Project Abstract and Summary

The next generation of particle accelerators, and the first generation of productive fusion reactors, will use highly-reflective metallic components with superconducting interior surfaces. These components must be arranged precisely along a line and fastened together in a procedure we call "string assembly". The slightest amount of dirt or residue upon their polished interior surfaces will compromise their efficiency. To avoid such contamination, we would like to avoid touching the parts by hand while their interior surfaces are exposed. If we place the components on motorized stages, we can, in theory, move them into position for assembly. But we will not know how far to move the components unless we know their initial positions precisely, and the problem is: **no existing computer vision system is capable of measuring the position of these highly-reflecting components with sufficient accuracy**.

We propose a computer vision system that will permit us to measure the location of such components to within a fraction of a millimeter by finding the edges of silhouette images. We will place a uniform, infrared backlight behind each component. We will view each component with two low-aberration, infrared cameras. Each of these stereoscopic cameras will be located within a string assembly coordinate system we set up with reference platforms, light sources, and survey cameras distributed around the perimeter of the string assembly room. We will obtain stereoscopic silhouette images of each component, and we will use these to determine the position of the component within our string assembly coordinate system. Once we know where they are, we can move the components to where they are supposed to be, check they are in the right place, and bolt them together.

In Phase I, we will determine the feasibility of a silhouette-based computer vision system for string assembly. We will build prototype infrared backlights and cameras. We will produce an image analysis program that traces the outline of silhouette images and uses them to measure component position. We will set up typical string assembly components on motorized stages to test. **By taking silhouette images of components, and applying our outline-tracing image analysis, we will determine whether or not such silhouette images will permit us to measure component position with an accuracy of a fraction of a millimeter.**

In Phase II, we will construct a full test stand in which half a dozen highly reflecting components must be brought into contact for assembly. We will set up a coordinate system, stereoscopic cameras, infrared backlights, and mount all components on stages that provide precise indication of position and rotation. Through repeated placement and measurement we will test our analysis of silhouette outline location. We will perfect this system until it is ready for application in a real-world string assembly clean room. If we are successful in Phase II, we will have a contactless position measurement system for highly reflective components that may be applied to superconducting string assembly.

Keywords: computer-vision, highly-reflecting components, string assembly, contactless.

Summary for Members of Congress: Particle accelerators and fusion reactors will require automated assembly with little or no human handling of components. This proposal will determine the feasibility of a novel computer-vision system that measures the locations of highly reflective components so that they may be moved into position without contact.

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Topic no.:	30. Radio Frequency Accelerator Technology b. Automation of SRF Cavity String Assembly
Project Title:	Contactless Position Measurement for Highly Reflective Components

Proprietary Data Statement

The enclosed narrative and application does not contain any information which is secret. All information in the entire application may be shared both within the Department of Energy and also with the public.

Contactless Position Measurement for Highly Reflective Components

Identification and Significance of the Problem

Superconducting Radio-Frequency (SRF) resonators offer significant advantages over traditional particle accelerators. Room-temperature klystrons, for example, over-heat if operated continuously, and require the beam cross-section to be narrow. We expect future large-scale, particle accelerators to be constructed out of SRF cavities. One initial design for the proposed International Linear Collider, for example, uses nine-cell SRF cavities. The construction of SRF cavities is demanding and complex. They must be assembled into strings without interior surface contamination of any sort, and they must be aligned precisely to permit a high-energy beam to move in a straight line without perturbation through the string. According to our collaborators at the Fermilab, one of their greatest difficulties in assembling SRF strings is the contamination of component surfaces as they are put into position by hand [11].

The greatest risk of contamination occurs in the final stages of component alignment. The interior surfaces are exposed at either end of each component as we prepare to fasten it to the next component in the string. The Fermilab SRF assembly group are in active pursuit of a means to automate these final stages of alignment, but find that the highly-reflective external surfaces of their components make it impossible for traditional computer vision systems to measure their location and orientation with sufficient precision. **The contactless measurement strategy we propose in this application is a general-purpose, optical system for measuring the position and orientation of multiple, highly-reflective components in a single, global coordinate system without human contact.** These measurements will make it possible to move the components to their correct locations for assembly using motorized stages, thus avoiding human contact or proximity. The SRF components at Fermilab must be aligned with accuracy ±300 μm, this being the accuracy required for a bolt to pass through a clearance hole in one component to mate with a threaded hole in the next.

Our contactless computer vision system will provide absolute position measurements which can be used to move components into place. **The most significant technical problem will be to image highly reflective components, which we will surmount by illuminating them from behind with a flat panel of diffuse infrared light.** Our proposed system of measurement obtains stereoscopic, silhouette images of each component with a pair of low-aberration, calibrated cameras. We define a global coordinate system with a network of calibrated platforms around the perimeter of a string assembly room. These platforms are equipped with calibrated cameras and light sources. The cameras on one platform view the light sources on neighboring platforms. Some platforms hold silhouette cameras. The cameras and light sources allow us to determine the location of all platforms within a single global coordinate system. The stereoscopic cameras allow us to measure the position and orientation of each component within this coordinate system. These measurements will be passed to the computer system that controls the motorized stages upon which the components are mounted, thus allowing for alignment for assembly without human contact.

We will use the existing SRF assembly activity at Fermilab as an example application of the system, and we consult with Fermilab in the development and demonstration of the measurement system. Our ultimate objective is to develop a system that measures the position of all component with accuracy ±300 μm along and entire string assembly line.

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Anticipated Public Benefits

The position measurement system we propose is a general-purpose survey system for use with highly-reflecting components in a clean-room assembly procedure. Future large-scale particle accelerators, supporting HEP research, which is generally publicly funded, present the most compelling demand for this system. These projects involve thousands of cavities and require a major and sustained assembly effort at multiple sites. In the near-term, upgrades to smaller accelerators at SLAC, CERN, and other existing sites would benefit from a reduction in contamination during string assembly. In the longer term, the assembly of fusion reactors will benefit from automatic alignment of superconducting components around a toroidal string.

One of the great advantages of the system we propose is its speed, its low cost, and the ease with which it can be expanded to larger strings. For ~$100k, we can survey five components in a ten-meter assembly room. For ~$400k, we can survey twenty components in forty-meter room. Preparing for survey takes ten minutes as we move backlights into position. Subsequent alignment may take ten minutes as we make several complete surveys as the motorized stages are moved. Compare this to photogrammetry, in which a team of surveyors with $200k worth of equipment spends an hour surveying each 10-m section of the string to obtain a single survey of its components, or to monitoring the orientation and position of each component with three laser trackers costing $30k each.

Technical Objectives

1. Demonstrate that we can obtain clearly-defined silhouette images of highly-reflecting metallic components in the presence of overhead lighting.

2. Demonstrate that our silhouette images will permit us to track the movements of these components at a range of two meters with accuracy ±300 μm in all directions.

Work Plan

Our objective is to develop a system of cameras, illuminators, and support platforms that measures the position and orientation of highly-reflective components with an absolute accuracy of ±300 μm. The system will compare the desired and measured positions of the components and calculate the translations and rotations required to bring them to the desired position. In the following paragraphs, we divide the measurement process into a series of steps.

Figure 1: Example Clean-Room Environment, Superconducting Radio-Frequency (SRF) Assembly Room at Fermi National Laboratory (FNL). Courtesy of Mattia Parise, FNL.

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Obtain Useful Images: Our first step is to obtain useful images of the components that are to be aligned. By *useful* we mean images that contain sufficient information to constrain the location of the component, while at the same time being sufficiently free of undesirable optical artifacts. When taking pictures of metallic objects, ambient light reflections create lines and edges that remain stationary in the view of the camera as the metallic object moves. Suppose we see a reflection of an overhead light in a reflecting square of metal. We move the square sideways parallel to its surface and the reflection remains stationary while the square is moving. These reflections tell us nothing about the translation of the square, but they make it difficult for us to find the edges of the square. We propose to illuminate highly-reflecting objects from behind with a flat panel of diffuse, infrared light. The camera will be equipped with an infrared-only filter. The clean room in which we obtain our images will be lit by fluorescent or solid-state lighting, neither of which emit infrared light, and the blinds of nearby windows will be shut so as to keep out sunlight, because sunlight is bright with infrared.

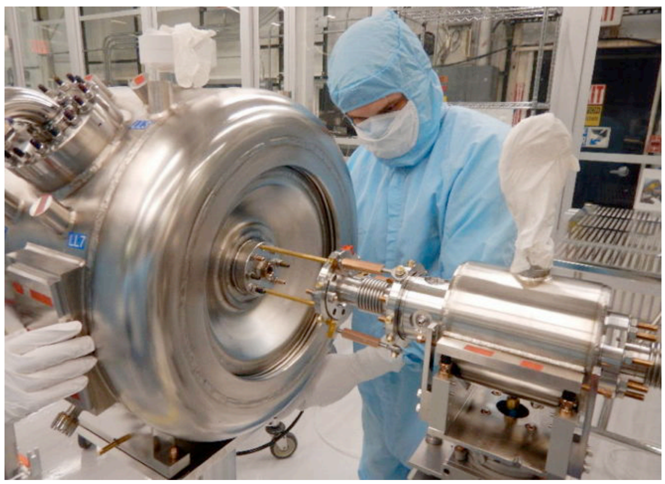

Figure 2: Highly-Reflecting Metallic Components. Some are easy to illuminate from behind, other are harder to illuminate from behind. Courtesy of Mattia Parise, FNL.

We place a diffuse panel behind each component, so that the panel forms the background of our image, and the component is the foreground. The camera sees only infrared, and the diffuse panel is the only source of infrared light, so the camera obtains a silhouette image of the component. Some components are easier than others to illuminate from behind. In Figure 2, the component on the right, with the bellows, is easy to illuminate: we can place the diffuse panel behind the object. But the flange of the cavity on the left in Figure 2, to which the bellows must mate, is harder to illuminate from behind, because it is recessed into its cavity. If we know the location of the recessed flange with respect to the outer diameter of the cavity, we could, in principle, illuminate the entire cavity, measure its position, and so deduce the position of the flange. But we would rather measure the flange directly by inserting dowel pins into precise sockets in the flange. We set the pins in their sockets before we remove the flange cover, so the interior surfaces are not exposed while we place the pins. After we remove the cover, we illuminate the pins from behind so as to obtain a direct and robust measurement of the flange position. After assembly, the interior surface is no longer exposed, and we remove the pins. We note that placing the pins in their sockets by hand does not require that we touch the component, only the pin itself.

In Phase I, we will focus on obtaining useful images of components that are easy to illuminate from behind. In Phase II, we will develop a set of diffuse panels of varying shapes and sizes, and a set of procedures for

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inserting pins or other fudicial markers onto components so as to provide useful images. Our objective is to develop enhancements that can be incorporated into the design of highly-reflective components at little or no cost, but which allow the components to be illuminated effectively for position measurement.

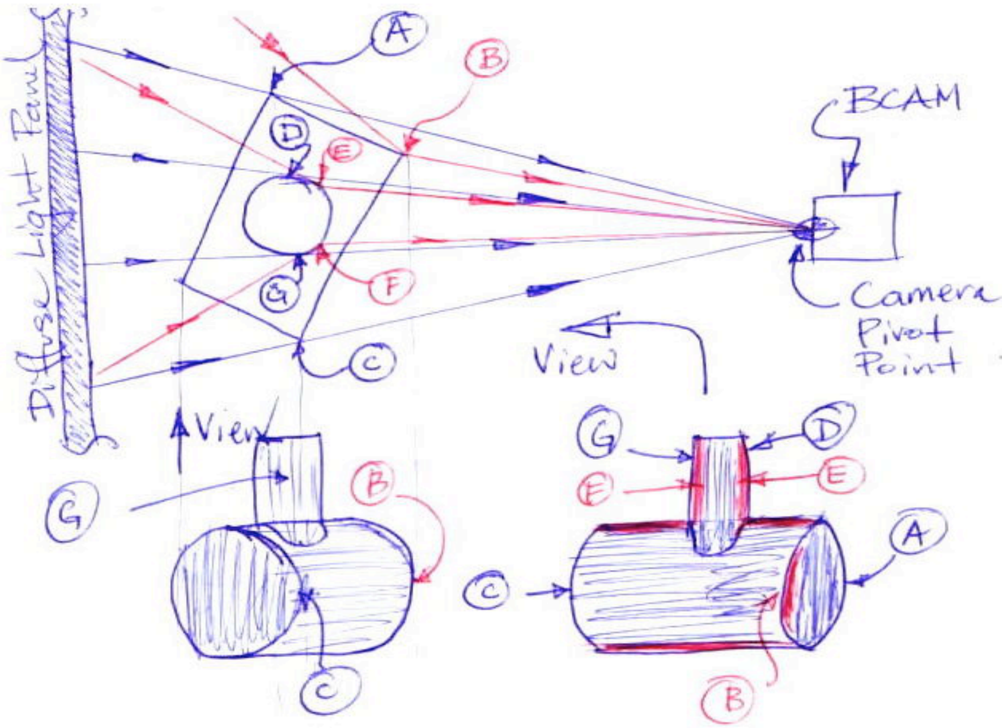

Figure 3: Reflections of Diffuse Panel Light in a Silhouette Image.

The silhouette will not be entirely free of reflections, even when our only source of light is a diffuse panel. Figure 3 shows how these reflections arise. Point D marks the edge of the upright cylinder, and Point E is the source of a reflection from the diffuse panel. The curved surface at Point E acts as a convex mirror, spreading reflected light over a wide angular range, and decreasing its intensity so greatly that the brightness of the reflection seen by the camera will be significantly less than the brightness of the panel directly in the background of Point D. Thus the reflections are always less bright than the background, and the silhouette outline will always be distinct.

We have ample experience working with silhouette images of highly-reflecting cylindrical objects. Our Wire Position Sensor (WPS) [1] uses stereoscopic silhouette images of a stretched wire to measure the wire's position. Figure 4 shows a highly-reflecting, stainless steel pin viewed by a WPS camera with a white paper background. The reflections within the silhouette are visible, but the edges of the silhouette are obvious.

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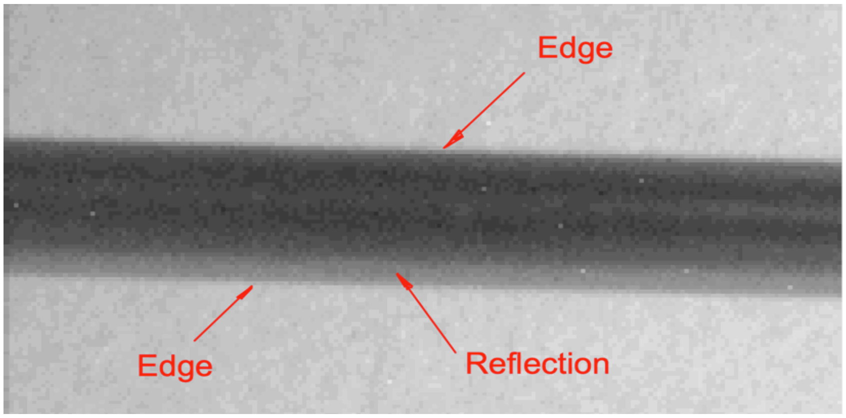

Figure 4: Image of Stainless Steel Pin in front of Diffuse Panel Illumination. Showing edges and reflections. Our existing image analysis routines find the silhouette edges with accuracy 1% of a pixel width.

We will equip several BCAM (Brandeis CCD Angle Monitor) [2] cameras with infrared-only filters. As we describe in more detail below, these cameras provide geometrically precise images. Their focus is not sharp, but slightly blurred, so as to spread sharp edges over several pixels, which improves the accuracy with which we can locate the edges.

Figure 5: Blue H-BCAM Manufactured by OSI.

We will design and build several diffuse, infrared, illuminator-panels. Each panel will consist of an array of infrared light-emitting diodes (LEDs) mounted on a printed circuit board along with an opal glass diffuser supported a short distance in front of the LEDs. Each panel will be controlled by our existing data acquisition system [12], the same data acquisition system we use to control and read out WPS and BCAM instruments. The infrared panel will be bright and powerful, but it will not be illuminated continuously. Our existing data acquisition software [13] will clear the silhouette camera's image sensor, flash the infrared panel, and read out the silhouette image.

We will collect an assortment of representative, highly-reflecting metallic components. We will learn how to obtain useful silhouette images of these components, and so generate a library of such images to support our image analysis efforts, including sequences of images in which the camera has remained stationary and the component has been moved in known steps with a translation stage.

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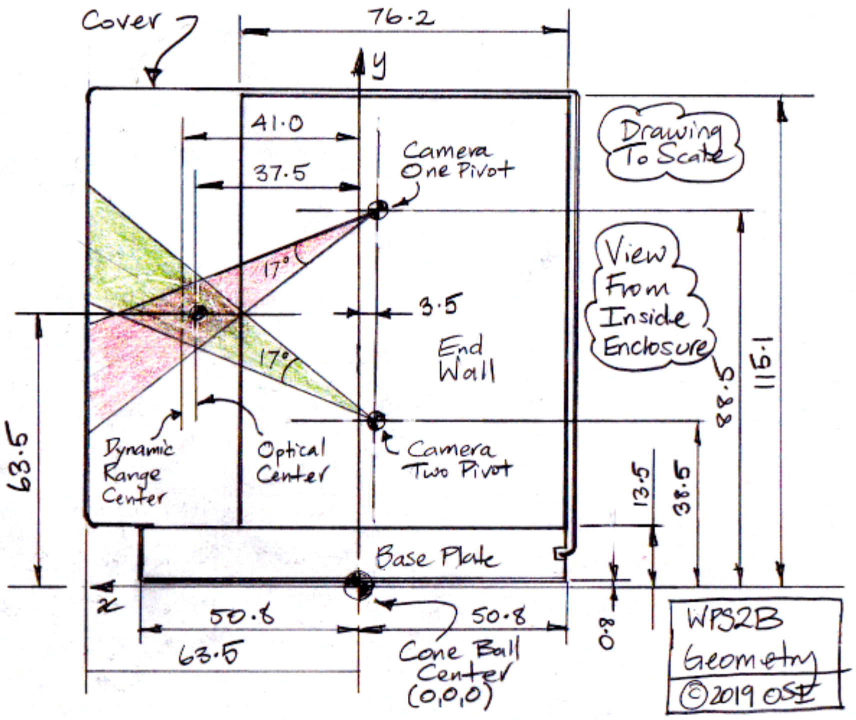

Figure 6: Stereoscopic Position Measurement by the Wire Position Sensor (WPS). Shaded in green and red are the intersecting fields of view of the two cameras.

Trace Component Outline: Having obtained useful silhouette images, our next step is to find the outline of the component silhouette in each image, overlay the calculated outline on the image so that we can see for ourselves if it is approximately correct, and store the outline in a compact form. For the sake of simplicity in this proposal, let us assume we store the outline as a list of points that, when joined by lines, provide us with a sufficient representation of the outline. The edge-finding analysis we use in our existing WPS instrument is able to find the edges of wire silhouettes with a precision of 0.1 μm on an image sensor with 10-μm square pixels. The WPS wire silhouette consists only of two parallel lines. The components we wish to align for string assembly will have outlines consisting of many lines, some curved, some straight, as well as both inner and outer corners of varying angles. With the help of our library of silhouette images, we will develop an outline-tracing algorithm that provides 1-μm or better precision in tracing the silhouette of a complex component. We will demonstrate the algorithm's linearity and precision by applying it to sequence of images for which we know the relative position of the component viewed in silhouette.

Transform Image Points Into Lines in Space: Our camera consists of a lens, aperture, and image sensor. Suppose it views a point of light. The point source appears as a spot on the image sensor. The location of this spot constrains the source to lie upon a line in space. The source might be close to the camera, or far away, but it must lie upon this line, which we call its *bearing line*. An *accurate* camera is one that allows us to calculate the bearing line in our global coordinate system. When two accurate cameras view the same point source, the intersection of their two bearing lines gives us the location of the source. If two accurate cameras view the same component in silhouette, we claim that we can deduce the pose of the component, with the exception of its rotation about an axis of radial symmetry.

The applicants have been building and calibrating accurate cameras for the past twenty years. We designed and built the thousands of BCAMs installed in the ATLAS detector at CERN, as well as hundreds more BCAMs installed in a dozen other physics experiments. More recently, we designed and built the WPS instruments for test stands at CERN (Switzerland) and NSRL (China). Our cameras sit on three-ball kinematic mounts. The three balls define a local coordinate system, which we call *mount coordinates* [3]. If we know the location of the three balls in global coordinates, we can transform bearing lines in mount coordinates into bearing lines in global coordinates. Now our problem is to characterize the camera in mount coordinates.

Figure 7: P-BCAMs Manufactured by Brandeis University and Installed in the ATLAS End-Cap Alignment System [9]. Each BCAM is mounted upon a surveyed reference bar.

When we build a camera for a precision position measurement, we keep the aperture small (0.5 mm in the WPS and 2 mm in the BCAM) and place the lens close behind the aperture (0.1 mm in the WPS and 1 mm for in BCAM). We keep the field of view as small as the application permits, and assemble the image sensor, lens, and aperture in a rigid aluminum chassis. The result is an optical arrangement equivalent to a pin-hole camera [4]. The *pivot point* of the camera is the point in space through which we can assume all rays pass. The *axis* of the camera is the line joining the center of the image sensor and the pivot point. We define the camera completely with six parameters: the mount coordinates of the pivot point, a unit vector parallel to the axis, the separation of the pivot point and the image sensor center, and the rotation of the image sensor rows with respect to the mount coordinate x-axis. Because the third component of a unit vector may be deduced from the first two components, we need only seven numbers to define the camera.

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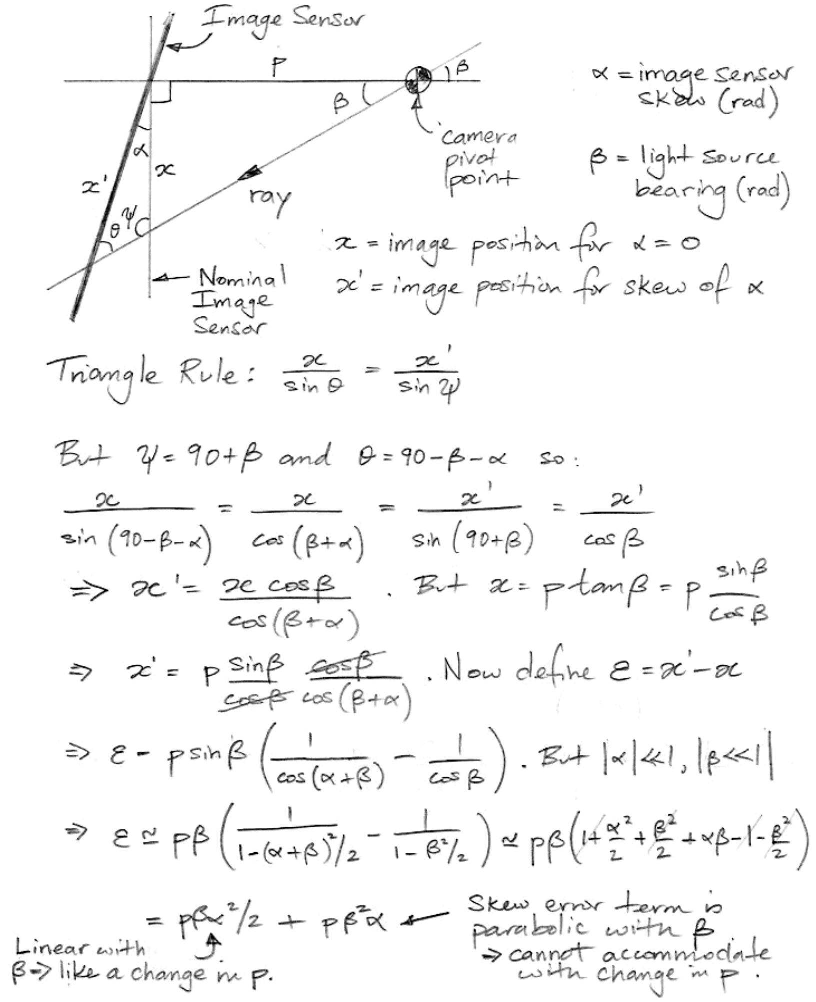

Figure 8: Calculation of Camera Non-Linearity Caused by Skew Angle.

These seven numbers are sufficient to define the camera provided that the camera axis is sufficiently perpendicular to the surface of the image sensor. The angle between the camera axis and a normal to the image sensor is the *skew angle* of the camera. When we move a light source perpendicular to the axis of the camera, the translation of its image across the image sensor will be linear with translation of the light source only if the skew angle is small. Otherwise, our assumption that the camera is linear will result in an error near the edges of the field of view, which we call the *skew error* [8].

The maximum error caused by image skew is proportional to the square of the angular field of view. In the camera of the N-BCAM [7], for example, the image sensor is 50 mm from the pivot point and the field of view is ±50 mrad. If we want the skew error to be less than 1 μm, the skew angle must be less than 7 mrad. We estimate that the required field of view for aligning highly-reflecting components is closer to ±100 mrad, providing us with a ±200-mm field of view at a range of 2 m. If we are to keep our skew error below 1 μm, the ±100-mrad field of view requires us to mount the image sensor with skew angle tolerance of only ±2 mrad. We achieved ±7-mrad tolerance in the N-BCAM with the image sensor soldered to a printed circuit board. To achieve ±2-mrad tolerance, we will need to glue the image sensor to a precision metal

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frame. That is: we must design and build a specialized camera for silhouette viewing. We will not, however, attempt this design in Phase I. We will instead use our existing cameras with ±50-mrad field of view, and use our experience in Phase I to inform our design of the specialized camera in Phase II.

The process by which we determine the seven numbers that define a camera is the process of *camera* calibration. We refer to the seven numbers as the camera's *calibration constants*. We developed our BCAM calibration procedure twenty-two years ago [4]. The procedure involves a roll-cage that holds and rotates the camera, an array of visible light sources, and a straight edge along which we slide the sources. The roll cage we measure separately with a CMM (Coordinate Measuring Machine). The array of light sources we calibrate separately on a granite beam [6]. Our WPS calibration procedure [5] involves a two-axis stage mounted on the bed of a CMM. We move the WPS to different positions around a stationary steel pin, we measure the location of the WPS at each position with the CMM, and we capture images of the pin at each point with the WPS.

We will be able to calibrate infrared-only cameras by incorporating infra-red light sources into one of our our existing camera calibration procedures. But we do not plan to calibrate infrared-only cameras in Phase I. We will take two existing cameras calibrated with visible light, place infrared-only filters over their lenses, and use them to obtain infrared silhouette images. The addition of the infrared-only filter will invalidate our calibration of the camera axis directions. In Phase I, however, our objective is to demonstrate the linearity and precision of position measurement by silhouette images, not to measure make absolute measurements of bearing lines in mount coordinates. We will wait until Phase II to make such absolute measurements. At that time, we will build an array of infrared light sources with which to calibrate infrared-only cameras.

Establish A Global Coordinate System: If we are to bring two or more components into proper alignment for assembly, we must measure their relative positions. We do not assume we can view all components with a single camera. For example, we may need to align eleven rings on a common axis, one every forty centimeters over a four-meter distance. The system we propose to build in Phase II must be able to measure the relative position of components that are several meters apart with sufficient precision for them to be assembled correctly. Our objective is to define a global coordinate system, locate our infrared-only cameras within this coordinate system, and measure the position and orientation of the components within this global coordinate system.

We place around the perimeter of the assembly room a set of aluminum plates, each horizontal and each raised to a convenient height. We equip each plate with at least four calibrated BCAMs, each sitting on its own set of three balls. Each plate we survey with a CMM so that we know the coordinates of all its kinematic mounting balls with ±2 μm accuracy in a coordinate system defined by the plate, which we call the *plate coordinate system.* Each BCAM provides not only a camera, but two light sources as well. All the BCAM have been calibrated with respect to their mount coordinates, and we have surveyed the plates, so we know in plate coordinates the locations of the sources and of the camera pivot points to 20 μm rms, the direction of the camera axes to 50 μrad rms, the separation of the pivot point and image sensor to 300 ppm rms, and the rotation of the image sensor about the camera axis to 200 μrad rms.

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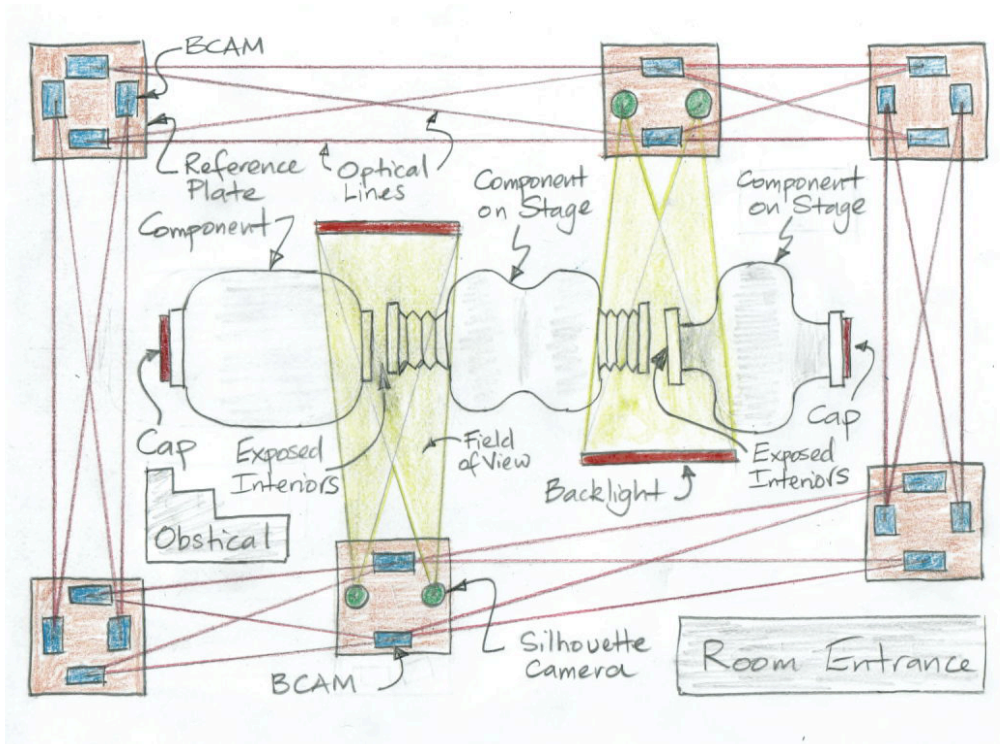

Figure 11: Global Coordinate System Established by Reference Plates and BCAMs. Silhouette cameras complete the measurement of flange position in global coordinates.

The cameras one plate view the sources on neighboring and opposite plates. We assume we will be able to use one or two lines of sight across the assembly room in addition to lines of sight around the perimeter. These lines of sight must be clear for viewing only when we are establishing the reference grid, which will take no more than a minute, and need not be repeated more than once an hour. If the diagonal of the perimeter is 10 m, and we have four times as many measurements as we need to constrain the relative positions of the plates, we will be able to locate all the plates in a *global coordinate system* with absolute accuracy better than 250 μm rms and 25 μrad rms. This procedure by which we take BCAM measurements to construct a reference grid that defines a global coordinate system is similar to the procedure we used in the construction of the ATLAS End-Cap Alignment System [9], where we measure the global position of monitored drift tube (MDT) chambers with an absolute accuracy of 40 μm rms in a 20-m in diameter volume. In the case of the ATLAS system our reference plates were 9-m long aluminum bars surveyed and monitored to an accuracy of 20 μm rms, which allowed us to improve upon the 250-μm rms accuracy that we would have obtained with small, independent reference plates such as those we propose for our global coordinate system.

Locate Silhouettes in Global Coordinates: We arrange for a reference plate to be present at a range of 2 m from each component we want to align. Two infrared-only cameras mounted on the plate view the component. These cameras will be calibrated, and their mounting balls known in the global coordinate system. With them we obtain a stereoscopic view of the component. According to our calculations, one silhouette is sufficient to determine the location of the component, but we propose to obtain two stereoscopic silhouettes whenever possible, so that our system is over-constrained. An over-constrained system allows us to identify failures of image analysis and estimate the accuracy of our position

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measurement, so we always try to obtain at least twice as many images as we need, and four times as many if possible.

Figure 9 illustrates how the accuracy of axis calibration dictates the accuracy of position measurement. Two calibrated cameras view the same point source and deduce its range from the angle it subtends at the camera pivot points. The cameras measure this subtended angle with an accuracy 70 µrad rms, which is the sum in quadrature of 50 µrad for each camera axis calibration. Our error in measuring the range of the point source increases in proportion to the square of the range, and in inverse proportion to the separation of the cameras. At range 2 m, with the cameras 1 m apart, our error will be 300 µm rms, which does not meet our target accuracy of ±300 µm.

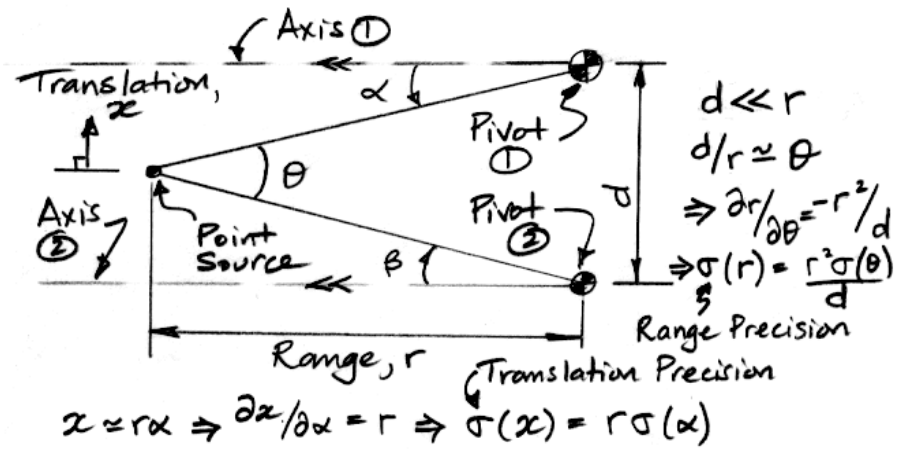

Figure 9: Locating a Point Source with Two Cameras. Without loss of generality, the two camera axes are parallel and their pivot points are at the same range. We indicate the standard deviation of a measurement with a sigma character.

Each camera makes its own, independent measurement of translation perpendicular to its axis. In Figure 9, each camera's error in measuring translation in the *x*-direction is equal to the product of the range and our 50-µm rms error in camera axis direction. At range 2 m, our accuracy is 100 µrad rms. By taking the average of the two camera's measurements, we reduce our error to 70 µm rms. Our measurement of transverse position is well within our requirement of ±300 µm, but our measurement of range is not. When our target has a well-known width, however, we can measure its range with a single camera with far better accuracy.

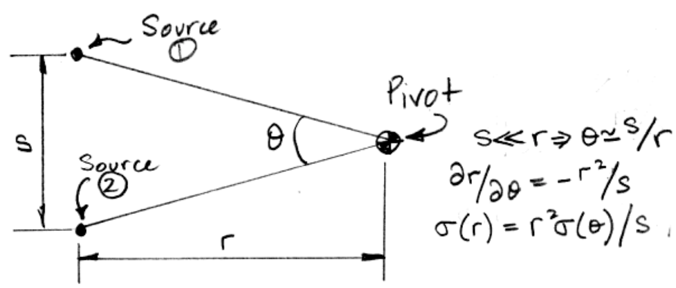

Figure 10: Measuring Range of a Pair of Sources of Known Separation with a Single Camera.

In Figure 10, we see two point sources separated by a well-known distance, *s*, at an unknown range, *r*. The two sources subtend an angle, θ, at the camera pivot point. The camera's measurement of this angle does not depend upon the absolute calibration of the camera axis, but rather upon the calibration of the image sensor position and rotation. When measuring angles subtended at a single camera pivot point, our accuracy is 5 μrad rms, which is ten times better than the absolute calibration of the camera axis. Our accuracy in measuring the range of two sources separated by exactly 200 mm at range 2 m is therefore 100 μm rms, which is well within our requirement of ±300 μm.

The above estimate of range accuracy assumes that we know the separation of the sources exactly. If our uncertainty of a 200-mm separation is ±200 μm, our range measurement will suffer an uncertainty of one part per thousand, or ±2 mm at range 2 m. We can, however, overcome this uncertainty by viewing the two sources from opposite sides. Our reference grid will tell us the sum of the two ranges, and our cameras will tell us the ratio of the two ranges, which allows us to solve not only for both ranges, but also for the actual separation of the sources. By this means, we are sure to arrive at an accuracy of better than ±300 μm in all coordinates.

Consider the outline of a component seen in silhouette by a single camera. Let us represent the outline with a sufficient number of points, and consider the bearing lines of these points. Taken together, these bearing lines constrain the location of the component. If we have the exact dimensions of the component, we will be able to place the component in global coordinates using the silhouette bearing lines. With two cameras viewing the same component, we will have two sets of bearing lines that intersect, and the location of our component is doubly constrained. A single pair of bearing lines constrains a point with accuracy better than ±300 μm. Our hope is that a multitude of intersecting silhouette bearing lines will constrain the location of a three-dimensional component with the same accuracy or better.

We will not construct a reference grid in Phase I of our work. We will construct a single reference plate, survey it with a CMM, and upon it we will mount our two prototype infrared-only cameras to obtain stereoscopic silhouettes of our example components. We will measure the linearity and precision of our measurement of range, transverse position, and rotation. Our observations will inform our design of infrared-only cameras and reference plates for Phase II. In Phase II we will construct a reference grid of a size and complexity representative of a real-world application.

Predict Silhouette Outlines: We need an analysis routine that takes as input the calibration constants of a camera, the global coordinates of its mounting balls, a three-dimensional model of a component, and the global position of this component, and produces as output the silhouette outline we would see if all the inputs to the routine were exact representations of reality. Once we have this outline-generating routine, we can compare the actual silhouette outline we see in our camera image to the one we expect to see for an estimated component pose, and use the disagreement between the two outlines as a measure of the error of our estimate. This problem of determining the outline of an object from a particular point of view has been solved by numerous commercial and open-source drawing programs. In Phase I we will develop an outline-calculating routine, either by adapting an existing open-source package or by writing our own code, whichever seems most efficient.

Measure Location of Components: We calculate the locations of the components by means of a minimization algorithm. Our first minimization gives us the global coordinates of the balls upon which our component-viewing cameras are mounted. This minimization algorithm already exists in a general form for application to arbitrary reference grids made with BCAMs [10]. Subsequently, we apply a minimization algorithm to reduce the disagreement between the observed and expected silhouette outlines of the components we are aligning. Our minimization algorithm might operate upon the entire outline, or upon only certain portions of the outline. It could be that some components are precise in certain regions, such as at their end flanges, but not in others, such as in their central bellows. We will be able to ignore parts the outline that would otherwise degrade the accuracy of our fit. Once our minimization algorithm has converged, we have our best estimate of each component's position. In Phase I we will implement a minimization algorithm for one component viewed by two cameras. In Phase II we will implement the algorithm required by the reference grid. Our ultimate objective is to measure the absolute position of all points on each component with a precision of ±300 μm.

Performance Schedule

Open Source Instruments Inc. (OSI) proposes to consult with Fermi National Laboratory (FNL) in the development of a contactless position measurement system for SRF assembly. The design, construction, and programming of the system will take place at OSI. Engineers at FNL will advise uspon the details of SRF assembly so as to ensure that we test our system with realistic components and movements. In the paragraphs below, we present our performance schedule as a series of milestones. For each milestone, we name the institute that has primary responsibility for completing the work.

Milestone 0, Beginning of Month 0: Receive funding for SBIR Phase I. (OSI)

Milestone 1, End of Month 2: Obtain first images of infrared panel illuminator using infrared camera, and demonstrate that the required exposure time for a bright background at range two meters is no more than 100 ms. (OSI)

Milestone 2, End of Month 3: Obtain high-contrast silhouette images of opaque objects at range 2 m in the presence of bright, fluorescent overhead lights. Assemble a library of high-contrast silhouette images of simple, highly-reflecting metal objects such as spheres, rods, and disks. (OSI)

Milestone 3, End of Month 3: Complete assembly of a computer-controlled, motorized stage that allows us to translate by ±10 mm in two directions, and rotate by ±100 mrad. (OSI)

Milestone 5, End of Month 4: Demonstrate outline-tracing image analysis for our library of simple silhouette images. (OSI)

Milestone 6, End of Month 5: Demonstrate the prediction of silhouette outlines for our library of simple objects given an assumed position and orientation of the object with respect to the camera mount coordinate system. Overlay predicted outlines on actual silhouette images so we can compare with human eye the disagreement between the actual and predicted outlines. (OSI)

Milestone 8, End of Month 6: Complete first version of program that minimizes disagreement between actual and predicted outlines by adjusting the assumed position and orientation of the object. (OSI)

Milestone 10, End of Month 7: Demonstrate ±300 μm precision and linearity in measuring the position of simple objects while we translate them by ±10 mm at a range of two meters. We obtain the standard deviation of the measured position of stationary objects, and this is our precision. We obtain the residuals of a straight line fit to measured position versus stage position, and this is our non-linearity. (OSI)

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Milestone 11, Middle of Month 8: Complete a library of images of more complex, highly-reflecting objects representative of those present in SRF cavity assembly. (OSI)

Milestone 12, End of Month 8: Extend silhouette outline tracing and silhouette outline prediction algorithms to support more complex objects. Extend minimization program to operate upon these more complex outlines. (OSI)

Milestone 14, End of Month 9: Demonstrate ±300 μm precision and linearity in measuring the location of surface features on complex objects while we translate the object by ±10 mm and rotate it by ±100 mrad at a range of two meters. (OSI)

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Facilities and Other Resources

Open Source Instruments

Open Source Instruments has its laboratory and manufacturing facility at 22 Bedford Street, Waltham, MA. Our 2,000 square foot, rented space has an open floor plan. It is well lit with natural and artificial light. There are eight distinct work stations in the space, which are comprised of a work-bench surface, seating, magnifier lights, computers, and specialized equipment. We have three general-purpose electronic assembly stations and an additional three stations dedicated to the manufacture of subcutaneous transmitters. Other stations include an optical fiber stretcher and radio frequency testing space with Faraday enclosure.

The facility is large enough to include space for storing items related to manufacturing such as electronic components, flux, potting epoxy, manufactured parts ready for sale, and Faraday enclosures. There are also shelves for disposable items like mixing tips, paper containers, and wipes. The space is large enough to absorb growth in both projects and people.

The Open Source Instruments billing and correspondence address is 130 Mt. Auburn Street, Watertown, MA. This is the address under which our paperwork is filed and it is where we receive our mail. Accounting, invoicing, and bill paying happen from this address.

Open Source Instruments is a small company with five regular employees, four of whom are on-site at the manufacturing facility. The relationship between them is collegial. There are several projects on-going within the facility, some of which all staff participate in and some of which are completed independently. The engineers tend to discuss and trouble shoot each-others' issues.

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Equipment

Open Source Instruments

In its laboratory, Open Source Instruments has equipment necessary for electronic design and assembly. Items include:

Six soldering irons at the electronic assembly stations

Three complete telemetry set-ups for testing and programming transmitters, which have LWDAQ Drivers and Octal Data Receivers, antennas, and spectrometers

Optical fiber stretcher to heat and divide optical fibers to create tapers

Two oscilloscopes

One Vector Voltmeter

Photometers

Lab oven for elevating temperature during accelerated testing

Inspection optics

Anti-static mats

Cleaning station with hot water and specialized brushes for electronics

Compressed air

Vacuum chamber for device encapsulation

Motorized rotators for encapsulation curing

A custom silicone curing enclosure

Custom-made Faraday enclosures

For the alignment project with FermiLabs, Open Source Instruments will require some additional equipment for the manufacture and testing of specialized components. This includes a low profile optical laboratory table. Should the project get continued Phase II funding, we will purchase a coordinate measuring machine (CMM). These items will be included in the budget.