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School of Engineering

*Functional Nanomaterials*



# ***SURP 2021***

UCLA SAMUELI SUMMER UNDERGRADUATE RESEARCH PROGRAM



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## DEAN'S MESSAGE



**Ronald and Valerie Sugar Dean**

The Summer Undergraduate Research Program (SURP) provides an intensive summer research experience in a wide range of engineering and physical science fields. Undergraduate students from all walks of life participate in research with UCLA Samueli School of Engineering faculty to gain real-world lab experience.

Due to the COVID-19 pandemic that is still affecting us this summer, SURP has had to transition the program into a remote learning environment for many of its scholars. Despite this challenge, SURP's many scaffolding resources and social events have still been able to occur and students were able to:

- Conduct research in a cutting-edge field at a world-renowned research institution.
- Meet and network with a community of peers who have similar goals and interests.
- Create a professional scientific poster and publish a research abstract.
- Learn to communicate research outcomes and present a detailed Summary of Project.
- Gain a competitive advantage for engineering graduate schools.
- Learn how you can impact your community as an engineer.

This year, a record 66 undergraduate students were selected to join the 2021 SURP cohort, spread out across 31 faculty in 6 engineering departments. We are happy to announce 64% of these are women, 20% are underrepresented minorities, and many are first generation and low income students. SURP is involved with ongoing efforts in fostering a more diverse, equitable and inclusive community at UCLA Samueli Engineering.

Creating new knowledge is a very difficult yet important task, and these high-performing students have done an outstanding job working through the rigors of academic research. These students should be very proud of all that they have accomplished in a short time this summer. I encourage you to explore our publication and learn about all the cutting-edge knowledge that is being created here.

Sincerely,

A handwritten signature in black ink, appearing to read "Jayathi Murthy".

Dr. Jayathi Murthy  
Ronald and Valerie Sugar Dean

Arlene Constantino



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# LiDAR Data Classification Using Convolutional Neural Network Based on Pointnet Architecture

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**ABSTRACT**

Convolutional neural networks are the state-of-the-art algorithm for object classification. Due to the various types of objects that are processed and to facilitate training, typical convolutional neural networks (CNNs) require data preprocessing like zero padding or 3D to 2D space projections and do not work with point cloud data. Light Detection and Ranging (LiDAR) is one of the main technologies used in self-driving cars and terrain mapping. Since LiDAR uses time of flight from laser beams to create a 3D map of the area, the generated data is a point cloud. In order to solve these problems, here we present an implementation of CNNs using a modified PointNet architecture. PointNet architecture is directly capable of taking a point cloud and running it on the classification algorithm, which is much more efficient than transforming the data before being fed to the network. In this study, we optimize the said convolutional neural network based on PointNet architecture. We train the model using LiDAR data taken in Westwood and tune its parameters accordingly to achieve close to state-of-the-art performance. As of now, in preliminary testing, the model achieves an 89.82% training accuracy. The goal is to further achieve a model that can be able to map external environments to aid driver-safety and autonomous navigation.

## LiDAR DATA CLASSIFICATION USING CONVOLUTIONAL NEURAL NETWORK BASED ON POINTNET ARCHITECTURE

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### Introduction

Convolutional neural networks (CNNs) are state-of-the-art algorithms for object classification. However, typical CNNs do not directly process data in irregular formats, like point clouds, as an input.

A **point cloud** is a set of 3D points which represent arbitrary objects. It is the data generated by using **Light Detection and Ranging (LiDAR)** since it uses the time of flight to create a 3D map of the area. Working with point clouds requires dimensionality data transformations before being fed to the network because of its irregular size and shape.

This data preprocessing can make LiDAR data classification memory and time expensive. To accomplish the task efficiently, we implemented **PointNet based architecture**, which directly consumes point cloud data.

### Objective

To optimize a convolutional neural network based on PointNet architecture to achieve a similar state-of-the-art performance.

### Significance

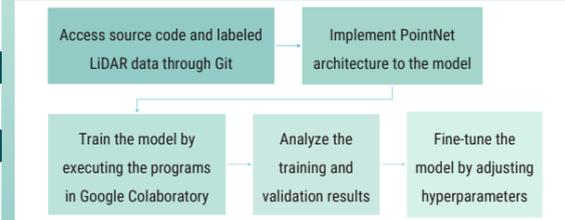
The network will be used to accurately classify objects seen in LiDAR data taken in Westwood. And eventually, be used to map our external environments to aid driver-safety and autonomous navigation.

### Materials

- Codes are written in Python
- Source code and the labeled LiDAR data are accessed through Git
- Programs are executed in Google Colaboratory



### Methods



### PointNet Architecture

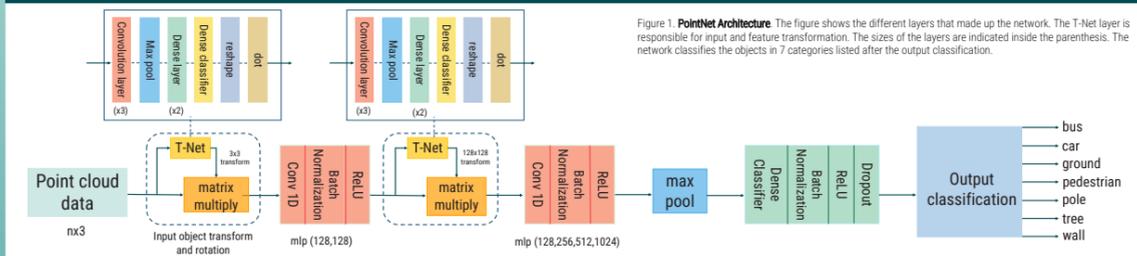
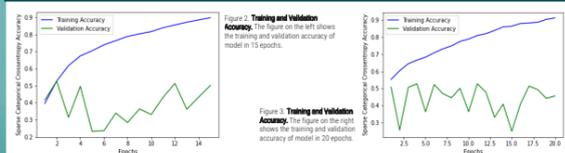


Figure 1 **PointNet Architecture**. The figure shows the different layers that made up the network. The T-Net layer is responsible for input and feature transformation. The sizes of the layers are indicated inside the parenthesis. The network classifies the objects in 7 categories listed after the output classification.

### Results and Discussion



We implemented a PointNet based architecture using CNN for classifying LiDAR data. We ran multiple models with different hyperparameters such as learning rate, number of epochs, and dropout rate. Initially, the network was trained in 11,047 clusters with 6 categories. As a result, the model achieved an 89.82% training accuracy and a 59.38% validation accuracy, seen in Figure 2. Afterward, car clusters were retrieved, and the data increased to 11,770 clusters with 7 categories. In Figure 3, the training accuracy went up to 91.25%.

As seen in the figures above, there is a distinct gap between the training accuracy and validation accuracy. Presented above are preliminary results as further work needs to be done to achieve state-of-the-art performance.

### Conclusion

In this project, we developed a model based on PointNet architecture that performs LiDAR data classification. The network classifies the objects seen in LiDAR data in 7 categories: bus, car, ground, pedestrian, pole, tree, and wall. In preliminary testing, the model achieves a training accuracy of 89.82% in 6 categories and 91.25% in 7 categories. In conclusion, further work is needed for the model to map our external environments to aid driver-safety and autonomous navigation. Labeling more clusters for some categories, especially cars and buses, would be beneficial for the model.

### References

- [1] C. Qi, H. Su, et al. *PointNet: Deep Learning on Point Sets for 3D Classification and Segmentation*, arXiv preprint arXiv:1612.00593v2 (2017).
- [2] F. Chollet. *Deep Learning with Python*. Manning Publications Co. (2018).

### Acknowledgement

I would like to thank Dr. Chee Wei Wong, Arturo Hernandez, and the Summer Undergraduate Research Program for this research opportunity. I would also like to thank the National Science Foundation (NSF) for funding the project. Additionally, I would like to acknowledge Jaime Flor Flores and Noah Himed for their help and guidance throughout the program.



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# Wearable & Mobile Bioanalytical Technologies for Personalized Medicine

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## ABSTRACT

Exponential growth in Internet of Things (IoT) devices and wearable sensing technologies has created an unprecedented opportunity to enable personalized medicine through real-time individual biomonitoring. Although these commercialized platforms are capable of tracking physical activities and vital signs, they fail to access molecular-level biomarker information which provide insight into the body's dynamic chemistry. Thus, as sweat is a rich source of biomarkers that can be retrieved unobtrusively, sweat-based wearable biomonitoring has since emerged as one of the most promising candidates to merge this gap. By designing and integrating compact electrochemical sensors into wearable electronic devices, we can non-invasively and accurately track specific biomarkers in sweat and provide actionable feedback about users' health status. We develop a signal modulation strategy to stimulate our electrochemical sensors for wearable biomarker monitoring. We also design a novel sensor readout methodology for improved and accurate biomarker tracking. Then, we integrate these designs into a wireless electrochemical readout circuitry to noninvasively track intended biomarkers. As a result, we successfully demonstrate our signal modulation solution's efficacy through electrodeposition of prussian blue films. Additionally, we show this sensing methodology improves signal readout and sensitivity by 3 times. Thus, we can non-invasively track subjects' biomarkers and underlying health status in a wireless and wearable format. This platform can further be utilized for real-time glucose monitoring in diabetic patients without requiring conventional painful extraction methods, or monitoring lithium levels in bipolar patients for drug abuse/compliance.

# Wearable & Mobile Bioanalytical Technologies for Personalized Medicine

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### INTRODUCTION

The exponential growth in Internet of Things (IoT) devices and wearable sensing technologies have created an unprecedented opportunity to enable personalized medicine. Although commercialized IoT devices and wearable sensors are capable of tracking physical activities and vital signs, they fail to access molecular-level biomarker information that provide insight into the body's dynamic chemistry. Sweat-based wearable biomonitoring has since emerged as one of the most promising candidates because sweat is a rich source of biomarkers that can be retrieved unobtrusively<sup>1</sup>. However, a series of wearable sensors and electronic systems need to be designed to provide access to these biomarkers and realize wearable sweat sensing.

### OBJECTIVES

1. Define a signal modulation strategy to stimulate our electrochemical sensors for wearable biomarker monitoring.
2. Develop a novel sensor readout methodology for improved and accurate biomarker tracking.

### TECHNICAL TERMS

**Near Field Communication (NFC):** Inductive coupling between a reader and a tag  
**Cyclic Voltammetry (CV):** Detect the electrochemical properties of biomarkers at the sensor for accurate sensing.

### PRINCIPLES

Figure 1: a) Induced CV at the sensors. b) Modulated signal transmission through NFC.

### OUR WEARABLE TECHNOLOGY

Figure 2: Flow chart of the proposed readout circuitry.

The flexible reader circuit delivers power to and communicates with the flexible tag on the skin. The circuitry of the tag then rectifies the modulated signal to scan the sensors.

### MATERIALS

**Circuit Simulation:** LTSpice, Microsoft Excel  
**Sensor & System Development:** Lithium (Li) solutions, Li Ion-Selective-Electrodes (ISE sensors), a commercial potentiostat, custom-developed flexible printed circuit board (FPCB), and electronic components.

### METHOD FOR SENSOR TESTING

1. Choosing & preparing Li concentrations
2. Preparing Li sensor
3. Setting up sensor and reference
4. Experimental setup and testing

### CIRCUIT SIMULATION PROCESS

1. Oscillator, EMC filter, match network characterizations
2. Evaluate the signals at different nodes
3. Use Excel to plot the amplitude modulated signal

### SENSOR STIMULATION METHODS

Figure 3: Signal modulation circuitry generating a spectrum of sine waves at 13.56 Mhz.

To realize the waveform for CV, we specifically designed the circuit to modulate voltages for analyte detection.

Figure 4: Simulated waveform at the reader showing effect of programming a trimmer at the EMC filter on modulating and generating the intended waveform.

Accordingly, we can modify the reader to demonstrate the accuracy and application of our design.

### SENSOR DEVELOPMENT

Figure 5: Equivalent circuit for ISE sensors<sup>1</sup>.

**ISE Sensor Technical Terms:**  
Rm: solution resistance  
Cg: geometric capacitance of the electrode  
Csc: fabricated sensor's capacitance  
ISE: acts as a transducer which converts ion activity into electric potential for biomarker sensing

Figure 6: Transient current waveforms following the reduction of the internal capacitance.

We utilize ISE sensors to perform biomarker sensing in sweat and in a wearable format. Understanding of the equivalent circuit portrays how the sensor works and interacts with the tag.

The sensors demonstrate a transient response due to the internal capacitance of the sensor (Csc) causing shift in the readout signal. By adding an external real capacitance in the circuit we can suppress this transient response and stabilize sensor measurement, decreasing potential drift.

Figure 7: Circuit diagram of ISE with added capacitance.

As demonstrated in Fig. 6, by incorporating a real capacitance into the circuit, we can reduce the internal capacitance of the sensor for improved and accurate sensing results.

### RESULTS

Figure 8: Results for a) improved sensor signal readout method and b) effective signal modulation.

We observed improved sensitivity in Li readouts by manipulating the internal electrochemical capacitance of the ISE sensor and successfully deposited Prussian Blue on the gold electrode as an indication of correct application of CV amplitude modulation by the circuit.

### CONCLUSION & FUTURE WORK

1. Achieved wireless CV scanning of sensors enabling active biomarker sensing in a series of electrochemical sensors.
2. Improved the tag's sensitivity to current drifts of ISE sensors through specific adjustment of internal capacitance.

This system can further be utilized to track and monitor biomarker profiles in biological media and enable a tracking systems for the healthcare system to realize personalized medicine.

### REFERENCES

[1] Emaminejad, Sam, et al. "Autonomous sweat extraction and analysis applied to cystic fibrosis and glucose monitoring using a fully integrated wearable platform." PNAS (2017): 201701740.

### ACKNOWLEDGEMENTS

We would like to thank the National Science Foundation for funding our project through the UCLA Summer Undergraduate Research Program. Additionally, we would like to thank Professor Emaminejad, our PhD student advisor Hannaneh Hojajji for her advice and support, and Will Herrera for his guidance throughout the research program.



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# A Process for Implementing Accessible Cardstock-made Robot Cars Equipped with A Variety of Robotic Behaviors

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## ABSTRACT

As the world rapidly turns to robots, it is important to make robot creation ubiquitous, but there are barriers – accessibility and limitation of resources – that inhibit such phenomena. In this study, we proposed and tested a possible solution that can lessen those barriers by building origami robots made with accessible resources. Origami is defined as the Japanese art of folding. To test our hypothesis, we implemented a process that fabricates origami robot cars made from single-layered materials like cardstocks while ensuring that these cars can still carry out several robotic behaviors. The process includes gathering accessible hardwares, programming behaviours using Arduino, designing the origami-inspired body of the car using LEMUR's RoCo, and testing the car to determine if its origami-structure can handle the programmed robotic functionalities: driving on a variety of surfaces, using differential and pivot steering, detecting obstacles, implementing PID control through IMU and visual sensors, and enabling communication with other robots through mesh networking. The scheme yielded robot cars that are useful and fairly accessible with cardstock-made bodies and with a variety of robotic behaviours as mentioned above. The result of our study justifies that the implementation of origami robots has a huge potential in terms of lessening the resource-related barriers of robot creation which increases both the number of people who can build robots and the probability of robot creation being ubiquitous.

**UCLA** **ORIGAMI ROBOTS:**  
A Process for Implementing Accessible Cardstock-made Robot Cars Equipped with A Variety of Robotic Behaviors  
Jillian Naldrien Pantig | Dr. Ankur Mehta  
The Laboratory for Embedded Machines and Ubiquitous Robots

**GOAL**  
To lessen the barriers to robot creation, **accessibility and limitation of resources**, by implementing a process that fabricates origami robot cars made from cardstocks while ensuring that these cars can still carry out several robotic behaviors.

**AN ACCESSIBLE ROBOT COMPILER**  
RoCo: Robot Compiler  
One of the main resources used in this study is **UCLA LEMUR'S RoCo**, which stands for Robot Compiler.

**PROCESS**

**1 GATHER MATERIALS**  
accessible hardware  
cardstock

**2 DEVELOP FUNCTIONALITIES**  
FUNCTIONALITIES  
MOVEMENT: Differential and pivot steering  
SWARM CONTROL: Mesh Networking  
FEEDBACK CONTROL: IMU, Lidar, and Vision  
an example of how the hardware will be assembled to fit the functionalities

**3 DESIGNING CAR'S BODY (ROCO)**  
DRAW AND MEASURE  
CODE  
CUT  
GENERATE  
INTEGRATE AND ASSEMBLE

**TESTING AND RESULTS**

**ACTUATION**  
REACT APP – DASH  
CONTROLLING THE CAR USING A JOYSTICK + SEEING DATA FROM THE CAR (E.G., SENSOR DATA)

**FEEDBACK CONTROL**  
INERTIAL MEASUREMENT UNIT  
TO MAKE THE CAR DRIVE STRAIGHT (PID)  
cars not driving straight → corrected using IMU PID

**LIDAR**  
USED FOR OBSTACLE DETECTION.  
does not detect obstacle – car moves  
detects obstacle less than 100mm – car stops

**VISION**  
FOR PID, OBSTACLE DETECTION, AND FOLLOWING  
green car with a camera follows red blob (red cup) from a car that is being controlled with a joystick

**SWARM**  
GETTING INSTRUCTIONS FROM ANOTHER MICROCONTROLLER  
microcontroller with camera from above controls cars to go to target April tags

**CONCLUSION**  
This study has accomplished the following:  
• Lessened the barriers to robot creation by using accessible and efficient resources – cardboard and hardware that can function in many ways  
• Established a process of testing origami robots through actuation, feedback control, and swarm  
• Allow for robot creation in several areas: academic and entertainment

**FUTURE PLANS**  
• Adding and designing more objects such as a robotic arm  
• Making the process low-cost such that it can yield robots that cost less than \$20

**ACKNOWLEDGEMENT**  
I would like to thank the following people who made this research possible:  
Dr. Ankur Mehta, William Herrera, National Science Foundation, Summer Undergraduate Research Program, Team Arnhold – Jashoon Song, Marisa Duran, Grace Kwak, Sudarshian Seshadri, Bhavik Joshi, and Kamil Hassan, AND UCLA LEMUR.

REFERENCES  
[1] J. N. Pantig, A. Mehta, "Origami Robots: An Integrated Design and Fabrication Strategy for Embedded Mechanical Systems," November 16, 2020.

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# Expanding Human-Computer Interaction via Object Recognition Implemented into a Hand Signal Actuated Robotic Arm (SARA)

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## ABSTRACT

Human-computer interaction (HCI) has advanced the efficacy of a multitude of sectors such as communication and consumerism. However, there exists a gap where most HCI research is conducted to improve quality in industrial aspects rather than personal aspects. Our research extends HCI to improve quality of life by designing and implementing a hand signal response AI into a six degree of freedom (6DoF) robotic arm. We call this our hand signal actuated robotic arm, SARA. An implementation of forward kinematics (FK) and inverse kinematics (IK) in python allows the robotic arm to actuate in response to complex hand signals, made possible via our hand recognition software. This software presents a real-time object-tracking process that recognizes hand signals by finger landmark mapping. A rule classifier distinguishes different variations of raised fingers. To confirm mechanical actuation and limitations, we developed a simulator in MATLAB using a virtual robotic arm that parallels SARA. Our research ultimately produced a design that, when implemented, gives SARA the capability to react to diverse hand signals independently. Qualitative demos conducted with a variety of hand signals validated our research design and implementation. A set of thirty-two hand signals was displayed to SARA that resulted in successful actuation in accordance with the simulator. The application of this design aims to assist individuals with physical limitations, making HCI more personal. The success of implementing a hand signal response AI makes the interaction with a robotic arm intuitive, ultimately expanding the scope of HCI to enhance the human experience.

# Expanding Human-Computer Interaction via Object Recognition Implemented into a Hand Signal Actuated Robotic Arm (SARA)

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### Introduction

Human-computer interaction (HCI) has advanced the efficacy of a multitude of sectors such as communication and consumerism. However, there exists a gap where most HCI research is conducted to improve quality in industrial aspects rather than personal aspects. Previous research has shown that it is possible to enhance HCI by integrating robotic arms into the human body.[1]

The focal point of our research involves a robotic arm, which is a mechanical appendage consisting of 6 anthropomorphic joints.

### Methods

**Step 1: Coding in Python**

- Utilizing the library MediaPipe, we implemented a hand tracking and signal recognition software
- Using FK and IK concepts, we created software that outputs the six joint angles with an input of a position
- Referencing the motor documentation, we created code to actuate SARA to our preferences

**Step 2: Simulator**

To confirm mechanical actuation and limitations, we developed a simulator in MATLAB using a virtual robotic arm that parallels SARA. This was written with the help of Peter Corke's Robotic Toolbox.

**Step 3: Experimental**

In-lab qualitative demos conducted with a variety of hand signals enhanced our research design and implementation. Actuation was observed, recorded, and analyzed. The code was optimized based on the previous results.

### Results

Below are specific results obtained from our research. The first of each set of images is the hand signal displayed to SARA. The middle image contains the simulated positions and joint angles obtained through our simulator. The last image is what SARA has actuated to after processing the hand signal shown to it.

Similar to the results shown above, an additional twenty-nine hand signals were displayed to SARA that resulted in successful actuation in accordance with our simulator.

### Objective

Our research extends HCI to improve quality of life by designing and implementing a hand signal response AI into a six degree of freedom (6DoF) robotic arm. We call this our hand signal actuated robotic arm, SARA. Using SARA, we aim to bridge the gap between humans and computers.

### Principles/Concepts

**Forward Kinematics (FK)**

is the mathematical process that allows us to find the position and orientation of the end effector on the X, Y, and Z axes from the joint angles.

Figure 1 shows the relationship between joint angles ( $\theta_1, \theta_2, \theta_3$ ) and the position of the end effector through FK.[2]

**Inverse Kinematics (IK)**

is the mathematical process that allows us to find the joint angles from the X, Y, and Z coordinates of the end effector.

Figure 2 shows the relationship between the position of the end effector and the joint angles ( $\theta_1, \theta_2, \theta_3$ ) through IK.[2]

### Mathematical Methods

**DH Parameters**

A DH parameter table was used to find the end-effector position, via FK. The DH parameters consist of four factors: 1. link length, 2. link twist, 3. link offset, 4. joint angle. These factors can be inserted in the following table:

Joints	Theta	Link Twist (alpha)	Link length(l)	Link Offset (d)
0 - 1	$\theta_1$	$90^\circ$	2"	0"
1 - 2	$\theta_2$	$0^\circ$	6.75"	0"
2 - 3	$\theta_3$	$0^\circ$	8"	0"
3 - 4	$\theta_4$	$90^\circ$	0"	0"
4 - 5	$\theta_5$	$90^\circ$	0"	0"
5 - 6	$\theta_6$	$90^\circ$	0"	0"

**Rotation Matrix**

Rotation matrices were derived from the DH Table above. The following formula shows the relationship between the different matrices:

$$R_6^3 = R_3^{0-1} R_6^0$$

The formula corresponding to the rotation for joints 3-6 is:

$$R_6^3 = \begin{bmatrix} -s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 & s\theta_3 c\theta_4 c\theta_5 - c\theta_3 c\theta_4 & -s\theta_3 s\theta_4 & c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & -c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & -s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 \\ c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & -c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & -s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 & s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 & c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 \\ -s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 & s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 & c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & -s\theta_3 s\theta_4 & c\theta_3 c\theta_4 c\theta_5 - s\theta_3 s\theta_4 & -s\theta_3 c\theta_4 c\theta_5 - c\theta_3 s\theta_4 \end{bmatrix}$$

The formula to find all theta angles is:

$$\theta_1 = \tan^{-1}(y/x)$$

$$\theta_2 = \tan^{-1}(s_3/c_3)$$

$$\theta_3 = \tan^{-1}(\frac{(c_3 a_3 + a_2)(z - s_2 4a_4) - s_3 a_3 (x c_1 + y s_1 - c_2 4a_4)}{(c_3 a_3 + a_2)(x c_1 + y - c_2 4a_4) + s_3 a_3 (z - s_2 4a_4)})$$

$$\theta_4 = 234 - 2 - 3$$

$$\theta_5 = \tan^{-1}(\frac{c_2 34 (c_1 a_3 + s_1 a_2) + s_2 34 a_2}{s_1 a_3 - c_1 a_2})$$

$$\theta_6 = \tan^{-1}(\frac{-s_2 34 (c_1 a_3 + s_1 a_2) + (c_2 34 a_2)}{-s_2 34 (c_1 a_3 + s_1 a_2) + (c_2 34 a_2)})$$

\* s = sin, c = cos, x, y, z = end position; # =  $\theta_n$ , a = link length; O = link twist; n = origin

### Conclusion

In this research, we successfully implemented a hand signal recognition AI, an accurate simulator, and actuation with FK and IK. Our research ultimately produced a design that, when implemented, gives SARA the capability to react to diverse hand signals independently.

**Impact**

This design aims to assist individuals with physical limitations, making HCI more personal. This ultimately reduces the communication gap between computers and humans.

**Future Work**

Continued research of signal recognition could explore the possibility for machines to read and react to human emotions. Future studies may involve the expansion of the SARA prototype to include an applicable end effector, such as a gripper or other tools.

### References

[1] Sasaki, Tomoya, et al. "MetaArms: Body Remapping Using Feet-Controlled Artificial Arms." The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings, 11 Oct. 2018, pp. 65-74, doi:10.1145/3286037.3271628.

[2] "Forward and Inverse Kinematics Part 1." YouTube, August 3, 2011, https://www.youtube.com/watch?v=Vjsu8T4NpXk

### Materials

- Python IDE Pycharm
- Python Library MediaPipe
- R+ Manager
- a six degree of freedom (6DoF) robotic arm
- six Dynamixel XM540 motors
- 11.1 V Battery
- Peter Corke's Robotics Toolbox MATLAB

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# Flexible Printed Circuit Boards for Panofsky Quadrupole Electron Beam Guiding

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## ABSTRACT

Electron beam therapy (EBT) utilizes electrons to kill cancer cells with up to 60% less radiation affecting surrounding healthy tissue compared to photon-based radiation therapies. EBT typically uses cm-scale beams; this project focuses on using Panofsky quadrupoles to guide sub-millimeter beams in a flexible and changeable trajectory so that beam placement, and therefore treatment outcomes, are improved. Flexible Printed Circuit Boards (PCBs) were designed in a Panofsky quadrupole-like geometry, which consists of parallel copper traces that generate a quadrupolar magnetic field. The flexible material of the PCB allows for manipulation of electron beams in hard-to-reach areas for deeper tissue treatment. Joule heating of the PCBs was simulated in COMSOL Multiphysics, and the limiting current density extracted. The limiting current density was used in magnetostatic simulations to find the magnetic characteristics of these devices. Particle tracing simulations were then performed to investigate efficiency of guiding electrons at different curvatures of the flex-PCB. Flex PCBs were fabricated for testing and the thermal response of the PCBs was experimentally measured using a FLIR OnePro thermal camera.

# Flexible Printed Circuit Boards for Panofsky Quadrupole Electron Beam Guiding

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Introduction	Materials and Methods	Test Results
<p><b>Flexible printed circuit boards</b> were designed, simulated, and tested for potential use in <b>Electron Beam Therapy (EBT)</b> treatments.</p> <p>EBT is a cancer treatment currently administered to patients around the world. It is highly effective and valued for its ability to treat tumors without causing excessive damage to surrounding healthy tissue. This makes EBT ideal for surface tumors, but treatment can improve with greater precision and control of electron beam placement.</p>	<p><b>01 CREATE A PCB DESIGN</b></p> <ul style="list-style-type: none"> <li>Determine magnetic properties of design using FEMM.</li> <li>Use Python to simulate electrons passing through multiple quadrupoles.</li> <li>Create Gerber files to send to the PCB factory for fabrication.</li> </ul> <p><b>02 SIMULATE IN COMSOL MULTIPHYSICS</b></p> <ul style="list-style-type: none"> <li>Joule heating of PCBs was simulated and current density limits extracted.</li> <li>The limiting current density was used in magnetostatic simulations to find the magnetic characteristics of these devices.</li> <li>Particle tracing simulations were then performed to investigate efficiency of guiding electrons at different curvatures of the flex-PCB.</li> </ul> <p><b>03 TESTING OUR DESIGNS</b></p> <ul style="list-style-type: none"> <li>PCBs were bought and tested with various amounts of current.</li> <li>Thermal response was recorded using FLIR OnePro thermal cameras.</li> <li>The results were compared to expected results from simulations.</li> </ul>	<p><b>Figure 6:</b> The test setup used consists of a 12V power supply (1), a buck converter (2), steel wire as a variable resistor, (3) and a multimeter to measure current (4). The quadrupole being tested is at (5).</p> <p><b>Figure 7:</b> (Left) A picture of the quadrupole under test, with alligator clips to provide current. (Right): A picture of the same quadrupole but imaged with a thermal camera. The PCB is getting slightly warm in the picture.</p>
<p><b>Objectives</b></p> <ul style="list-style-type: none"> <li>Design smaller, cheaper, and easier to manufacture quadrupoles using Printed Circuit Board (PCB) technology.</li> <li>Test characteristics of these PCB quadrupoles to determine if they are feasible for use in real applications using simulations.</li> <li>Check if the quadrupoles still work even if they are bent.</li> <li>Measure thermal response with manufactured PCB designs.</li> </ul>	<p><b>01</b></p> <p><b>02</b></p> <p><b>03</b></p>	<p><b>Figure 8:</b> A plot of the temperature of the quadrupoles versus the amount of current passing through them. The temperature increases quadratically with respect to the current as predicted by Joule's Law of Heating. Due to outgassing, only a temperature increase of 10 degrees is allowed. The data shows that pulsed power is necessary for our PCB quadrupoles to reach the required field strength, otherwise overheating would occur with DC currents.</p>
<p><b>Principles</b></p> <p>Electrons are influenced by magnetic fields. This behavior is demonstrated in this research project using flexible printed circuit board (Flex-PCB) technology to induce magnetic fields via electric current. Flex-PCBs used as <b>Panofsky quadrupoles</b> guide electrons, focusing them in one axial direction.</p> <p>A configuration of magnets as shown in Fig. 1 create a magnetic field focusing beams of charged particles.</p>	<p><b>Figure 3:</b> A cross sectional magnetic FEMM simulation of a flex-PCB Panofsky device with current running out of the page. The field lines are similar to that of an actual quadrupole.</p> <p><b>Figure 4:</b> Our heating simulation results (shown by the colored lines) versus experimental results (shown by the data points). The simulation tracks the experimental results closely.</p>	<p><b>Conclusions and Applications</b></p> <p>Flexible Printed Circuit Boards are viable for use in Panofsky quadrupole electron guiding, but they require pulsed power. Research can further explore the limitations of different designs and their use for Electron Beam Therapy application.</p> <p>The next step with this research would be to conduct real life tests with electron beams to determine how well the quadrupole directs beams. We could also determine how the quadrupole performs when bent at various angles. A suitable power supply for driving the quadrupole would also need to be designed in order to provide the pulsed power.</p> <p>In the future, better designs using thicker copper or using superconductors could be created to mitigate heating issues and allow for continuous operation without overheating. A separate cooling system using heat pipes to dissipate heat could also be used.</p>
<p><b>Figure 1:</b> A quadrupole created by four permanent magnets with magnetic field direction.</p> <p><b>Figure 2:</b> Magnetic force diagram of quadrupole configuration. Forces focus in vertical direction, and push away from the center in the horizontal direction.</p> <p>Quadrupoles can be created using either permanent or electromagnets. Electromagnets are generally preferred as they are more easily controlled, allowing adjustment of the amount of current going through to achieve a desired magnetic field strength.</p> <p>Quadrupole fields linearly vary with the distance from the beam axis. The field gradient of the quadrupole describes how fast the field strength changes with respect to distance from the center. A higher value for this parameter means that particles feel a stronger force towards/away from the center.</p>	<p><b>Figure 5:</b> Particle tracing with electrons traveling at 10 MeV. (Left) View from the side. The electrons are following the bent quadrupole (with a 1 meter radius of curvature), and the electrons are focusing at around the 0.03 meter mark. (Right) View from the top. The simulation clearly shows that the electrons are defocusing, as predicted.</p> <p><b>References</b></p> <p>D. C. Meecker, Finite Element Method Magnetics, Version 4.2 Magnetic field of an idealized quadrupole with forces.svg. (2021, June 1). <i>Wikimedia Commons, the free media repository.</i> Magnetic quadrupole moment.svg. (2020, September 27). <i>Wikimedia Commons, the free media repository.</i></p>	<p><b>Acknowledgements</b></p> <p>We appreciate the <b>National Science Foundation</b> for funding this research and thank the <b>UCLA SURP</b> for arranging this opportunity. We give special thanks to <b>Rob Candler</b> and <b>Benjamin Pound</b> for allowing us to assist with their great work.</p>

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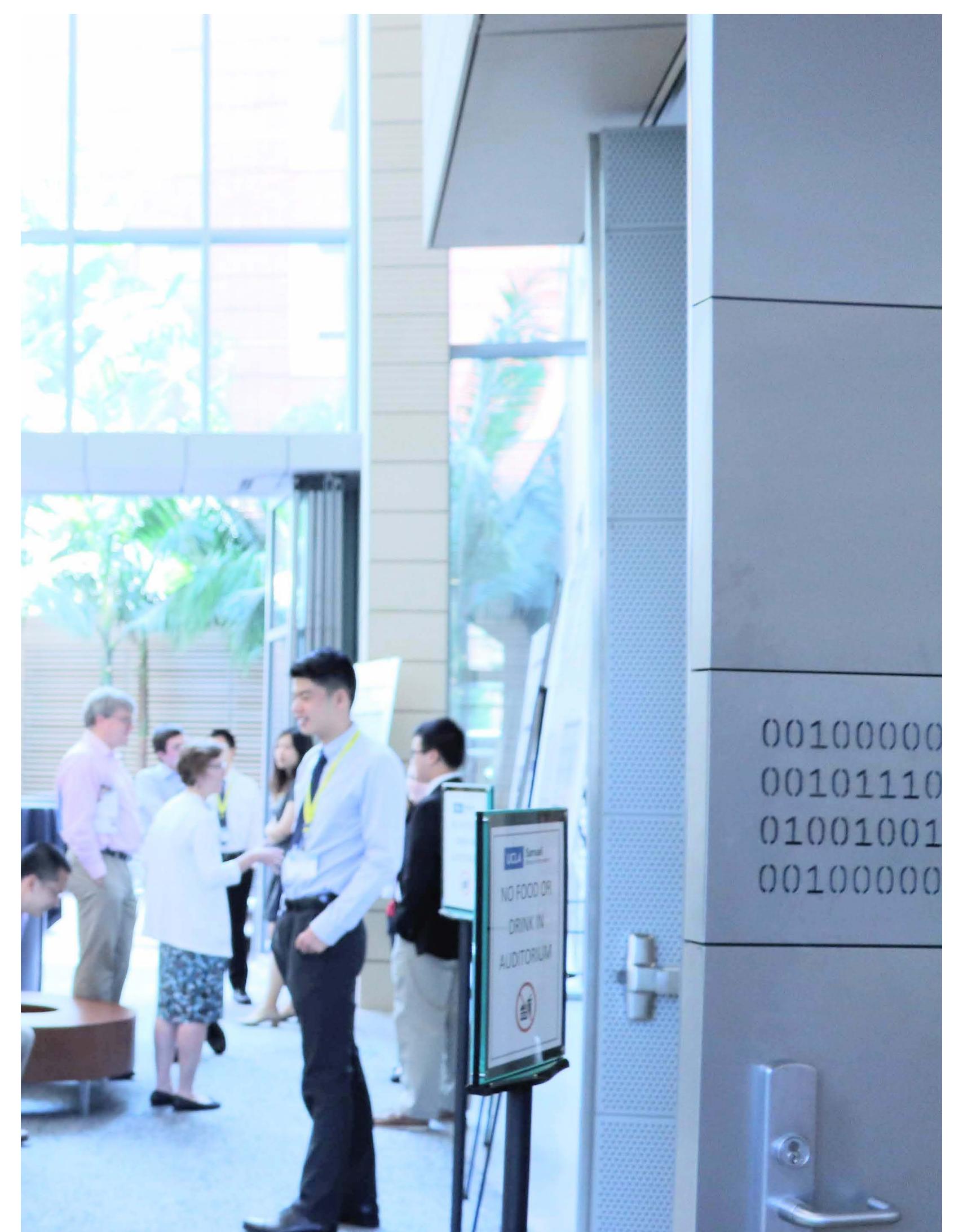
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