Interim Research Performance Progress Report - April 2023

Email this report to Kenneth Marken and copy sbir-sttr@science.doe.gov because there was no task present in PAMS or in FedConnect.

I. Cover Page

Phase I SBIR Award Identification No. DE-SC00022581
Department of Energy SBIR Phase I started on 6/27/2022
Project Title: Contactless Position Measurement for Highly Reflective Components
PI: Kevan Hashemi hashemi@opensourceinstruments.com cell: 617-335-3472
For Open Source Instruments, Inc.

II. Accomplishments

a. What were the major objectives of this project?

The objective of our Phase I project is to demonstrate that it is possible to obtain sharp, clear, silhouette images of highly-reflective components using an infrared backlight and infrared-only cameras. We can use stereoscopic silhouette images to determine the location and orientation of any two such components, with sufficient precision to bring their flanges into contact and align their bolt holes. Our application lists the following milestones.

Milestone 0, Beginning of Month 0: Receive funding for SBIR Phase I. We received funding towards the end of August 2022. Our Month Zero is September, 2022

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. This we achieved in Month Zero. We built a prototype backlight consisting of nine infra-red LEDs 100 mm from a ground glass diffuser. We equipped some of our existing metrology cameras with infra-red-only filters. We used our existing edge-finding image analysis program to find the edges of reflecting cylinders. At a range of 2 m, exposure time of 10 ms was sufficient to obtain 20-μm accuracy in measuring the location of cylinder edges.

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. This we achieved in Month One. We chose to work at 1 m instead of 2 m. We are convinced that our measurement errors will scale linearly with range. If we need 300-μm precision at range 2 m, we must demonstrate 150-μm precision at range 1 m. Working at range 1 m was more convenient because it allowed us to use a smaller backlight. Our library of silhouettes contains a few dozen images of spheres and posts in various locations, taken with various exposure times and camera apertures.

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.

We decided not to start with a motorized stage, but rather a manual micrometer stage so that we could separate the problem of moving the objects from the problem of measuring their position. Our manual stages allowed ±10-mm movement and arbitrary rotation about the vertical axis. We set up our stages in Month Two.

Milestone 5, End of Month 4: Demonstrate outline-tracing image analysis for our library of simple silhouette images. We tried outline-tracing as a way to analyze silhouette images. We have used outline-tracing successfully in the past, to find wires and ellipses in x-ray and optical images. But when it came to the compound shapes that the CPMS must locate, outline-tracing proved to be cumbersome and unreliable. We developed a more versatile analysis, one that can accommodate complex components with no fundamental changes in the way it operates. In all CPMS applications, we will have drawings of every component, and every component will be machined with high precision. Our analysis constructs a computer model of each component by combining simple shapes like spheres and cylinders until the combination matches the actual component. When we measure the location of a component, we start by giving our modeled component a location that is close to that of the actual component. We project the modeled component onto the image sensor of our camera and obtain a modeled silhouette. The modeled silhouette and the actual silhouette are not aligned. We proceed to adjust the position of the modeled component until we align the modeled and actual silhouettes as best we can. The final position of the modeled component is our measurement of the position of the actual component. We first implemented this analysis in Month Seven.

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 the human eye the disagreement between the actual and predicted outlines. Our model-projection analysis (Milestone 5), provides this comparison naturally, because it is this comparison that drives the analysis. We first started comparing projections and silhouettes in Month Seven.

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. Once we switched to our new analysis, this result came immediately in Month Seven.

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. We are now in Month Eight, and this work remains to be done. Our existing analysis takes two minutes to obtain a component position from one pair of images. It is possible to proceed with our linearity measurement with two-minute analysis per step, but we are going to speed up the analysis first, then perform our linearity checks. We do, however, have a lot of experience measuring position by triangulation, so we do not expect any surprises when it comes to these tests.

b. What was accomplished under these goals?

We proved that we can obtain high-contrast, sharply-defined silhouettes of mirror-finish spheres and cylinders in the presence of overhead lights and with sunlight shining through windows. We are able to obtain sharp images for ranges that vary by a factor of two: half-way to the backlight and all the way to the backlight. Our silhouette image analysis provides precision 100 ppm (parts per million) of the range of the component: 50 μm at 50 cm, 100 μm at range 1 m. With precision of 100 ppm, we are confident we can track movements of 100 mm with linearity 200 μm at range 1 m, which is well within our 300-μm rms target.

We have not yet had the opportunity to measure the linearity of the CPMS when tracking components across its field of view. We first want to accelerate our image analysis routines. We have hired a programmer to work from May to September on accelerating the analysis. We are hiring an undergraduate from May until August to perform systematic tests on the precision and linearity of the CPMS measurement.

We did not build a motorized stage, but instead invested in a manual three-dimensional linear stage and rotation stage. The motorized stage would have required additional programming and interface hardware, but would not have helped us in our study of the fundamental sources of error in the CPMS optics and image analysis, in which our manual stages were perfectly sufficient.

c. What opportunities for training and professional development has the project provided?

There have been no opportunities for training or development so far, but in the coming months we will have one apprentice programmer working on accelerating our analysis software, and an undergraduate working on systematic tests of our measurement accuracy using our manual stages.

d. How have the results been disseminated to communities of interest?

We keep a detailed record of all our work on our CPMS web page. All our designs and software are open-source. We have been in communication with our collaborators at Fermilab, and we have shared links to our progress to everyone we have spoken to in our marketing outreach.

e. What do you plan to do during the next reporting period to accomplish the goals and objectives?

We are going to accelerate our silhouette image analysis, which is currently one hundred times slower than we would like it to be. We have hired a programmer to accomplish this acceleration. We want to compose and track objects made out of five or six cylinders and spheres. In particular, we have a stainless-steel copy of a superconducting resonant cavity coupling that we would like to measure as it moves across our field of view.

III. Products

a. Publications, conference papers, and presentations

Nothing to report

b. Websites or other internet sites
The website for the Contactless Position Measurement System is here: https://www.opensourceinstruments.com/CPMS/ where all of our findings and descriptions of our work can be found. This site is available to anyone with interest to look. From it, one can access the development log for the project: https://www.opensourceinstruments.com/CPMS/Development.html

c. Technologies or techniques

Design of an infra-red backlight suitable for taking silhouette images. The backlight lends itself to extension to dimensions of several meters square. Another product is our silhouette image analysis, which can be adapted to arbitrarily complex objects and provides precision of better than 10% of a pixel on the image sensor.

d. Inventions, patent applications, and or licenses

All our work is open-source, released under the GNU Public License.

e. Other products - data or databases, physical collections, audio or video products, software or netware, models, educational aids or curricula

IV. Participants and Other Collaborating Organizations

Participants

Kevan Hashemi, Principal Investigator, 4 person-months worked
Contribution to Project: Provided conceptual design, liaison with collaborator, set-up test stand, designed optics, wrote software for finding edge, tested fitting analysis

Nathan Sayer, Electrical Engineer, 3 person-months worked
Contribution to Project: Designed and built the infra-red backlight, analyzed diffuser glass, analyzed different distances of diffuser from backlight for camera image saturation.

Kirsten Hashemi, Operations Manager, 3 person-months worked
Contribution to Project: Marketing and outreach to potential customers.

Partners
FermiLab
Batavia, Illinois, United States
Partner's Contribution: FermiLab provided details of implementation requirements for SRF cavity assembly and drawings of SRF cavity components.

V. Impact

a. What was the impact on the development of the principal discipline of the project?

Nothing to report.

b. What was the impact on other disciplines?

Nothing to report.

c. What was the impact on the development of human resources?

Nothing to report.

d. What was the impact on physical, institutional, and information resources that form infrastructure?

Nothing to report.

e. What was the impact on technology transfer?

Nothing to report.

f. What was the impact on society beyond science and technology?

g. What percentage of the award's budget was spent in foreign country(ies)?

None (0%) of the budget of this Phase I project was spent in a foreign country.

VI. Changes or Problems

a. Changes in approach and reasons for change

None.

b. Actual or anticipated problems or delays and actions or plans to resolve them.

None.

c. Changes that have a significant impact on expenditures

Nothing to report.

d. Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to report.

e. Change of primary performance site location from that originally proposed

Open Source Instruments moved offices October 1, 2022 to another building in the same city. The new office and manufacturing facility is larger, offers separate rooms, among other advantages that increase productivity. Our new address is 135 Beaver St, Suite 207, Waltham, MA 02452.

g. Carryover Amount

Open Source Instruments does not anticipate there being any carryover amount of funds left at the end of Phase I work.

VIII. Demographic Information

Kevan Hashemi hashemi@opensourceinstruments.com
Nathan Sayer sayer@opensourceinstruments.com