Development of an EEG-Based Brain-Controlled Mini Industrial Robotic Arm

Mahdi Yazdanpour, Leslie Ferrao, and Biplov Ale
Northern Kentucky University

Abstract

Advancements in the fields of neurotechnology and robotics have paved the way for the development of brain-controlled systems. This emerging technology utilizes the power of the human mind to directly interface with electromechanical devices, which enables remarkable levels of control and interaction. In this project, we developed a brain-controlled mini-industrial robotic arm which can be operated using an electroencephalography (EEG)-based brain computer interface (BCI) through the user's intentions or mental commands. Our BCI interacts directly with neurosignals captured from the brain using a wireless EEG brainwear. The system is trained to recognize the user's unique brain patterns associated with different commands. Our interface recognizes changes in brainwaves when the user imagines performing a specific movement. We process and classify these neurosignals and convert them to meaningful commands to control the robotic arm. Our desktop robot is adapted based on the open-source Zortrax robotic arm, incorporating Marlin firmware and Pronterface to monitor and control the robot operations by processing the G-code commands. This project aims to enhance human-machine interaction by integrating cutting-edge technologies into industrial automation. In addition, this project is designed to assist engineering technology students learn the integration of mechatronic system components, robot programming fundamentals, articulated robot configurations and movements, and the evolution of human–robot collaboration in modern industry.

Introduction

The integration of the electrical activities of the human brain with electromechanical devices to develop mind-controlled systems has become one of the most cutting-edge research topics in the fields of neuroscience, biomechatronics, human-computer interaction, robotics, and fourth industrial revolution known as Industry 4.0. This interdisciplinary effort brings together experts from different domains to explore the potential of connecting the human brain to electromechanical devices and pave the way for innovation and technological advancement in modern industry. In recent years, there have been significant advancements in the field of human-robot interaction and robotics, specifically in the integration of artificial intelligence algorithms and natural language processing techniques within the context of industrial automation, smart manufacturing, intelligent factories, and Industry 4.0 [1]. These developments have enabled industrial robots to understand and respond to human commands, leading to more seamless and effective communication between humans and machines. This progress has opened up new possibilities for applications in various domains, including healthcare, manufacturing, autonomous vehicles, and home automation, where human-robot collaboration plays a crucial role in enhancing efficiency and productivity. While our previous work primarily focused on indoor path planning for humanoid robots [2], [3], this paper explores the intersection of AI with robotics to address smart industrial automation and its transformative impact on modern manufacturing practices in the context of Industry 4.0. Our area of research focuses on developing mind-controlled robotic systems and brain computer interfaces that enable direct communication and control between the human brain and robots or other mechatronic devices. It holds significant potential for enhancing the capabilities of human-machine interfaces and revolutionizing related fields.

The key concept behind brain-controlled systems involves capturing and interpreting electrical signals generated by the human brain. These signals are produced by the firing of neurons in the brain and carry important information about an individual's intentions, emotions, and cognitive states. By employing advanced signal processing and machine learning techniques, researchers can decode and interpret these signals to extract meaningful commands or intentions.

Electroencephalography (EEG) is a monitoring method to record the electrical activity of the brain [4]. These signals are electrical fluctuations with a small amplitude in the microvolt range and at different frequencies, resulting from ionic current within the neurons of the brain. The EEG signals are classified into several distinct frequency bands, each associated with specific brain states and functions. The primary EEG frequency bands include delta (δ), theta (θ), alpha (α), beta (β), and gamma (γ). Delta waves (0.5-3 Hz) are the slowest brainwaves and are typically associated with deep sleep stages. Theta waves (3-8 Hz) are associated with drowsiness, daydreaming, and the early stages of sleep. Alpha waves (8-12 Hz) are prominent when a person is awake but relaxed with closed eyes. They are often associated with a state of calmness, relaxation, and meditation. Beta waves (12-38 Hz) are typically observed when a person is awake and engaged in active cognitive tasks or focused mental activities. They are associated with alertness and concentration. Gamma waves (38-42 Hz) are the fastest brainwaves and are associated with high-level cognitive functions, such as memory recall, perception, and problem-solving [5]. As shown in Table 1, each frequency band is associated with different mental states and cognitive processes.

Table 1. Types of human brainwaves and associated mental states.

Waves	**Frequency**	**State**	**Shape**
Delta	0.5 - 3 Hz	Deep Sleep, Dreaming	
Theta	3 - 8 Hz	Drowsiness, Deep Meditation	
Alpha	8 - 12 Hz	Restful, Physically and Mentally Relaxed	
Beta	12 - 38 Hz	Awake, Alert Consciousness, Active Mind, Attentive	
Gamma	38 - 42 Hz	Problem Solving, Learning, Concentration	

A brain-computer interface refers to the technology that enables direct communication between the neurosignals of the human brain and an external device, such as a computer or a robotic system. BCIs enable individuals to control or interact with external devices or systems using their brain activity, without need of traditional means or physical movements. BCIs work by recording and interpreting electrical or neurophysiological signals generated by the brain, typically through electroencephalography electrodes which can be non-invasive or implanted. These signals are then processed, classified, and translated into actionable commands that can be used to control a device such as a computer cursor, a robotic arm, a drone, a wheelchair, or even to compose text. There are several types of BCIs, including invasive BCIs (implanted directly into the brain), non-invasive BCIs (external sensors on the scalp or skin), and hybrid BCIs (combining multiple sensor types) [6]. In this project, we implemented a non-invasive EEG-based brain computer interface which can capture the EEG signals using a wireless EEG brainwear and convert them to significant commands to control a robotic system.

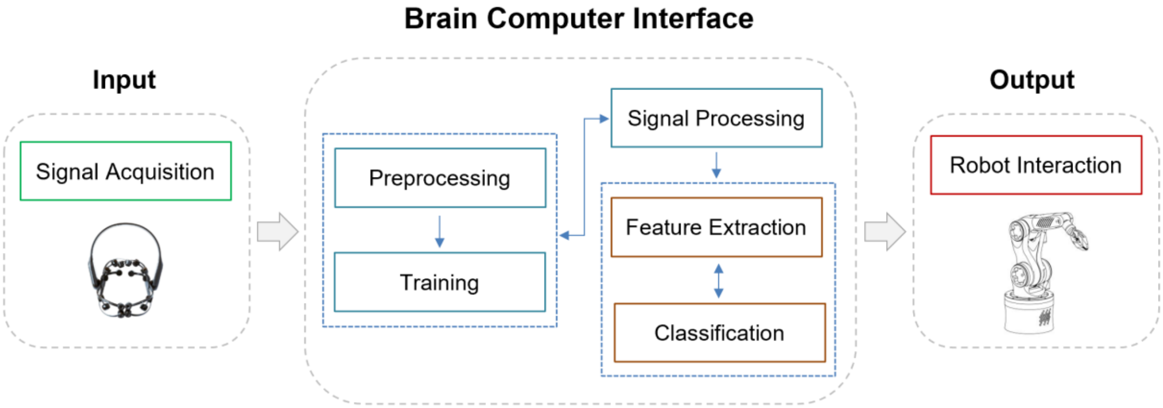


Fig. 1. The pipeline of our proposed brain computer interface.

Methodology

Our proposed pipeline for EEG-based brain computer interface, consisting of three subsystems, is shown in Fig. 1. We used a 14-channel wireless EPOC X headset [7] with saline-based electrodes for brain signal acquisition. A saline-based EEG headset is a type of electroencephalography headset that uses saline solution (saltwater) as the medium for electrode contact with the scalp. Saline electrodes, also known as wet electrodes, typically provide better signal quality because they rely on a conductive gel or saline solution to establish a low-impedance electrical connection between the scalp and the electrodes [8], [9]. This approach enhances the quality of the recorded EEG signals by minimizing signal distortions caused by impedance fluctuations and is well-suited for long-term EEG recording.

The 14-channel configuration indicates that the system employs 14 electrodes strategically placed on the scalp to capture the electrical signals generated by the brain. The position of our electrodes during EEG recording is shown in Fig. 2. These electrodes are specifically designed to pick up signals from distinct regions of the brain which allows for a more detailed and comprehensive analysis of brain activity compared to systems with fewer channels. Each electrode has a letter to identify the brain lobes. Prefrontal (Fp), frontal (f), temporal (t), parietal (p), and occipital (O). Even numbers refer to electrode placement on the right side of the head, whereas odd numbers refer to those on the left.

Our interface operates through pattern recognition-based classification and requires training sessions for each user to learn and recognize the patterns of brain activity related to their command state. During the training process, the user generates or modulates specific brain signals by imagining particular movements or focusing on specific thoughts. This step helps the brain computer interface to adapt the user's unique brain activity patterns in different mental states. These mental commands enable specific control through trained recognition of the user's thoughts. We store the training dataset for mental commands in training profiles when users imagine performing specific movements, such as rotate, left, right, up, and down. The accuracy of the interface increases as the user goes through more training sessions.

Once the EEG signals are acquired, they go through signal processing and feature extraction steps to identify meaningful patterns of the recorded signal. This step involves filtering out noise or unwanted signals and enhancing the quality of the EEG data. The extracted features are then fed into classification algorithm which are trained to recognize and classify different brainwave patterns. Once the BCI system has been trained, it can be used for real-time operation. During this phase, the user's EEG signals are continuously monitored and processed in real-time. The classification algorithm determines the user's intended command or action when they imagine a specific movement based on the extracted features, and the corresponding command is then executed by the external device or system.

Fig. 2. EPOC X EEG headset and the position of the EEG electrodes on the scalp [7].

Our desktop robotic arm is configured based on the open-source Zortrax [10] model and is completely printed using a Fused Filament Fabrication (FFF) 3D printer. This desktop-sized pick-and-place machine has five movable axes: V, W, X, Y, and Z, as shown in Fig. 3, with three of them being electrically driven: X, Y, and Z. The whole mechanism is based on three high-performance (National Electrical Manufacturers Association, size 17) bipolar stepper motors which are combined with A4988 microstepping drivers that allow the robot to produce the sequence of automatized movements on three axes X, Y, and Z.

A combination of an Arduino Mega 2560 board and a RAMPS 1.4 driver shield has been used as the main control unit for this robot, as shown in Fig. 5. The RAMPS board provides additional functionality and compatibility with various motor driver modules which makes it suitable for robotic applications that require precise motor control. The RAMPS 1.4 board interfaces with the Arduino Mega and facilitates the connection of stepper motors, endstops, and other peripherals required for robotic movement and control.

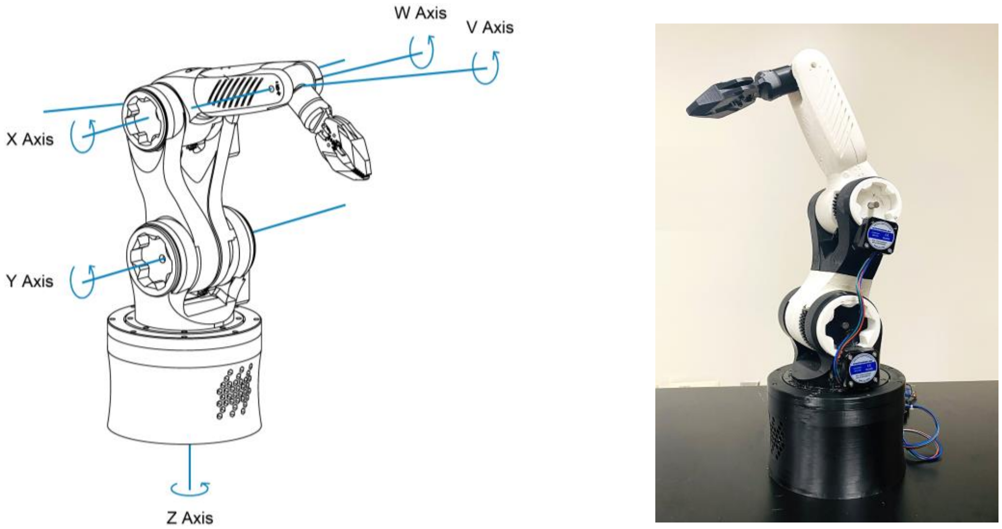
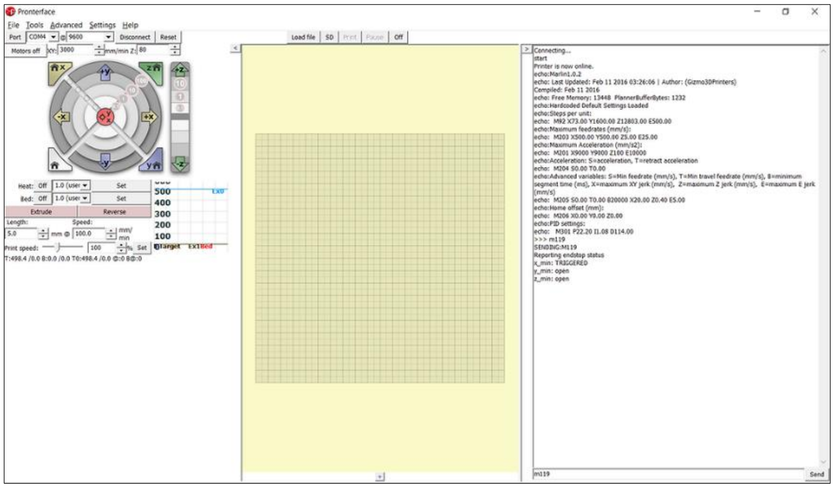


Fig. 3. Zortrax robot axes [10] and the 3D printed robotic arm.

The open-source Marlin firmware [11] with Pronterface [12] has been used to control the real-time activities of the machine by receiving the geometry code (G-code) commands. Pronterface is an open-source graphical user interface, licensed under the GNU General Public License that allows users to interactively monitor and control the machine by executing the G-code commands, as shown in Fig. 4. Marlin is an open-source firmware developed for Atmel AVR microcontrollers that translates G-code to electrical signals to control stepper motors. It interprets the commands and converts them into motor movements, which enables the robot to move in different directions along the X, Y, or Z axes. In addition to basic motor control, the Marlin firmware offers additional functionalities that enhance the precision and efficiency of the robot’s movement.

The Pronterface interface plays a prominent role in controlling the direction and speed of the robotic arm. It serves as an intermediate between the operator and the robotic arm and facilitates command input and parameter adjustment for movement control. The neutral position starts by referencing the robot at the initial home position and then moves it to a standing position. Different G-codes are written to control the stepper motors and instruct the robot to move along one or multiple axes at the specified feed rate. These G-code instructions are transmitted to the robot control unit to instruct the motors on movement direction, speed, and the designated path to follow. We used this interface to call and upload our G-codes when the user thinks about a specific command, and to have precise control over the robot's direction, speed, and coordination. The software establishes a serial connection with the robot controller, allowing for real-time data exchange. This connection enables the user to send movement commands and receive feedback from the robotic arm, which provides a responsive and interactive control experience.

Through Pronterface, we were able to access the intuitive graphical interface that presents various controls and settings related to movement. These controls typically include options to specify the desired movement direction (X, Y, or Z axes), speed, acceleration, and step size. The software translates the operator's inputs into appropriate commands, which are then sent to the Marlin firmware. Finally, with the inspiration of how these software systems control stepper motors, we integrated our code to interpret signals from the EEG brainwear to control the robotic arm. Our brain computer interface enables users to command this mini-industrial robotic arm in different translational directions using the power of their minds, as shown in Fig. 6.



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Connecting...
start
Printer is now online.
echo:Marlin1.0.2
echo: Last Updated: Feb 11 2016 03:26:06 | Author: (Gizmo3DPrinters)
Compiled: Feb 11 2016
echo: Free Memory: 13448  PlannerBufferBytes: 1232
echo:Hardcoded Default Settings Loaded
echo:Steps per unit:
echo:  M92 X73.00 Y1600.00 Z12803.00 E500.00
echo:Maximum feedrates (mm/s):
echo:  M203 X500.00 Y500.00 Z5.00 E25.00
echo:Maximum Acceleration (mm/s2):
echo:  M201 X9000 Y9000 Z100 E10000
echo:Acceleration: S=acceleration, T=retract acceleration
echo:  M204 S0.00 T0.00
echo:Advanced variables: S=Min feedrate (mm/s), T=Min travel feedrate (mm/s), B=minimum
segment time (ms), X=maximum XY jerk (mm/s),  Z=maximum Z jerk (mm/s),  E=maximum E jerk
(mm/s)
echo:  M205 S0.00 T0.00 B20000 X20.00 Z0.40 E5.00
echo:Home offset (mm):
echo:  M206 X0.00 Y0.00 Z0.00
echo:PID settings:
echo:   M301 P22.20 I1.08 D114.00
>>> m119
SENDING:M119
Reporting endstop status
x_min: TRIGGERED
y_min: open
z_min: open
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Fig. 4. The Pronterface graphical user interface.

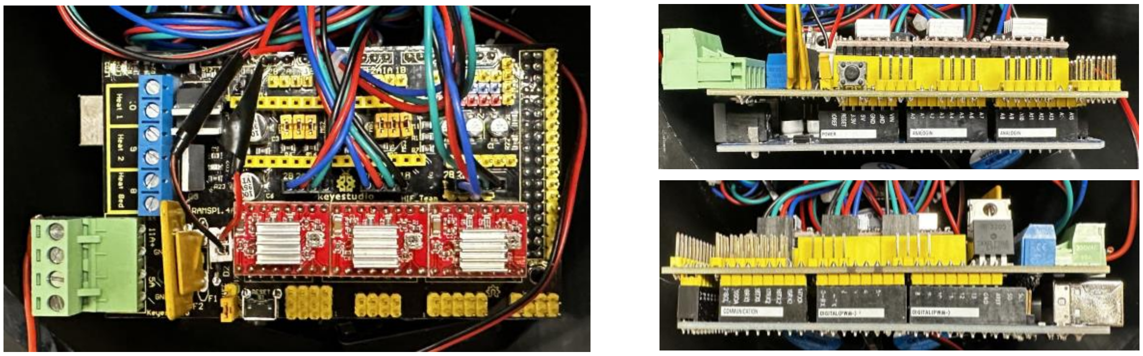

Fig. 5. Our control unit consists of a Mega Arduino 2560 microcontroller and a RAMPS 1.4 driver shield with three A4988 microstepping drivers.

Benefits and Applications in Engineering Technology Education

This project is developed collaboratively by a faculty member and engineering technology student researchers in the Mechatronics Research Lab for use in two core courses in the Mechatronics Engineering Technology program at Northern Kentucky University: "EGT 408 – Mechatronic Systems" and "EGT 320 – Robotic Systems and Material Handling." Its primary objective is to instruct students in integrating the key components of Mechatronic systems, including actuators, sensors, signal conditioning and interfacing, control systems, and user interfaces. This project also teaches students the fundamentals of industrial robot programming, articulated robot configurations, robot movements, and the evolution of industrial robots by incorporating intelligence and human-machine interaction.

Furthermore, this project goes beyond theoretical knowledge and offers hands-on experiences and practical exercises that educate students on the foundational principles of industrial automation, smart factories, and intelligent robotic systems. It empowers them with the essential skills needed to navigate the complex domains of mechatronics and robotics.

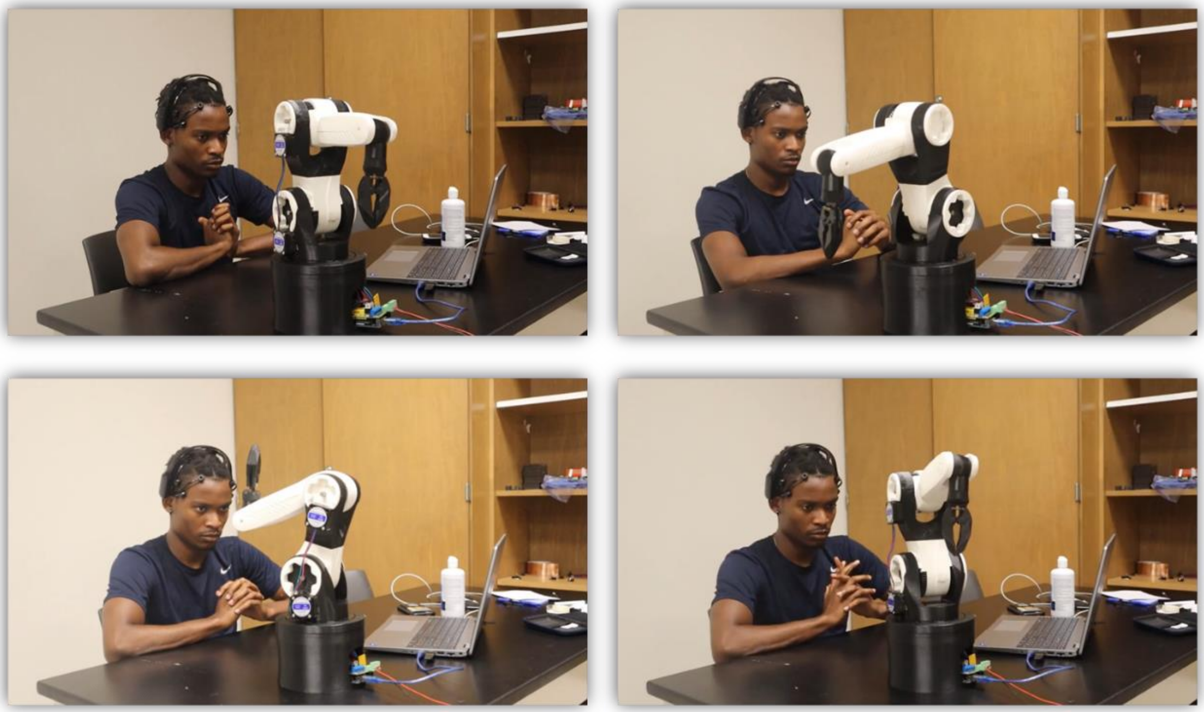

Fig. 6. The user controls the robotic arm using the power of his mind.

Future Applications

One of the primary applications of mind-controlled systems is in the development of neuroprosthetics, which are artificial devices that can restore or enhance the functionality of individuals with limb amputation. We are currently working on the development of a hybrid brain computer interface using multiple machine learning techniques and a mind-controlled prosthetic arm. This breakthrough technology offers new hope for individuals with limb loss and enables them to regain independence and improve their quality of life.

Another significant area of research in mind-controlled systems is the development of brain computer interfaces for communication and control purposes. BCIs enable individuals with severe motor impairments or disabilities to communicate with the outside world and control various devices using their brain signals. This can range from controlling a computer cursor, typing on a virtual keyboard, or even operating household appliances.

Furthermore, mind-controlled systems have shown great potential in enhancing human performance and cognitive capabilities. For example, researchers have explored the use of brain-controlled drones or robotic systems for applications in search and rescue missions, hazardous environments, or military operations [13], [14]. By integrating the human brain's cognitive abilities with the speed and precision of robotic systems, these brain-controlled interfaces can greatly enhance human capabilities and enable us to accomplish different tasks that would otherwise be impossible or too dangerous.

Conclusion

Brain-controlled systems have the potential to create more intuitive interfaces for interacting with machines and technology. This can lead to increased efficiency and reduced learning curves for complex tasks. Our proposed brain computer interface enables users to control a 3D printed mini-industrial robotic arm in different translational directions using the power of their minds. Our interface interacts directly with electroencephalography (EEG) signals captured from the brain using a wireless EEG brainwear. Our BCI recognizes changes in brainwaves when user imagines performing a specific movement. We process and classify these neurosignals and convert them to commands to control the robotic arm. This project was developed for use in the Mechatronics Engineering Technology program's courses, aiming to help students learn to integrate the main mechatronic system components, robot programming fundamentals, robot configurations, and the evolution of industrial robots through the incorporation of intelligence and brain computer/human machine interfaces. The ultimate goal of this research is to use the power of our thoughts and intentions to control robotic systems and to revolutionize the way we interact with and manipulate our surroundings. The BCI created from this project can be used as a control interface for any robotic system which uses human thoughts or motor imaginations as action drivers.

Acknowledgment

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Biography

MAHDI YAZDANPOUR (senior member, IEEE) is an assistant professor and the program coordinator of Mechatronics Engineering Technology at Northern Kentucky University. His research interests include intelligent mechatronic systems, brain computer interfaces, human robot interaction, mind-controlled systems, medical robotics, and computer/machine vision. He has received numerous awards and recognitions, including the NKU College of Arts and Sciences Outstanding Junior Faculty Award and the Kentucky Commercialization Ventures (KCV) Impact Competition Award in 2023. His research has been published in prestigious peer-reviewed journals and conferences, such as IEEE, ASEE, CVPR, VCIP, and TVCG. He serves as the PI for an NIH grant and has also received multiple internal grants.

LESLIE FERRAO is a senior Mechatronics major at Northern Kentucky University. He is currently working as an intern at Bosch where he helps manufacture automotive steering systems. He has been involved in multiple research projects, including the development of the 3D printed industrial robotic arm, designing a brain computer interface to control robotic systems, and designing an Origami-inspired self-folding robot. Leslie's dedication to advancing technology and robotics is evident in his academic pursuits, and he is driven by the desire to contribute to innovative solutions in the field.

BIPLOV ALE is a senior Computer Science major at Northern Kentucky University. He has been involved in multiple research projects, including development of an augmented reality (AR) application for visualizing 3D rock/mineral models, mind-controlled robotic systems, and microcontroller-driven hearing tester and aid. He has received the Research Award in Physics, the International Achievers Award, and the EDGE Award. His commitment to advancing knowledge in the field of Mechatronics motivates his academic journey with the goal of making substantial contributions in the future.