Design and Fabrication of a Flexible Multi-Sensor Wearable Platform Using Kapton Tape and Copper-Foil Traces

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***Abstract*—Flexible electronics offer significant potential in wearable sensing applications due to their ability to conform to curved surfaces and provide continuous physiological monitoring. This project aimed to design and fabricate a flexible multi-sensor platform capable of measuring physiological, environmental, and motion parameters. Originally intended to be produced via conductive ink printing on Kapton tape, fabrication constraints led to the development of an alternative technique using copper foil traces on Kapton layers. The final prototype integrates a MAX30100 pulse oximeter, BMP280 barometric sensor, MPU6050 accelerometer, and an ESP32 microcontroller, achieving reliable data acquisition and CSV-based logging. The work demonstrates both adaptability and engineering creativity in realizing a functional flexible substrate–based sensing system.**

I. Introduction

Flexible electronics are emerging as a key technology in wearable health monitoring, soft robotics, and next-generation human–machine interfaces. Their ability to bend, twist, and conform to curved surfaces makes them ideal for continuous physiological sensing, where comfort, mechanical compliance, and unobtrusiveness are essential. In this context, the goal of this project was to design and fabricate a flexible, Kapton-based multi-sensor wearable platform capable of capturing physiological, environmental, and motion-related data in real time.

The initial vision for the system involved creating a fully printed flexible circuit by depositing conductive silver ink directly onto a Kapton substrate. This approach would have allowed precise trace geometry, lightweight integration, and a fully monolithic flexible design similar to commercial flexible PCBs. However, due to the unavailability of conductive ink printing technologies—such as screen printing, aerosol jet printing, or nanoparticle-based inkjet systems—on campus, the fabrication approach had to be reconsidered.

In response to these constraints, the team adopted an alternative fabrication method using manually patterned copper-foil traces adhered to layered Kapton tape. Although more hands-on and less automated, this method provided excellent conductivity, mechanical robustness, and compatibility with standard soldering processes. Cut-out regions were created to embed the sensors and ESP32 microcontroller, resulting in a low-profile and highly flexible assembly.

Despite deviating from the original printed-electronics workflow, the final prototype successfully integrated the MAX30100 pulse oximeter, BMP280 pressure/temperature sensor, and MPU6050 accelerometer/gyroscope onto a single flexible platform. The system demonstrated stable data acquisition and validated that reliable flexible circuits can be prototyped using low-cost materials and manual fabrication techniques when advanced facilities are not available.

II. Intended System Design

A. Motivation and Concept

The original goal was to fabricate a flexible printed circuit that integrates:

- MAX30100 – Heart rate and SpO_2
- BMP280/BMP180 – Temperature and pressure
- MPU6050 – Accelerometer and gyroscope
- ESP32 – Control and communication

All components were intended to be mounted on a single Kapton substrate with conductive silver-ink traces.

B. Planned Fabrication Steps

1) Printing conductive ink traces on Kapton
2) Curing the conductive pathways
3) Mounting sensors and ESP32
4) Encapsulation for durability

Kapton was chosen due to its flexibility, thermal stability, and compatibility with flexible PCB manufacturing.

III. Challenges and Adaptations

A. Lack of Conductive Ink Printing

Conductive ink printing requires specialized tools such as screen printers, aerosol jet printers, or inkjet printers with nanoparticle ink. These facilities were not available, preventing direct fabrication of conductive pathways.

B. Design Constraints

The system still needed to maintain:

- Flexibility
- Reliable electrical conductivity
- Compatibility with sensors and ESP32

This prompted a redesign using materials available on campus.

IV. Final Fabrication Method

A. Layered Kapton Base

To create a mechanically stable yet flexible foundation, multiple layers of Kapton tape were laminated together. Stacking the layers increased tensile strength and stiffness while preserving bendability, ensuring that the circuit could withstand repeated flexing without tearing or deforming. The multilayer structure also provided a smooth, uniform surface for adhering copper traces.

B. Cut-out Regions for Sensors

Precision cut-outs were made in the Kapton sheet to partially embed the sensors and the ESP32 module. This recessed placement allowed the components to sit flush with the substrate, reducing the overall thickness of the wearable and preventing bulky protrusions. The cut-outs also helped mechanically stabilize the components, reducing stress on solder joints during bending.

C. Copper Foil Traces

Thin copper foil was manually cut into narrow strips to emulate the conductive pathways of a flexible PCB. These strips were carefully shaped and aligned to match the required interconnect layout and then adhered to the Kapton surface. Copper was chosen for its excellent electrical conductivity and compatibility with manual soldering, making it a practical alternative to printed silver-ink traces.

D. Soldered Connections

Once the copper traces were laid out, jumper wires were soldered to establish reliable electrical connectivity:

- Between each sensor pin and its corresponding copper trace
- Between the copper traces and the relevant GPIO pins on the ESP32

Proper fluxing and controlled heating ensured that the solder joints remained mechanically flexible and electrically robust. The combination of copper traces and soldered jumper wires provided a stable interconnect network capable of surviving repeated flexing, making the final assembly suitable for wearable use.

V. System Integration

A. Electrical Interfacing

All sensing modules were integrated on a common I^2C communication bus to minimize wiring complexity and maintain compatibility with the flexible substrate. The ESP32 served as the master device, while each sensor functioned as an I^2C slave. The two communication lines were mapped as:

- **SDA (Data Line):** GPIO 21
- **SCL (Clock Line):** GPIO 22

Using a shared bus allowed the sensors to be addressed individually without requiring additional pins or connectors, which is particularly advantageous when working on a compact or flexible circuit where trace routing space is limited. Proper pull-up resistance was provided internally by the ESP32, ensuring signal integrity across the copper-foil traces.

B. Sensor Addressing

Each I^2C device communicates using a unique 7-bit address, allowing the ESP32 to distinguish between the different sensors on the shared bus. The assigned addresses detected during testing were:

- **MAX30100 (PPG + SpO_2):** 0x57
- **BMP280/BMP Sensor (Temperature + Pressure):** 0x76
- **MPU6050 (Accelerometer + Gyroscope):** 0x68

The correct detection of all addresses during I^2C scanning confirmed that the copper-foil interconnects and soldered jumper wires were electrically sound and free from cross-connections or open circuits.

C. Firmware Functionality

The ESP32 firmware was designed to coordinate sampling across all sensors while maintaining low latency and stable timing. Its responsibilities included:

- **Continuous sampling of the MAX30100:** The PPG sensor requires a high sampling rate to extract heart rate, SpO_2, and pulse waveform data. The firmware updates the pulse oximeter module in the main loop to avoid data loss.
- **Periodic sampling of BMP280 and MPU6050:** Environmental and motion data change at a slower rate compared to PPG signals. These sensors were sampled once every second to balance performance and computational load.
- **Formatted CSV data output:** Each data frame includes a timestamp, physiological readings (HR, SpO_2), environmental readings (temperature, pressure), and inertial readings (acceleration on all axes). This makes the system compatible with PC logging tools, dashboards, or downstream machine-learning pipelines.

This modular firmware architecture ensured smooth integration of multiple sensing modalities while keeping computational overhead low. The design also supports future expansion, such as adding Bluetooth Low Energy (BLE) transmission or running lightweight inference models directly on the ESP32.

VI. Results

A. Sensor Performance

The integrated sensing platform demonstrated stable and reliable operation across all three sensor modules. The MAX30100 pulse oximeter consistently produced clean PPG waveforms when placed on the fingertip, enabling accurate extraction of heart-rate and SpO_2 values. The signal exhibited good amplitude, minimal noise, and a clear systolic peak, confirming that the copper-foil interconnects and flexible substrate did not impede optical sensing performance.

The BMP280 sensor provided temperature and barometric pressure readings that closely matched reference values, with variations well within the expected tolerance of the device. This verified both the electrical integrity of the interconnects and the sensor's stability under repeated operation.

The MPU6050 inertial measurement unit delivered smooth acceleration data along all three axes. The readings showed no noticeable drift or discontinuities during mild movement, indicating that the flexible routing did not introduce disconnections or parasitic coupling. Together, these results confirm that the hybrid Kapton–copper fabrication method supports multiple sensing modalities without degrading signal quality.

B. Flexibility

Mechanical testing showed that the final wearable structure maintained full electrical continuity even under bending, twisting, and routine handling. The copper-foil traces adhered strongly to the Kapton substrate and did not peel, crack, or delaminate during flexing. Solder joints remained stable, and no intermittent connections were observed during I^2C communication.

The prototype could be bent along both longitudinal and transverse directions without any drop in sensor performance or communication stability. This demonstrates that the layered Kapton assembly is robust enough for practical wearable applications, where continuous deformation is common. The successful retention of functionality under mechanical stress validates the design as a viable low-cost alternative to professionally manufactured flexible PCBs.

C. System Workflow

To organize the sensing, processing, and interpretation stages of the wearable platform, a three-phase workflow was designed. The setup phase manages firmware flashing and initial dashboard communication. The calibration phase establishes baseline physiological parameters using a three-minute data window. Finally, the live classification phase continuously collects sensor data, processes feature windows, and classifies the user's emotional state.

D. Mood Detection Methodology

The wearable platform incorporates a preliminary mood–inference framework that operates on real-time physiological and motion data streamed from the ESP32 to a Python-based dashboard. The system classifies mood in two phases: an initial personal calibration period followed by continuous live classification.

Phase 1: Personal Baseline Calibration: Before mood detection can begin, the user performs a three-minute resting calibration. During this period, the system computes two personalized baseline values:

- **HR_{base}:** Median resting heart rate, representing the user's typical relaxed cardiovascular state.
- **ACC_sd_base:** Median accelerometer standard deviation, used as a measure of baseline stillness.

These baselines account for natural physiological differences between individuals and ensure that all subsequent classification is personalized rather than relying on population averages.

Phase 2: Live Mood Classification: After calibration, the system performs real-time mood detection using 30-second sliding windows of incoming sensor data (sampled at 1 Hz). The classification pipeline first determines the user's activity level and then categorizes their mood accordingly.

1) Motion Gating: The system compares the current accelerometer variability (*acc_sd*) with the user's baseline stillness (*ACC_sd_base*). If movement significantly exceeds baseline levels, the user is considered **physically active**, and mood is set to:

ACTIVE / UNKNOWN

This gating prevents misclassification of exercise-induced heart rate increases as emotional stress.

2) Resting-State Mood Classification: When the user is resting, mood is inferred by comparing current physiology (e.g., heart-rate deviation, temperature change, micro-movement) against their baseline. Five possible states are defined:

- **STRESS**: Elevated heart rate combined with a noticeable drop in peripheral temperature.
- **CALM**: Heart rate significantly below the user's baseline and stable motion patterns.
- **AGITATED**: High heart rate along with increased small-scale motion ("fidgeting").
- **NEUTRAL**: Physiological parameters remain close to baseline values, with no strong deviation.
- **UNKNOWN**: Data does not fit any of the above rules or classification confidence is insufficient.

This rule-based model is lightweight, interpretable, and suitable for real-time inference on low-power wearable systems. It also sets the foundation for future machine-learning approaches using richer multimodal datasets.

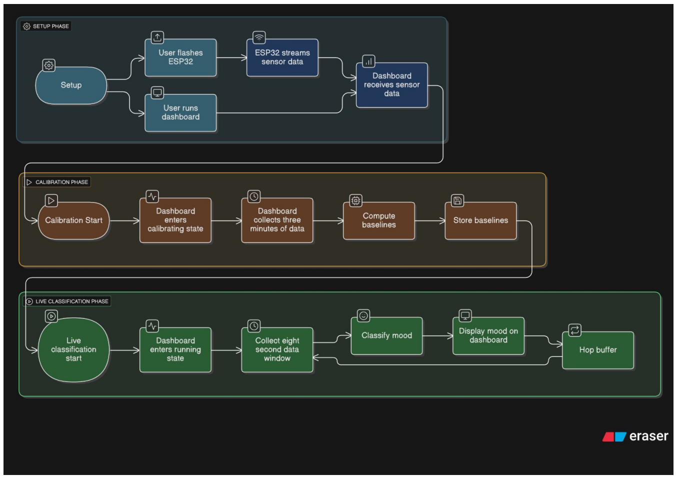

Fig. 1: Complete workflow of the wearable sensing and mood detection system, including Setup Phase, Calibration Phase, and Live Classification Phase.

VII. Figures

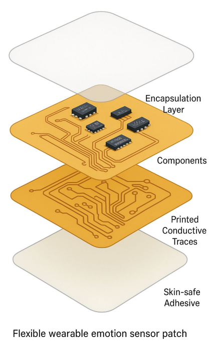

Fig. 2: Illustration of intended flexible circuit with printed traces.

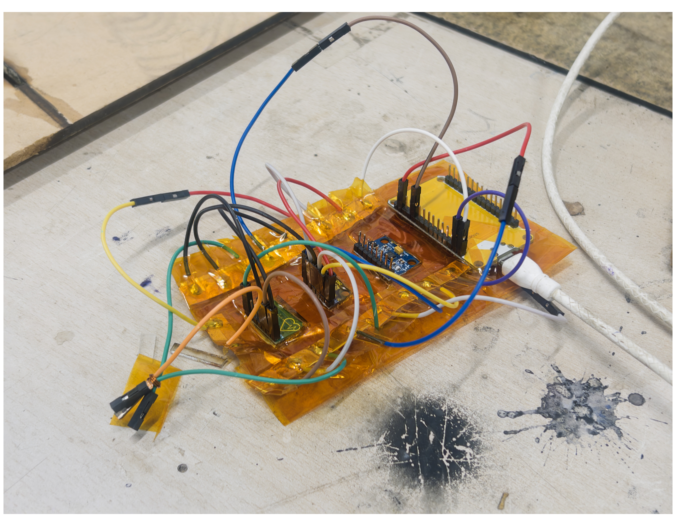

Fig. 3: Final fabricated flexible multi-sensor prototype using Kapton tape and copper-foil interconnects.

*1) **Software Interface and Mood Detection Simulator**:* To explore how the collected physiological data could be used for mood classification in a full wearable system, a graphical simulator was created. This interface displays simulated heart rate, SpO_2, inter-beat interval (IBI), and PPG data streams in real time, and uses simple threshold-based logic to assign a mood label such as *Calm*, *Stressed*, or *Active*. The simulator serves as a conceptual demonstration of how the final wearable device could visualize emotional state.

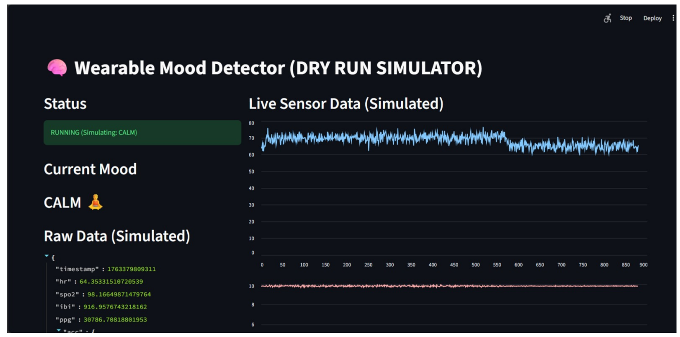

Fig. 4: Dry-run simulator interface showing live sensor data visualization and mood classification output. This represents the software-side concept for emotion detection using future real sensor data.

VIII. Discussion

Although the project initially aimed to implement conductive ink printing for creating a fully printed flexible circuit, the absence of suitable printing facilities necessitated a shift in fabrication strategy. This constraint led to a redesigned approach that relied on manually patterned copper-foil traces laminated onto stacked Kapton layers. Despite being more labor-intensive, this fabrication method proved to be both accessible and reliable, demonstrating that functional flexible electronics can be prototyped effectively even without specialized equipment. The resulting structure retained good mechanical flexibility and consistently preserved electrical continuity during bending, twisting, and normal handling.

The performance of individual sensors further validated the practicality of the hybrid design. The MAX30100 pulse oximeter delivered clean and stable readings when positioned on the fingertip, where optical PPG measurements are typically strongest. However, its performance degraded significantly when placed on the wrist. This behavior aligns with known limitations of the MAX30100 family, which lacks the dynamic range, LED drive efficiency, and ambient-light handling found in newer-generation sensors such as the MAX30102 or MAX86141. Therefore, the observed performance gap is expected and highlights the importance of proper sensor selection for wrist-mounted wearables.

The BMP280 environmental sensor and the MPU6050 inertial measurement unit both demonstrated stable and accurate operation throughout testing. Temperature and pressure readings were consistent with reference values, and accelerometer outputs remained smooth with minimal drift. Their correct performance confirms that the copper-trace interconnects did not introduce noise, cross-talk, or intermittent connections an important indicator of fabrication quality.

Overall, this project revealed several important insights. First, even improvised fabrication methods can yield dependable results when care is taken in material selection, interconnect routing, and mechanical support. Second, sensor placement and inherent device limitations have a significant impact on signal quality, particularly for optical biosensors. Finally, the combination of multiple sensing modalities physiological, environmental, and motion creates a rich data stream that can support future work such as mood inference, anomaly detection, or context-aware wearable computing.

IX. Conclusion

This project successfully delivered a functional flexible wearable sensing platform built using a Kapton–copper hybrid fabrication technique. Although the original intent was to fabricate the circuit using printed conductive inks, the lack of on-campus printing facilities required a complete redesign of the manufacturing workflow. The final approach, which relied on layered Kapton tape, manually patterned copper-foil traces, and carefully soldered jumper connections, proved to be both practical and mechanically robust while preserving the essential flexibility required in wearable systems.

The prototype integrates three key sensing modules—the MAX30100 pulse oximeter, the BMP280 environmental sensor, and the MPU6050 inertial sensor—along with an ESP32 microcontroller responsible for aggregation, timing, and data output. The system achieves stable real-time acquisition of physiological, environmental, and motion data, streamed in a structured CSV format suitable for downstream processing and analysis. Moreover, the flexible substrate maintained electrical continuity under repeated bending, demonstrating that low-cost materials can still enable mechanically compliant circuit architectures.

Beyond successful hardware integration, this work also lays the groundwork for building higher-level analytics such as mood or stress inference. With appropriate data collection and calibration pipelines, the sensor suite can support feature extraction from heart-rate, HRV, motion patterns, and environmental conditions. The dashboard prototype and workflow diagrams developed as part of this project illustrate the broader ecosystem required for a fully functional wearable mood-detection system.

Overall, the project highlights the value of adaptive engineering: when ideal fabrication methods were unavailable, the team was able to rethink the design, prototype iteratively, and still achieve a highly functional outcome. The final system demonstrates the feasibility of multilayer Kapton substrates for rapid prototyping in flexible electronics and provides a strong platform for future improvements such as printed traces, BLE-based transmission, and machine-learning-driven mood classification.

X. Future Work

- Adopt inkjet or screen printing for conductive traces
- Replace MAX30100 with MAX30102 or MAX86141 for wrist measurements
- Miniaturize the assembly with SMD components
- Integrate BLE for wireless data transfer
- Apply machine learning for emotion/stress inference

Acknowledgments

We thank the instructor, laboratory staff, and IIT Gandhinagar for support.

References

[1] J. A. Rogers, T. Someya, and Y. Huang, "Materials and Mechanics for Stretchable Electronics," *Science*, vol. 327, no. 5973, pp. 1603–1607, 2010.

[2] T. Sekitani and T. Someya, "Human-Friendly Organic Integrated Circuits," *Materials Today*, vol. 14, no. 9, pp. 398–407, 2011.

[3] DuPont, "Kapton Polyimide Film Technical Specifications," DuPont Electronics, 2019. Available: https://www.dupont.com.

[4] MAXIM Integrated, "MAX30100: Integrated Pulse Oximetry and Heart-Rate Sensor," Datasheet, 2015.

[5] Bosch Sensortec, "BMP280: Barometric Pressure Sensor," Datasheet, 2018.

[6] TDK InvenSense, "MPU-6050 6-Axis MotionTracking Device," Datasheet, 2013.

[7] M. Poh, N. Swenson, and R. Picard, "A Wearable Sensor for Unobtrusive, Long-Term Assessment of Electrodermal Activity," *IEEE Trans. Biomedical Engineering*, vol. 57, no. 5, pp. 1243–1252, 2010.

[8] S. J. Kim, J. Chung, and S. Lee, "Emotion Recognition Using PPG Signals and Machine Learning Techniques," *Sensors*, vol. 21, no. 11, 2021.

[9] A. H. Khandoker et al., "Cardiac Autonomic Dysfunction in Individuals with Anxiety and Stress: A Machine Learning–Based HRV Analysis," *Frontiers in Physiology*, 2020.

[10] R. P. Feynman and F. Torricelli, "Flexible Printed Circuit Technology and Applications," *IEEE Circuits and Devices Magazine*, vol. 9, no. 6, pp. 21–28, 2003.

[11] J. Perelaer et al., "Printed Electronics: The Challenge of Conductive Inkjet Printing," *Journal of Materials Chemistry*, vol. 20, no. 39, pp. 8446–8453, 2010.

[12] Espressif Systems, "ESP32 Technical Reference Manual," 2020.

[13] AffectiveROAD Project, "AffectiveROAD_Data_w1dqSB9 Dataset: Multimodal Physiological Signals for Mood and Affective State Estimation," 2018. Available: https://affectiveroad.org/datasets