ECE 445

SENIOR DESIGN LABORATORY

Project Proposal for ECE 445

Team #34

HENGYU LIU
(hengyu2@illinois.edu)
XUAN TANG
(xuant4@illinois.edu)
HAN CHEN
(hanc7@illinois.edu)
ZHANPENG LI
(zl88@illinois.edu)

TA: Zheyi Hang

March 21, 2024

Contents

1 Objective and Backgrounds

1.1 Goals Functions

The goal of the Virtual Band project is to provide a new instrument interface that provides users with a unique and engaging experience. Many Musical Instruments, due to their size and fragility, cannot support users to carry and play anytime and anywhere, such as the piano is very large. Using cutting-edge audio processing technology, pressure sensing systems and positioning systems, electrical pulses are converted into high-quality instrument sound output, providing consumers with a smooth, authentic music performance experience. To create a dynamic and engaging music interface, the Virtual Band project combines motion tracking, audio processing, and sensor technology - a new approach to music technology.

The virtual Band project are consist of three main components. The first goal is to create a portable instrument interface that can mimic a variety of instruments so that players can perform anytime, anywhere. Second, add a special feature that allows two hands to play two instruments at the same time, increasing the expressiveness and originality of the music. The ultimate goal of the project is to investigate how the system's ability to detect hand movement and stress sensitivity can be used to detect the condition of players when they are playing instrument, those data can be used for further analysis. If the team hits its target, the project will showcase software and hardware innovations such as seamless audio processing, compact and user-friendly sensor integration, and real-time instrument recognition algorithms. It may also make a significant contribution to the playing data analysis through new methods of motion tracking. If these goals are met, virtual bands will be recognized as cutting-edge and important instruments in the field of music technology.

1.2 High-Level Requirement List

1. **Accurate Piano Music Playback:** Our final product is designed to play piano music with high accuracy, capturing the precise note intended by the user. The system integrates precise sensors and CV algorithms to ensure that each note played is the exact pitch and duration as composed. This feature enhances the learning and performing experience, as it mimics the authentic response of a traditional piano, providing real-time feedback and assisting in the accurate execution of complex compositions.
2. **Versatile Instrument Simulation:** In addition to piano sounds, our product offers the capability to switch to other instruments, accurately reproducing the unique timbre of each. This functionality is achieved through sound synthesis techniques that emulate the acoustic characteristics of instruments like the violin, guitar, and flute. Users can explore these sounds seamlessly, allowing for a diverse and enriching musical expression, which is particularly useful for composers and arrangers interested in creating multi-instrumental arrangements.
3. **Advanced Finger Position Detection:** Our system utilizes CV hand landmarks de-

tection algorithms and sensor data analysis to precisely compute the positions of the fingers on the instrument interface. This technology leverages data transmitted from high-resolution sensors that monitor the movements and positions of each finger in real-time. Such precision is crucial for accurately capturing the dynamics and intention of the musician's hand movements, enabling a more intuitive environment for the user to perform.

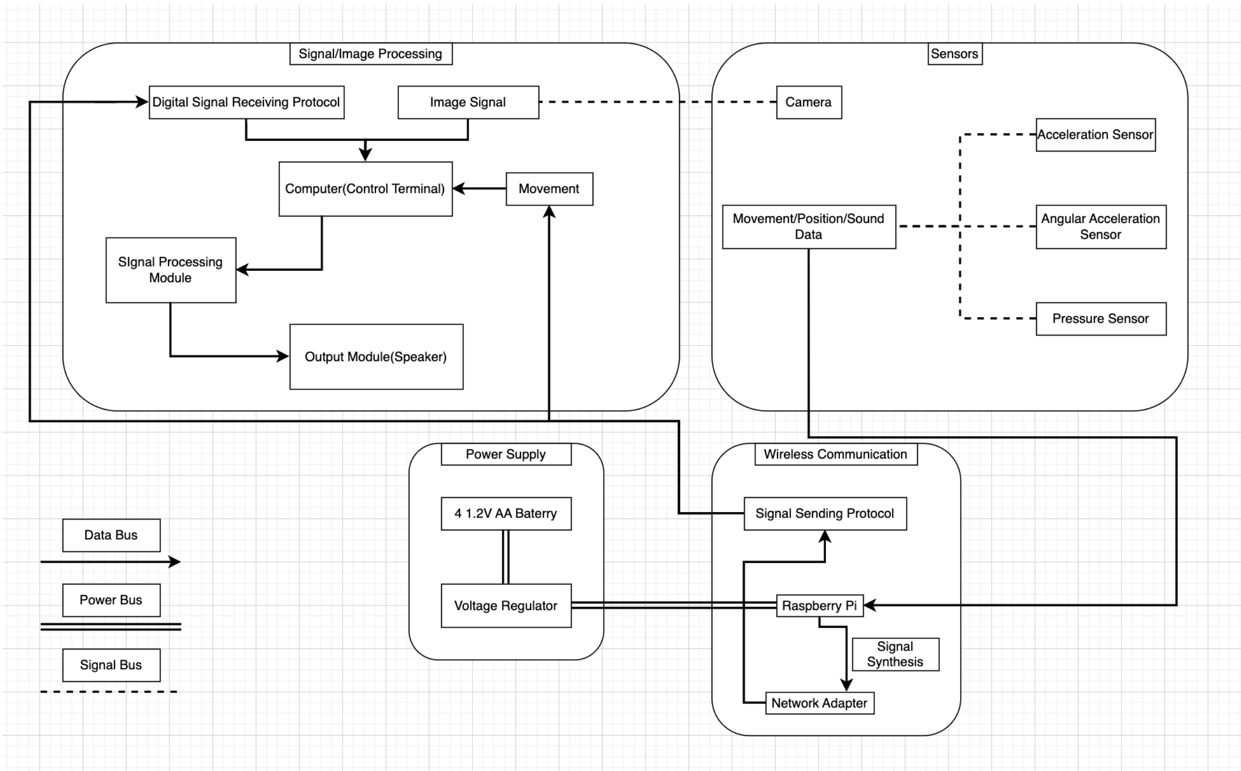

Figure 1: Block Diagram for Virtual Band project

2 Design

2.1 Block Diagram

2.2 Brief Description

The sensors will capture the motion data and press action from users, those data will be synthesised to Raspberry PI and transferred to our computer, the transition protocol is self-designed, which high efficiency and validity. When the computer receive those motion signal, it will integrate them to compute the exact position of our hands, then it will output notes according to our embedded piano model.

2.3 Block Description

2.3.1 Power Supplement Module

We choose to use 18650 Raspberry Pi dedicated power module as battery source for our project. It is a versatile solution designed to provide stable and reliable power to your Raspberry Pi projects. With its robust features and flexible design, this power module offers an efficient and convenient way to power your Raspberry Pi devices while ensuring optimal performance and extended runtime.

Figure 2: Power Supply

At the heart of this power module are two high-capacity 18650 lithium-ion batteries, each boasting a capacity of 6800mAh. These batteries are configured in parallel, providing a total capacity of 6800mAh for prolonged usage without the need for frequent recharging. This power module is able to deliver a consistent 5V-5.1V/3A output voltage to our Raspberry Pi. This ensures reliable and uninterrupted power supply, essential for maintaining the stability and performance of our projects. This includes the power supply to the Raspberry PI, position and pose sensors, pressure sensors, and a analog-to-digital converter.

Furthermore, the power module boasts three USB-A interfaces capable of delivering a 5V 3A power output each, providing ample power for various peripherals and devices. Additionally, it features a micro-B and a type-C interface, both capable of delivering a 5V 2A power output. This allows us to power additional we have with ease.

Requirement 1: The power module must provide a stable output voltage within the range of 5V-5.1V.

Requirement 2: The voltage output should be capable of delivering a current of up to 3A to the connected devices.

2.3.2 Signal Processing Module

The signal Processing Module will be deployed on computer with M-1 Chip, and the entire project will be run in `Go` and **C** Language, which will act as our terminal processing module which contains multiple features. It contains a Digital Signal Processing Protocol used to receive and process electrical signals from external modules, and a terminal computer used to model virtual keyboard, and adjust the output of timbre and volume according to the incoming electrical signal.

2.3.2.1 Digital Signal Processing Protocol

C/**Go** programming task, performing as a UDP-like receiving Protocol

Requirement 1: Implement efficient algorithms and techniques (a UDP-like protocol)for receiving and decoding electrical signals with minimal delay and processing overhead.

2.3.2.2 Terminal Computer

Analyze and provide audio output capabilities to produce synthesized sounds based on the processed electrical signals, allowing users to hear the music generated by the virtual band model. The keyboard key position is modeled by computer based on the camera position

2.3.3 Sensor Module

The sensor Module includes Acceleration Sensor, Angular Acceleration Sensor, Pressure Sensor and a camera. They are used to detect the position information of virtual keyboard gloves and the pressure when virtually pressing keys. The camera is also included to capture more accurate information.

2.3.3.1 6DOF Sensors

Translation and angular sensors are chosen to be MPU6050, which detects the translation and angular motion of the fingers and hands. Data collected by sensors will be sent to Raspberry PI and then computer for signal processing through WIFI. The desirable range scale for translational acceleration would be ±8wg, and ±10 rad/s^2, with precision of 0.1g and 0.1 rad/s^2.

Requirement 1: The sensor must accurately measure translational acceleration within the range of+8g with a precision of 0.1g.

Requirement 2: It should accurately measure angular acceleration within the range of ±10 rad/s2with a precision of 0.1 rad/s2.

Requirement 3: The sensor should support programmable control for adjusting sensitivity and range settings according to application requirements.

Requirement 4: It must offer programmable interrupts for various functions such as posture recognition, shake detection, image scaling, scrolling, high-G sensing, motion detection, tap sefnsing, and shake sensing.

2.3.3.2 Pressure Sensors

As we have mentioned before, the sound level of the instrument is determined by the data

Pin Number	MPU-6000	MPU-6050	Pin Name	Pin Description
1	Y	Y	CLKIN	Optional external reference clock input. Connect to GND if unused.
6	Y	Y	AUX_DA	I^2C master serial data, for connecting to external sensors
7	Y	Y	AUX_CL	I^2C Master serial clock, for connecting to external sensors
8	Y		/CS	SPI chip select (0=SPI mode)
8		Y	VLOGIC	Digital I/O supply voltage
9	Y		AD0 / SDO	I^2C Slave Address LSB (AD0); SPI serial data output (SDO)
9		Y	AD0	I^2C Slave Address LSB (AD0)
10	Y	Y	REGOUT	Regulator filter capacitor connection
11	Y	Y	FSYNC	Frame synchronization digital input. Connect to GND if unused.
12	Y	Y	INT	Interrupt digital output (totem pole or open-drain)
13	Y	Y	VDD	Power supply voltage and Digital I/O supply voltage
18	Y	Y	GND	Power supply ground
19, 21	Y	Y	RESV	Reserved. Do not connect.
20	Y	Y	CPOUT	Charge pump capacitor connection
22	Y	Y	RESV	Reserved. Do not connect.
23	Y		SCL / SCLK	I^2C serial clock (SCL); SPI serial clock (SCLK)
23		Y	SCL	I^2C serial clock (SCL)
24	Y		SDA / SDI	I^2C serial data (SDA); SPI serial data input (SDI)
24		Y	SDA	I^2C serial data (SDA)
2, 3, 4, 5, 14, 15, 16, 17	Y	Y	NC	Not internally connected. May be used for PCB trace routing.

Figure 3: Schematic of MPU6050

collected by the pressure sensor. The measurable range should be 0g - 1kg with precision of 1g.

This pressure sensor features a slim design with a thickness of 0.3mm, making it ideal for applications requiring space efficiency. It activates with a trigger force of 30g, signified by a default resistance of less than 200kΩ. Capable of measuring pressures within the range of 2g to 1.5kg, it accommodates both static and dynamic pressure measurements at frequencies up to 10Hz. With an initial resistance exceeding 10MΩ, it swiftly responds to pressure changes in less than 0.01s. Operating seamlessly across temperatures ranging from -40°C to +85°C, it offers long-lasting performance with a lifespan exceeding one million cycles. This sensor maintains excellent consistency, with resistance variations of +/-3% within individual units and +/-10% across batches under equivalent testing conditions. Additionally, it exhibits minimal hysteresis, with a drift of less than 5% after 24 hours under a static load of 1kg. Furthermore, it demonstrates immunity to electromagnetic interference (EMI) and electrostatic discharge (EDS), ensuring reliable operation in various environmental conditions.

Requirement 1: Pressure sensors' dimensions should be within 1 cm^2. In the meanwhile, the sensors should be flexible which allows appropriate attachment to the fingers.

Requirement 2: Pressure sensor should be able to detects force ranging from 1-20N.

2.3.4 Wireless Communication Module

Communication Module contains Signal Sending Protocol, Rasberry Pi and a Network Adapter. The raspberry Pi is used for wireless communication between virtual band gloves and terminal computer by the signal sending protocol.

2.3.4.1 Signal Sending Protocol

C/Go programming task, performing as a UDP like Sending Protocol

Requirement 1: Ensure reliable delivery of data packets, even in the presence of network disturbances or interference. Requirement2: Minimize delay in data transmission to provide real- time interaction between the gloves and the terminal computer, no greater than 25ms

2.3.4.2 Rasberry Pi

It provides the necessary computing power and interfaces to facilitate communication between the virtual band gloves and the terminal computer.

Requirement 1: Sufficient computational capabilities to handle the signal processing and communication tasks including data transfer for 3-freedom-degrees acceleration sensor

Requirement 2: Support for wireless connectivity protocols such as Wi-Fi or Bluetooth to communicate with the virtual band gloves, with a bandwidth approximately 70kb/s.

2.3.5 Network Adapter 2.4 GHz and 5.0 GHz IEEE 802.11ac Wireless, Bluetooth 5.0, BLE

Requirement 1: Sufficient range to establish and maintain connections over the desired distance between the Raspberry Pi and the terminal computer.

2.4 Risk Analysis

2.4.1 Risk Analysis for Computer Vision Task

The most challenging part for computer vision task is to retrain the mediapipe model or using preprocessing techniques like color space transformation algorithms[1] to fit the mediapipe[2] model which originally works on bare hands for gloved hands landmark detection tasks. The mediapipe hand landmarker model was trained on images of real world bare hands models. It's of great importance for retraining and fine-tune the model to make it fit in the gloved hands detection task.

Not only to ensure precise sensor alignment, it is crucial to accurately position and model the camera, checking that the tracking points are correctly placed. This facilitates precise key localization, which is further enhanced by integrating an auxiliary laser module. Hand recognition technology is implemented to improve fingertip positioning, allowing the system to accurately locate the center point and provide feedback during calibration. Audio feedback is provided corresponding to different key presses, and it is vital to verify the correctness of this audio feedback to ensure it matches the actual key presses.

Additionally, the system supports concurrent audio playback for multiple key presses, enhancing the user experience. A handshake debugging session is conducted to guarantee accurate tracking of finger movements, with the program capable of recording and comparing distances with the number of pixels displayed on the screen. To accurately model physical interactions, mathematical models are used for converting pressure exerted by the user into audio volume, and this pressure-to-volume conversion is validated through controlled pressure exertion and audio volume comparison. This comprehensive approach ensures a high level of precision and responsiveness in the system's operation.

In addition, in the positioning task, we plan to set the width of the white key to about 2.3 cm to 2.8 cm, and the black key to about 9.5 cm to 1.5 cm. Due to the error caused by the sensor accuracy and camera distortion, we increase the error range of 2 to 3 mm. If a position is in a blur between two keys, we choose the note near the center of the piano (reference note), because the farther away from the center of the hand distance error is greater.

2.4.2 Risk Analysis for submodule Module Communication and Data Processing

The system's accuracy and real-time responsiveness are dependent on the precision and reliability of multiple integrated sensors and communication protocols. Tolerance analysis becomes a crucial aspect of the system design to ensure seamless functionality.

Pressure sensors in the system are capable of detecting forces ranging from 1N to 50N. We assume a nominal tolerance of $\pm 0.5N$ for these sensors, which is reasonable considering the dynamic range and application. Acceleration sensors require a high degree of precision, and for the purposes of this analysis, a tolerance of $\pm 0.0001g$ is deemed acceptable, with g representing standard gravitational acceleration.

Data communication is facilitated through Raspberry Pi 4B modules, which handle sensor data at a frequency of 1000 Hz, with each degree of freedom (DOF) producing 4 bytes of data. To sustain real-time data transfer without perceivable latency for musical performance, we provision a bandwidth tolerance of 1Mbps above the computed requirement of 528000 bytes/sec, factoring in a 95% efficiency rate to accommodate protocol overhead.

Noise filtering is imperative for the system, with algorithms in place to maintain a signal-to-noise ratio (SNR) above 20dB. This ensures that the nuances of the musician's movements are captured accurately. The system's noise tolerance must not exceed levels that would compromise the SNR beyond this benchmark.

Synchronization tolerances across the system's components are set to a maximum permissible time drift of $\pm 5ms$ over a 1-minute interval. This specification is critical to maintain the timing and coherence of the musical output, ensuring a synchronous and harmonious performance.

3 Ethics and Safety

3.1 Ethics

In developing the Virtual Band Model Project, our team is committed to adhering to the highest ethical standards as outlined by the IEEE/ACM Code of Ethics. We recognize the importance of ethical responsibility in the development and implementation of our technology, particularly given its innovative integration of hardware and software components to create a virtual musical experience.

3.1.1 Professional Responsibility

We commit to making decisions and taking actions that are in the best interests of society, public safety, and the environment. This involves ensuring that our power supply module, signal processing module, sensor module, and wireless communication module are designed and tested to prevent harm. For instance, our voltage regulator and battery design considerations prioritize user safety and device reliability, avoiding potential overvoltage or undervoltage situations that could lead to damage or injury.

3.1.2 Quality and Reliability

We pledge to uphold the quality and reliability of our system by rigorously testing our components, such as the GY-521 PU6050 sensors and FSR 402 pressure sensors, to ensure they meet specified requirements for precision and force detection. By doing so, we safeguard against inaccuracies that could affect the user experience or cause unintended harm.

3.1.3 Privacy and Data Protection

Our project incorporates the use of cameras and sensors to detect user movements and interactions. We are committed to protecting the privacy of users by implementing robust data handling and storage protocols. Personal data collected through our system will be anonymized and encrypted to prevent unauthorized access or misuse.

3.1.4 Accessibility and Inclusivity

In line with the IEEE/ACM Code of Ethics, our project aims to be accessible and inclusive, providing a virtual musical experience that can be enjoyed by a wide range of users, including those with disabilities. We will seek to design our virtual band gloves and accompanying software with user-friendly interfaces and adaptive features to accommodate diverse needs.

3.1.5 Transparency and Honest

We will be transparent and honest in our communication about the capabilities, limitations, and ongoing development of our virtual band model. This includes openly discussing any potential risks or uncertainties associated with the use of our technology, as well as our strategies for mitigating such risks.

3.1.6 Compliance with Legal and Ethical Standard

Our project will comply with all applicable laws, regulations, and ethical guidelines, including those related to human and animal testing. Should our project's development process require any form of testing that involves human participants or animals, we will obtain the necessary approvals from Institutional Review Boards (IRB) or Institutional Animal Care and Use Committees (IACUC), respectively.

3.2 Safety

Safety is paramount in any project, and the virtual band model is no exception. Various safety concerns need to be addressed to ensure the well-being of both project developers and end users:

3.2.1 Electrical Safety

- Implement measures to prevent electrical shocks, such as using insulated cables, ensuring proper grounding, and enclosing high-voltage components.
- Clearly label areas with electrical hazards and restrict access to unauthorized personnel.
- Incorporate circuit protection devices like fuses and circuit breakers to prevent overloads.

3.2.2 Mechanical Safety

- Ensure that all mechanical components, including moving parts and sensors, are properly designed and securely fastened to prevent accidents or injuries.
- Conduct regular inspections of mechanical components to identify and address any wear or damage that may compromise safety.

3.2.3 Lab Safety

- Establish clear guidelines for laboratory use, including the proper handling of equipment, tools, and materials.
- Provide personal protective equipment (PPE) such as gloves and safety goggles where necessary.
- Clearly mark emergency exits and ensure that fire extinguishers and first aid kits are easily accessible.

References

[1] *Preprocessing color space for gloved hands*, Figure 11, https://stackoverflow.com/questions/76325975/how-to-make-the-hand-detection-of-mediap.

[2] F. Zhang, V. Bazarevsky, A. Vakunov, *et al.*, "Mediapipe hands: On-device real-time hand tracking," *arXiv preprint arXiv:2006.10214*, 2020, CVPR Workshop on Computer Vision for Augmented and Virtual Reality, Seattle, WA, USA, 2020.