases the inspection time due to a greater number of collected images.
3. The inspection at the R&D system is performed via rotating the boom, not a cavity. The boom has a longer mechanical relaxation time after every turn (1.5 sec.) than a cavity on the rollers (0.8 sec.) Another implication of rotating the boom is the necessity to focus more often if the boom is not centered with good precision. For example, the boom positioned close to the surface would cause focal distance to vary from zero to the diameter length during full turn.

Image Resolution

Image resolution is the only characteristic that describes the "power" of an optical system. The lower the resolution – the smaller the details a camera is able to detect. Resolution can be limited by two factors – pixel size in the camera sensor and optical components. If the pixel size is the limiting factor then two dots just several pixels away may be resolved. This is the case for the Fermilab production system.

If the issue is the optics, then pixel-size dots become blurred and resolution drops. We experience this on the Fermilab R&D system. The aperture in the boom (see Fig.1) is only 6 mm wide and diffraction effect becomes significant. Consequently resolution drops from 10 um to 35 um. To eliminate the effect, the aperture has to be widened comparative to the original design. The resolution data for R&D system in Table 1 is given for a wide aperture.

Calibrations

Differences between cavities require length and rotation angle calibrations, which complicate inspection. During cavity retuning, after removal niobium material with polishing, the cavity length may change by several mm. It makes it necessary to adjust the corresponding parameter accordingly. Outer diameters of equators also differ from cavity to cavity and rotary encoder needs to be calibrated.

REFERENCES

[1] Y. Iwashita and Y. Tajima, "Development of high resolution camera for observations of superconducting cavities," Physical Review Special Topics – Accelerators and Beams, 11, 093501 (2008).

[2] Y. Sun, S. Duthaler, B.J. Nelson, "Autofocusing Algorithm Selection in Computer Microscopy," IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005.

[3] E. Toropov, D. A. Sergatskov "Automation of optical inspection in Fermilab," Fermi National Accelerator Laboratory report TD-11-004, 2011.

[4] K. Ooi, K. Izumi, M. Nozaki, I. Takeda, "An Advanced Auto-Focus System for Video Camera Using Quasi Condition Reasoning," Consumer Electronics, 1990, ICCE 90. IEEE, 1990.

[5] J. He, R. Zhou, Z. Hong, "Modified fast climbing search auto-focus algorithm with adaptive step size searching technique for digital camera," Consumer Electronics, IEEE Transactions on, 2003.