Internship Report

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Introduction

Colorado State University Accelerator Laboratory

Who We Are

The Colorado State University Accelerator Laboratory group is made up of professors, research scientists, post-doctoral researchers, graduate students, undergraduate students, high-school students, and many collaborators. The group works under the leadership of Dr. Sandra Biedron and Dr. Stephen Milton to further develop the accelerator educational program at Colorado State University and to conduct particle and beam research projects.

What We Do

Working at the Colorado State University Accelerator Laboratory prepares students in the complex, but fascinating, field of accelerators. The work we perform helps bridge the gap between use of accelerators in laboratory settings and in manufacturing, medical, and military sectors.

There are four major systems at the Colorado State University Accelerator Laboratory facility: an accelerator and FEL system, a laser laboratory, a microwave test stand, and a magnetic test stand. After completing the construction of our facility, we will initially focus on generating long-wavelength free-electron lasers, electron-beam components, and peripherals for free-electron lasers and other light sources. Our laboratory will serve as a test bed for research and development projects.

Why We're Doing It

There is an expanding demand across a wide variety of disciplines in academia, laboratories, and industry for particle accelerators. The growing demand of trained accelerator experts continues to motivate the expansion of facilities in a university setting dedicated to training engineers and physicists in accelerator technology. Part of the goal of the Colorado State University Accelerator Laboratory is to provide a place where both accelerator research and training of high-school through post-doctoral students can flourish.

Projects and Tasks

"Voltage Pulse" Program

NI LabVIEW Training

According to the National Instruments official website: "LabVIEW is a highly productive development environment for creating custom applications that interact with real-world data or signals in fields such as science and engineering." LabVIEW uses an intuitive, flowchart-like dataflow programming model, which requires a shorter learning curve than traditional text-based programming. The program supports the integration of different kinds of hardware devices (e.g. scientific instruments, data acquisition devices, sensors, cameras, motors, and actuators). In addition, the libraries of signal processing, analysis, and control algorithms, as wells as interactive controls such as graphs, gauges, and tables structures, make it easy for data to be collected, analyzed, simulated, and displayed [1].
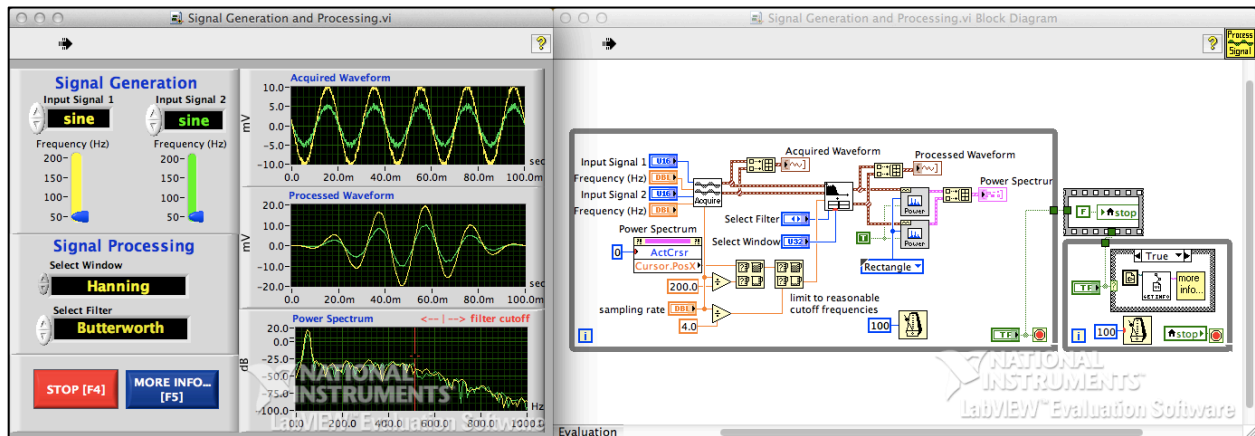

FIGURE 1. LabVIEW display interface and programming block diagram.

In order to familiarize myself with the LabVIEW program development interface and process, I completed several training sessions to learn the basics of LabVIEW programming and experiment with different tools, such as the virtual instruments that simulate data output from scientific equipment, as well as the analysis components that apply various customizable algorithms. Very useful were the example projects that were bundled with the software, which allowed me to explore actual applications of LabVIEW tools.

Project Creation

My project in LabVIEW was to create a program that measures the electrical voltage of a series of pulses, analyzes and displays the collected data in a table, outputs the sum of the voltages, and allows for easy user interaction through an intuitive UI format. I used the skills I gained from my training period to implement the project goals in the Voltage Pulses program (FIGURE 2).

In the development stage, the pulses used in the program were simulations, i.e. computer-generated using a waveform creator and randomization algorithm. However, my program ultimately

serve as a data analysis tool, to be connected with an exposure dose control system for a tabletop 46.9 nm capillary EUV laser.
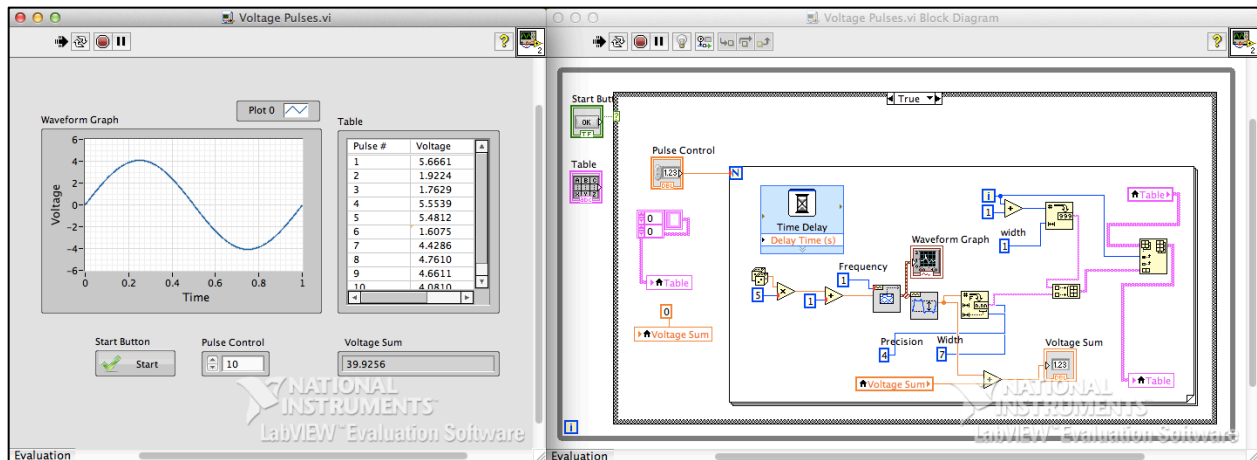

FIGURE 2. The Voltage Pulses user interface (with a real-time display table and voltage sum display) and the programming block diagram.

"Parallax: Interferometer Parallel-Plate Alignment" Program

In many photolithography experiments, it is necessary to precisely align a parallel-plate system, e.g. the optical mask and etching resist. One way to achieve this is to use the concentric-circle fringe pattern created by an interferometer as a guide for the plates' positioning. When the plates are exactly parallel, the concentric-circle pattern should be virtually nonexistent. As the plates are rotated from their parallel position, the number of circles visible increases, while the distances between the circles decease in a proportional manner with the angular difference in the tilt between the plates. Thus, it is possible to measure the distances between the circles and use those distances to precisely calibrate a mechanized positioning system. The interferometer pattern (or a partial image of it) is captured with a CCD camera, and the grayscale image file is uploaded to a computer network.

My responsibility was to develop software that uses image analysis and geometric manipulation techniques to determine the distances between the concentric circles. The main project challenges were: 1) the complexity of automated image analysis algorithms, 2) the requirement for high precision due to the size of captured patterns (usually on the scale of nanometers), and 3) the need to present data in a user-friendly (preferably graphical) format.

To implement this project, I created a program, using the Java programming language, that has an interactive image canvas, on which users select points to choose the circles for which distance analysis will be performed. In order to improve precision, there is the Pixel Display feature that allows users to choose points on the image with pixel-perfect accuracy (using both the mouse and keyboard as controllers). There is also the Color Map feature that maps grayscale values within a given range (controlled by the keyboard) to color values. Thus, subtle differences in value can be highlighted by color differences. In addition, users may input a pixel-to-SI units conversion factor,

so distances between circles will be displayed both in pixels (on the original image, not the smaller version displayed on screen) and in SI units (or another units system).

The three major components of this project were: the geometric algorithms, the tools for achieving near pixel-perfect accuracy, and the innovative yet intuitive user interface.

Geometric Algorithms

Many images of the interferometer fringe patterns will be partial: close-up shots of only a couple fringes. At such ranges, the concentric-circle pattern will seem distorted, and in some cases nearly straight. Since the most logical way of computing the distances between the concentric circle fringes is to subtract radii, it is necessary to compute the center and radius of each circular fringe.

The user first chooses 3 points on a circle that is to be analyzed. Elementary geometry dictates that 3 points make a triangle. Since the circle passes through all three points, it circumscribes the triangle, i.e. the circular fringe path is the circumcircle of the triangle made by connecting the 3 user-specified points [2]. Thus, the circumcenter (X, Y) and circumradius R are the values that the program must calculate:

$$K = 2\left[A_X\left(B_Y - C_Y\right) + B_X\left(C_Y - A_Y\right) + C_X\left(A_Y - B_Y\right)\right]$$

$$X = \frac{\left(A_X{}^2 + A_Y{}^2\right)\left(B_Y - C_Y\right) + \left(B_X{}^2 + B_Y{}^2\right)\left(C_Y - A_Y\right) + \left(C_X{}^2 + C_Y{}^2\right)\left(A_Y - B_Y\right)}{K}$$

$$Y = \frac{\left(A_X{}^2 + A_Y{}^2\right)\left(C_X - B_X\right) + \left(B_X{}^2 + B_Y{}^2\right)\left(A_X - C_X\right) + \left(C_X{}^2 + C_Y{}^2\right)\left(B_X - A_X\right)}{K}$$

$$R = \sqrt{\left(A_X - X\right)^2 + \left(A_Y - Y\right)^2} = \sqrt{\left(B_X - X\right)^2 + \left(B_Y - Y\right)^2} = \sqrt{\left(C_X - X\right)^2 + \left(C_Y - Y\right)^2}$$

NOTE: In order to minimize error, the user choose 3 points that are as far away as possible from each other on the circular path, i.e. 2 endpoints and 1 midpoint on the path.

NOTE: Because the circular fringe paths are concentric, it is only necessary to complete the 3-point process once. Afterwards, users need only select 1 point on each additional circle. Basing the circles on a common center ensures greater accuracy when subtracting radii to calculate the desired distances.

Pixel-Perfect Accuracy

To improve precision in the pixel selection process, there is the Pixel Display feature that allows users to select specific points on the image, using both the mouse and keyboard to control the pixel selector.

In addition, there is the Color Map feature (FIGURE 3) that maps grayscale values within a specific range to color values. Since both the lower bound and upper bound for the mapping range can be controlled by the keyboard, users may achieve a superior mapping result for any image. The Color Map feature also works for color images: each pixel is first converted to grayscale by taking the arithmetic mean of the red, green, and blue components.
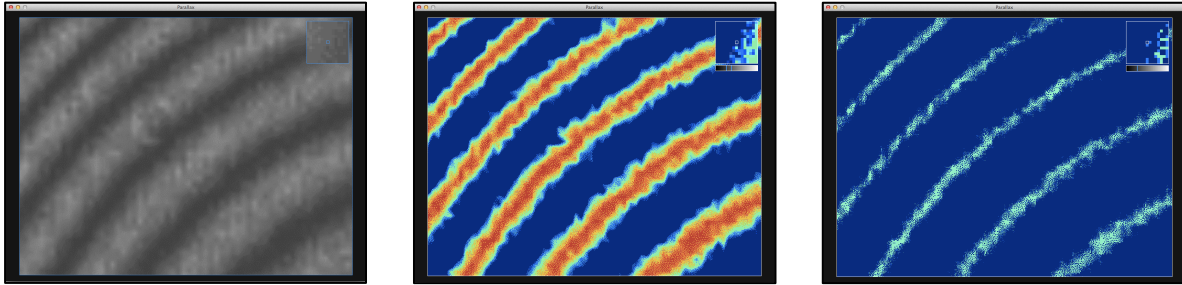
FIGURE 3. The Color Map feature highlights subtle differences in value, and editable mapping ranges (controlled by keyboard input) help users achieve a superior result.

To create the Color Map feature, I developed a mapping algorithm that works for both grayscale and color images. The map used in my program ranges from blue to red, and passes through the colors cyan, yellow, and orange. It is the map officially associated with astrophysical fluid jet simulations from the National Center for Supercomputer Applications.

User Interface

The user interface of Parallax is easy-to-navigate yet very powerful. Providing an elegant and simple way to present the information output by the complex behind-the-scenes algorithms, the interface is the connection between the user and the software.
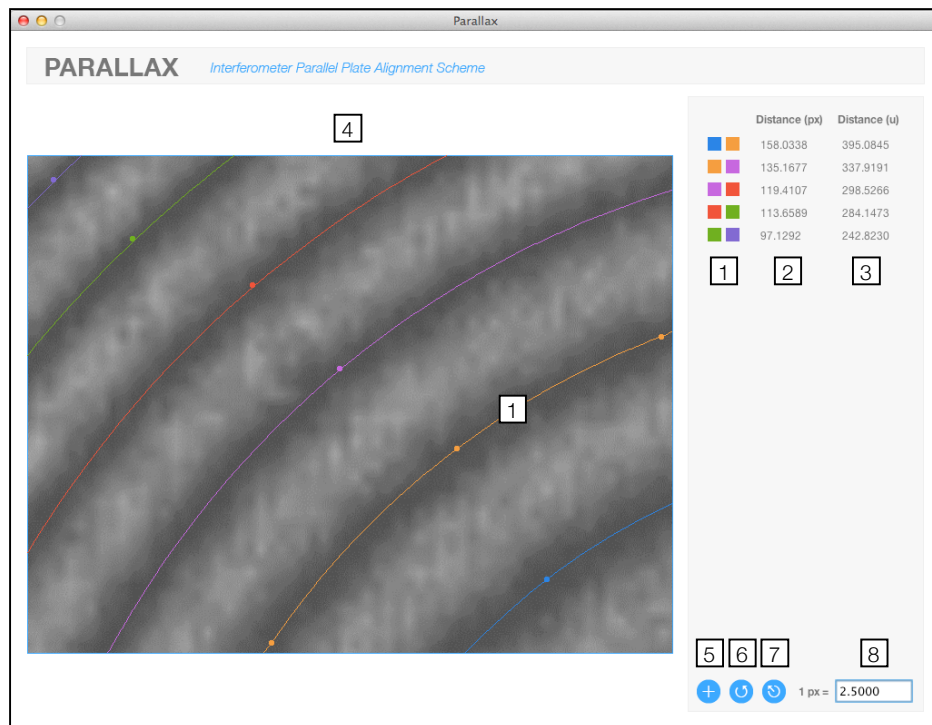

FIGURE 4. The main interface of Parallax program is innovative yet intuitive. The use of color-coding makes it easy to distinguish each distance value. A conversion input allows users to specify the real-world units scale in which the program outputs results.
1. Color-Coded Circles, **2.** Distance in Pixels, **3.** Distance in Real-World Units, **4.** Preview Window, **5.** Add Circles, **6.** Undo, **7.** Restart, **8.** Conversion Input
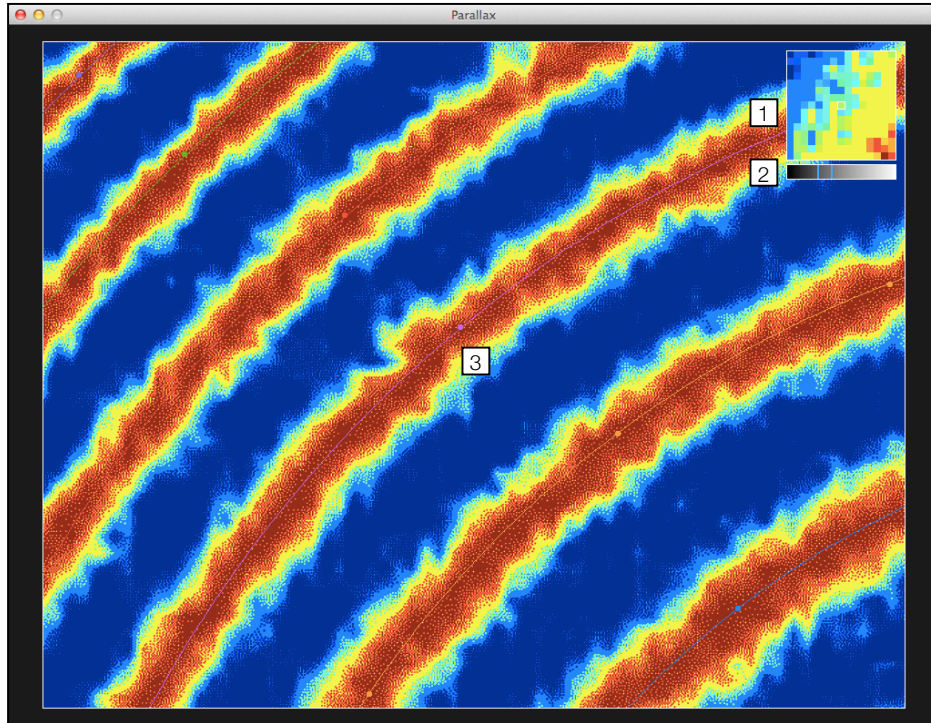
FIGURE 5. The edit interface of Parallax program is simple and useful. With both the Pixel Display and Color Map features on, it is easy to select exactly the right points.
1. Pixel Display, **2.** Color Map Range Indicator, **3.** Full-Screen Canvas

CSU Accelerator Laboratory Website

The official website for the Colorado State University Accelerator Laboratory is crucial in attracting potential team members, sponsors, collaborators, and parties interested in learning what we do. Thus, the team tasked with designing and coding a new website—comprised of Christian Carrico, Lucas Kang, and me—decided to keep two key principles in mind during the development process: professionalism and adaptability.

In order to achieve a professional-looking website, we chose an elegant, clean design style (i.e. sharp corners, crisp edges, few gradient graphics). The website is easily navigable and user-friendly; important information that our targeted audience would be interested in is readily available at their fingertips. Achieving this meant cutting the clutter and streamlining the website.

The first version of the site, Website 1.0, dealt primarily with the principle of professionalism.

After the design and functionality had been finalized, Christian and I worked on further cutting the clutter and streamlining the website, except that, this time, we were working behind the scenes. My previous experience with website creation taught me that a website was only truly great if *both* its aesthetics and its code were elegant. This is because an easy-to-understand and easy-to-edit code is adaptable; future webmasters may alter and update the site in a flexible way, focusing on new content rather than design and layout code.

The second version of the site, Website 2.0, dealt primarily with the principle of adaptability.

Website 1.0

Our software of choice was Adobe Dreamweaver CS6 because it is the industry-standard web creation tool, both for WYSIWYG creators and for coders. Having had the most experience on my team in coding in HTML and CSS, my responsibility was the overall design and implementation of the website.

The structure of the website is very user-friendly. The Homepage displays a slideshow of pictures taken of our team and our work. Below that is a multimedia news section, capable of housing articles, photos, and videos relating to the progress of our work.

The main linked pages of the website are: People, Documents, Labs, Press, Collaborators, Internships, and Photos.
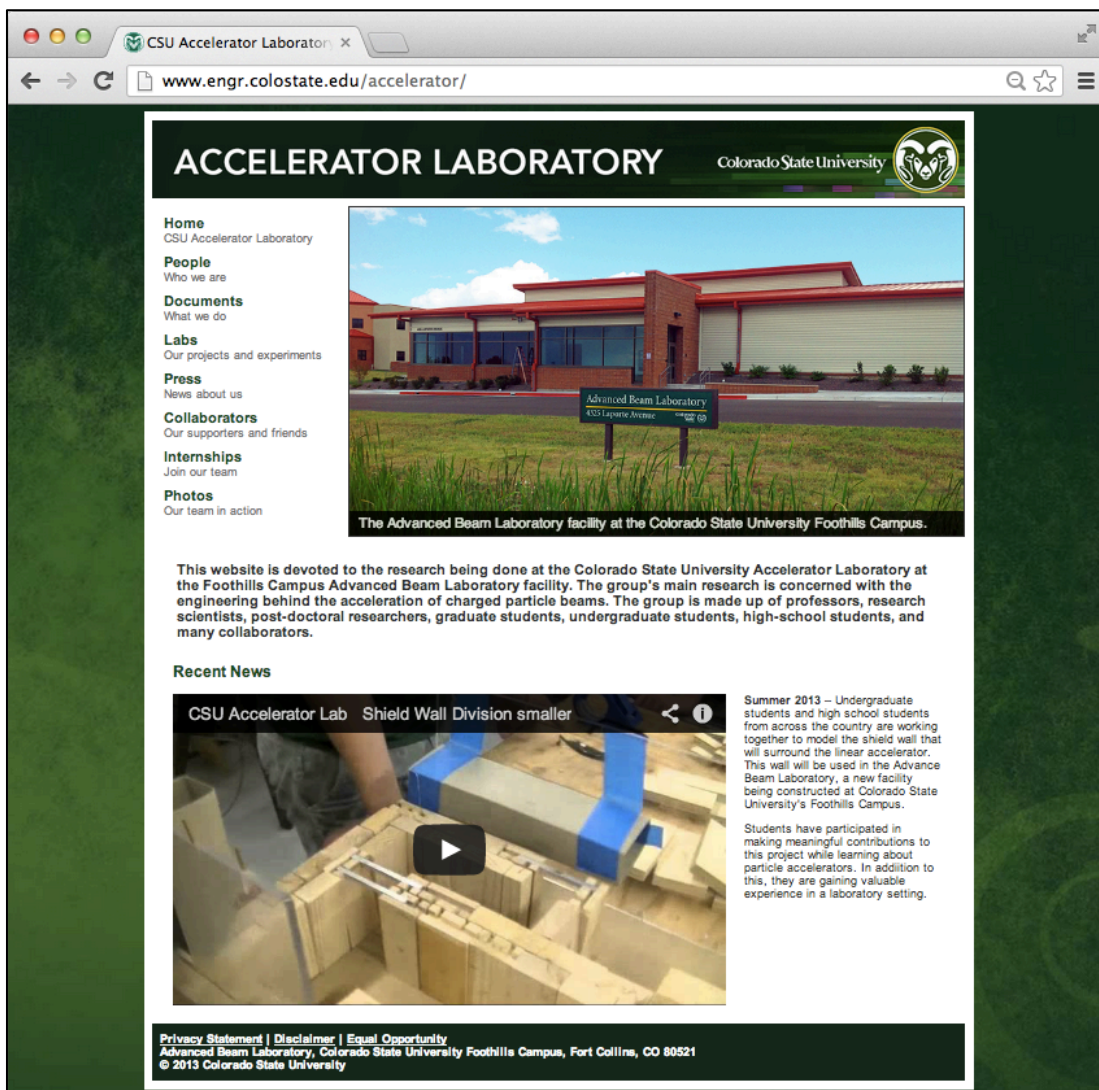

FIGURE 6. The main page of the CSU Accelerator Laboratory website, with its header/footer, navigation, slideshow, and news components. Consistent layout and text styles are achieved with external CSS files and PHP includes.

Website 2.0

The second stage of our development process involved the rewriting of code to use external CSS files and PHP script.

CSS, or cascading style sheets, is "the language for describing the presentation of Web pages, including colors, layout, and fonts. It allows one to adapt the presentation to different types of devices, such as large screens, small screens, or printers. The separation of HTML from CSS makes it easier to maintain sites, share style sheets across pages, and tailor pages to different environments. This is referred to as the separation of content from presentation" [3].

PHP is "an HTML-embedded scripting language. Much of its syntax is borrowed from C, Java and Perl with a couple of unique PHP-specific features thrown in. The goal of the language is to allow web developers to write dynamically generated pages quickly" [4].

Using external CSS files, we maintained consistent text formatting and presentation across webpages, in the different sections of the website. Using PHP, we leveraged the programming concept of encapsulation. The header, footer, and navigation sidebar code are stored in external files; each page of the website references these files. Therefore, making changes are extremely easy—editing a component once in the external file will allow it to update for every page on the site. Even the name of the website is stored as a PHP variable, so any changes to our website name can be made across the board. Furthermore, PHP allows easy implementation of components like profile pages. Rather than have a separate page for every person, which would bring inconsistent formatting and difficulties in editing/updating, the website has one master template, containing formatting and layout code, that pulls data from individual `.php` files for each person's profile (FIGURE 7). This method makes the profile section *extremely* flexible.

FIGURE 7. Entire code for an individual profile page: `JohnnyAppleseed.php`

```php
<?php

    $profile_id = "JonnyAppleseed";
    $profile_name = "Jonny Appleseed";

    $profile_profession = "Student Research Scientist <br />";
    $profile_field = "Biology and Ecology Department <br />";
    $profile_institute = "National Institute for Apple Cultivation <br />";
    $profile_email = "j.appleseed@gmail.com <br />";

    $profile_body =
    "
        The quick brown fox jumps over the lazy dog.
    ";

?>
```

Magnetic Field Mapping System

Much of the following information can be found in the document my team published, which is titled: "Design Proposal for a Magnetic Field Mapping System for Accelerator Beam Interaction Magnets."

Project Objective

The objective of this project was to design a system to map the field around several magnets that are being considered for use in a particle accelerator undulator or beam interaction system. In addition to needing to map the field structure around the magnet, this project would also test for field consistency between magnets.

In order to measure the field of a magnet, there were several variables that must be controlled for, including: x, y, z position of sense probe from magnet, temperature, and altitude/earth's magnetic field. In addition, depending on the probe used, it was possible that accuracy and repeatability would become a significant issue as a 1D probe would need multiple scans to build up a field map for a magnet. It was also important to do a zero-gauss calibration of the probe and an initial scan of the empty stage without the magnet under test to get a baseline for the field at each point.

The field mapping process consisted of moving the probe into position and reading the field strength from the gaussmeter at regular intervals in the desired mapping volume.

Design Proposals

Our team proposed several design ideas that would implement the project goals. These designs covered a broad range of costs and development durations, ranging from a design that would be mostly pre-manufactured and automated to one that would be primarily manufactured in-house or manually-operated. Specifically, the designs were variations of different ways of implementing certain tasks:

1. Three-Axis Probe, Automated 3D Stage
2. One-Axis Probe, Automated 3D Stage
3. Three-Axis/One-Axis Probe, Automated 2D Stage
4. Three-Axis/One-Axis Probe, Manual 2D Stage

Three-Axis Probe (Single Pass): A complete scan of a magnet utilizing the 3-axis probe would require a scan of each point on a 2D plane for the field parallel to the z-axis and another for the x- or y- axis field. The probe could be scanned along the z-axis, building a profile of the magnetic field layer-by-layer.

One-Axis Probe (Multiple Pass): A complete scan of a magnet utilizing the 1-axis probe would require a scan of each point on a 2D plane for the field parallel to the z-axis and another for the x- or y- axis field, followed by rotating the probe or sample by 90 degrees parallel to the sampling plane to sample the orthogonal field. The probe could be scanned along the z-axis, building a

profile of the magnetic field layer-by-layer. As the test setup changes when the probe is rotated, it would be most efficient to build up the full *z*-axis profile for each orientation before changing orientations.

Automated 3D Stage: An automated 3D stage would allow us to get consistent, non-assisted results. This would be the simplest method to characterize multiple magnets. The stage would be constructed from an adapted 3D printer, with the probe in place of the extruder. Some components would also need to being replaced with different versions made of material that would not interfere with the magnetic readings. The stage dimensions from the 3D printer are 195 mm × 195 mm × 140 mm, and the accuracy of movement is between 0.01 mm and 0.02 mm.

Automated 2D Stage: An automated 2D stage would require user calibration for the distance from the probe to the surface, introducing significant time and effort between scans. There would, however, not be a need to custom-build a 3D stage using a 3D printer.

Manual 2D Stage: A manual 2D stage would require user calibration for the distance from the probe to the surface as well as the *x*- and *y*-axis positioning. This would require very significant time and effort between scans, and repeatability and accuracy would be challenges. There would, however, not be a need to custom-build a 3D stage using a 3D printer.

Conclusion

Self-Assessment

Apart from the projects I completed this summer, I learned a lot about accelerators and laser systems, as well as photolithography and nanotechnology, by assisting and observing my team members in their work. I gained valuable experience working in a laboratory setting with teams of other engineers and scientists. My internship at the Colorado State University Accelerator Laboratory this summer was a great experience, and I am glad that I could contribute to the important work being conducted here. I would definitely recommend the experience to other high-school students interested in combining both physics and engineering skills in real-world application projects.

Acknowledgements

Along with my team here at the Colorado State University Accelerator Laboratory, we wish to thank the University of Twente and the Boeing Company for gracious donating the linear accelerator and laser, respectively. We also wish to thank the SLAC National Accelerator Facility for loaning us the X-Band structure, and Argonne National Laboratory for donating several RF cavities. Our work is supported by Colorado State University, the Office of Naval Research, and the High-Energy Laser Joint Technology Office. We thank these sponsors for their support. Finally, we wish to thank the senior management of Colorado State University for their support of the Accelerator Laboratory and accelerator education.

On a personal note, I would like to express my appreciation to Dr. Biedron and Dr. Milton for giving me this opportunity to learn a lot about accelerator research and for making me feel so comfortable at CSU. I feel very honored to have been part of the team constructing the particle accelerator and to have been a student research assistant in such a fascinating and important scientific field. I would also like to thank Dr. Marconi and doctoral student Wei Li for all their support and kindness in teaching me about the photolithographic processes and about conducting research in a laboratory setting.

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