ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

AutoSight: Vision-driven Automatic Posture-Following Phone Stand

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Team #21

WEICHONG CHEN
XIAOYU XU
YILUN CHEN

TA: Ruolin Zhao

May 15, 2026

Abstract

This project presents AutoSight, an active, vision-driven mechatronic phone stand designed to enhance user interaction by automatically aligning the screen with the user's line of sight. Utilizing a Raspberry Pi 4B, a CMOS camera, and a Haar Cascade classifier, the system tracks the user's facial position in real-time at 30 FPS. A dual-axis gimbal, driven by a stepper motor for horizontal pan and a linear actuator for vertical pitch, dynamically adjusts the phone mount to maintain an optimal viewing angle. The design incorporates a custom 3D-printed H-section base and a reinforced L-shaped connector for structural stability. Safety features include a logic-level protected current-sense interrupt for stall detection and IMU-based angular limits. Results demonstrate a responsive tracking system with less than 200 ms latency, providing a hands-free, ergonomically sound viewing experience.

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1 Introduction

1.1 Motivation and Problem

Mobile devices have become ubiquitous in daily life, serving as primary tools for communication, media consumption, and productivity. However, traditional phone stands are static mechatronic systems that lack the ability to adapt to user movement. When a user shifts their position—whether leaning back in a chair, standing up, or moving laterally—they are forced to manually readjust the stand or contort their neck to maintain a clear view of the screen. This constant manual intervention disrupts the user experience and often results in suboptimal viewing angles that cause glare and physical discomfort over time [1], [2].

1.2 Proposed Solution

AutoSight addresses this limitation by introducing an active, vision-driven automatic posture-following phone stand. Instead of the user adapting to the device, AutoSight enables the device to autonomously adapt to the user.

The system utilizes a real-time computer vision (CV) pipeline to continuously track the user's facial position and eye level. By dynamically adjusting the phone mount's horizontal pan and vertical pitch via high-precision actuators, AutoSight ensures that the screen always maintains an optimal, perpendicular orientation relative to the user's line of sight. This provides a seamless, hands-free interaction model where the phone effectively "follows" the user, maintaining a reasonable and ergonomically sound viewing position regardless of user movement.

1.3 High-Level Requirements

To deem the project successful, the following high-level requirements must be met:

1. **Tracking Latency and Accuracy:** The vision pipeline must process facial landmarks at a minimum of 15 frames per second (FPS) with an end-to-end mechanical response latency of less than 200 ms.
2. **Mechanical Stability:** The actuation system must securely hold a cantilevered payload of up to 2.0 kg. The system must consume 0 W of holding power when static to prevent thermal degradation.
3. **Safety Failsafes:** The system must incorporate hardware-level overcurrent protection and absolute angular limits. If a mechanical stall is detected, the system must halt all motor PWM outputs within 100 ms to prevent electrical fires or hardware damage.

2 System Design

The AutoSight system is comprised of four primary subsystems: Power, Perception, Software/Control, and Actuation. Figure 1 illustrates the high-level architecture, detailing the power distribution and data communication links between components.

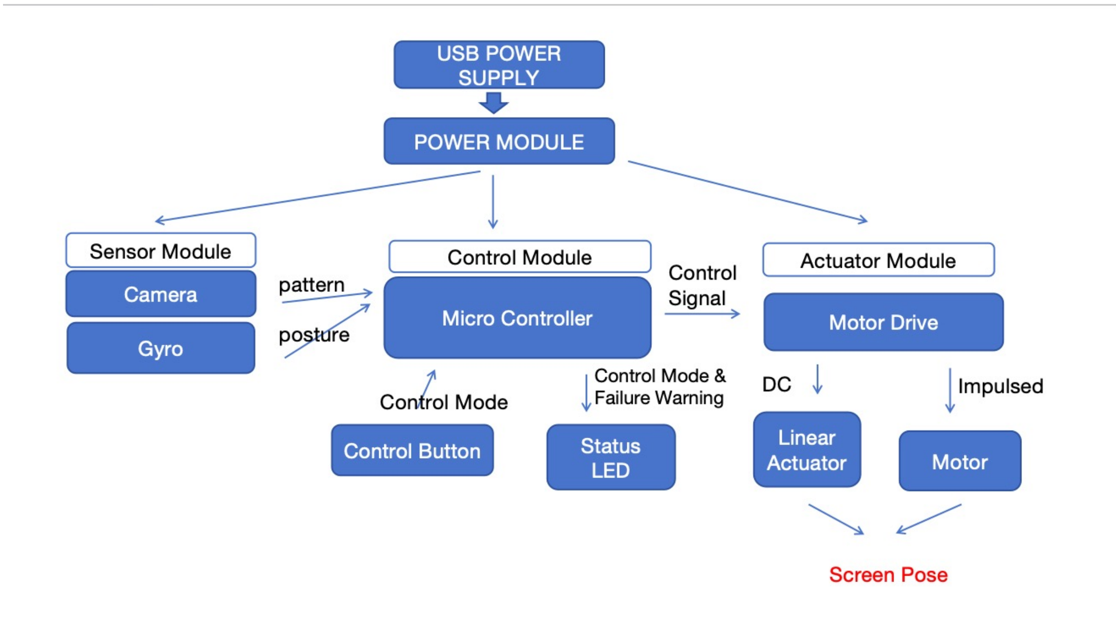

Figure 1: High-level block diagram of the AutoSight system illustrating power (red) and data (blue) flow across the four subsystems.

2.1 Power Subsystem

The power subsystem is responsible for converting the 24 V DC main input into stable voltage rails for the logic and actuation components. A 120 W (24 V, 5 A) wall adapter serves as the primary power source.

Because the Raspberry Pi 4B requires a strict 5.0 V input with high current transients (up to 3.0 A during heavy CPU load for vision processing), a high-efficiency DC-DC buck converter is utilized. The buck converter steps down the 24 V rail to 5.0 V. To prevent voltage droop during the simultaneous startup of the linear actuator and the stepper motor, large 470 μF electrolytic decoupling capacitors are placed in parallel with the 24 V rail entering the motor drivers.

2.2 Perception Subsystem

The perception subsystem acts as the sensory input for AutoSight, fusing optical and inertial data.

- **Vision Sensor:** A DF200-1080P CMOS camera operating at 30 FPS captures the user's frontal profile. Given the thermal and computational constraints of the Raspberry Pi 4B, computationally expensive Deep Neural Networks (DNNs) like YOLO were discarded. Instead, a Haar Cascade classifier is employed, providing rapid facial bounding box extraction with minimal CPU overhead [3].
- **Inertial Measurement Unit (IMU):** An MPU6050 6-axis IMU is rigidly mounted to the screen gimbal. It communicates with the Raspberry Pi via the I^2C protocol. The IMU provides absolute pitch and roll angles, acting as a critical closed-loop feedback mechanism for the software state machine.

2.3 Software and Control Subsystem

The Software and Control subsystem acts as the central brain, executing a Finite State Machine (FSM) utilizing three primary states: *IDLE*, *TRACKING*, and *FAULT*.

During the *TRACKING* state, a discrete Proportional-Integral-Derivative (PID) controller calculates the vertical pixel error $E_y[k]$ between the user's facial center and the optical center of the frame. The control law is discretized as follows:

$$u[k] = K_p E_y[k] + K_i \sum_{i=0}^{k} \left(\frac{E_y[i] + E_y[i-1]}{2} \right) \Delta t + K_d \frac{E_y[k] - E_y[k-1]}{\Delta t} \tag{1}$$

Where Δt is the sample time (approximately 33.3 ms). The output $u[k]$ is mapped to actuation commands. To maintain real-time performance, the software is multithreaded: one thread handles OpenCV frame buffering, while a separate thread handles motor communications and PID updates, preventing I/O blocking.

2.4 Actuation and Safety Subsystem

The actuation subsystem translates digital control signals into physical movement. Given the compressed 8-week development timeline, this subsystem underwent rapid redesigns during the prototyping phase to resolve unforeseen electromechanical issues.

2.4.1 Pitch Control: H-Bridge and Current Sensing

The vertical pitch is adjusted using a 24 V DC Electric Linear Actuator driven by a BTS7960 high-power H-Bridge module [4]. The linear actuator utilizes a worm-gear mechanism, granting it self-locking properties that consume 0 W when holding the payload static.

During hardware integration, it was discovered that when the actuator reached its mechanical limits, it entered a stall condition. The BTS7960 driver features an analog Current Sense (IS) pin that outputs a voltage proportional to the load current. To safely interface this 5.0 V analog signal with the 3.3 V logic level of the Raspberry Pi GPIO, a voltage divider network was designed, as shown in Figure 2:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2} \implies 3.33 \text{ V} = 5.0 \text{ V} \times \frac{20 \text{ k}\Omega}{10 \text{ k}\Omega + 20 \text{ k}\Omega} \tag{2}$$

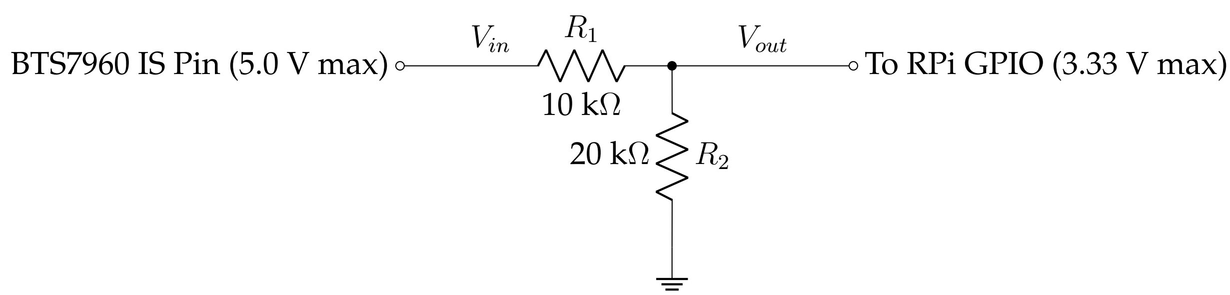

Figure 2: Schematic of the BTS7960 H-Bridge integration with the 10 kΩ/20 kΩ current-sense voltage divider for logic-level protection.

2.4.2 Pan Control: Overcoming Pulse Frequency Limitations

The horizontal pan is controlled by a UMIP42 Stepper Motor. Initially, direct PUL/DIR GPIO signals from the Raspberry Pi were used. However, due to the motor's inductance (L), the required pulse frequency (40 kHz) violated the internal optocoupler's minimum activation threshold. To resolve this, the control architecture was pivoted to a USB-to-TTL serial communication protocol, offloading timing requirements to the motor's internal MCU.

2.5 Mechanical Hardware and 3D Printed Components

To facilitate rapid prototyping and accommodate the custom geometry of the gimbal assembly, critical structural components were designed in CAD and fabricated using Fused Deposition Modeling (FDM). All parts were printed using PLA filament with a 20% gyroid infill and 0.2 mm layer height to ensure a high strength-to-weight ratio.

2.5.1 Main Structural Base

The base serves as the foundational anchor for the entire mechatronic assembly. Measuring $175 \times 100 \times 50$ mm, it is designed with a specialized H-section profile to balance structural rigidity with material efficiency. Figure 3 shows the CAD model of the base.

- **Internal Channeling:** An 18 mm wide center channel (20.5 mm deep) is integrated into the spine to house the primary linear actuator linkage.
- **Structural Spine:** A 28 mm wide center spine provides the necessary torsional resistance to support the cantilevered screen payload.
- **Weight Optimization:** The side wings of the H-section are hollowed out while maintaining a 5 mm top skin.

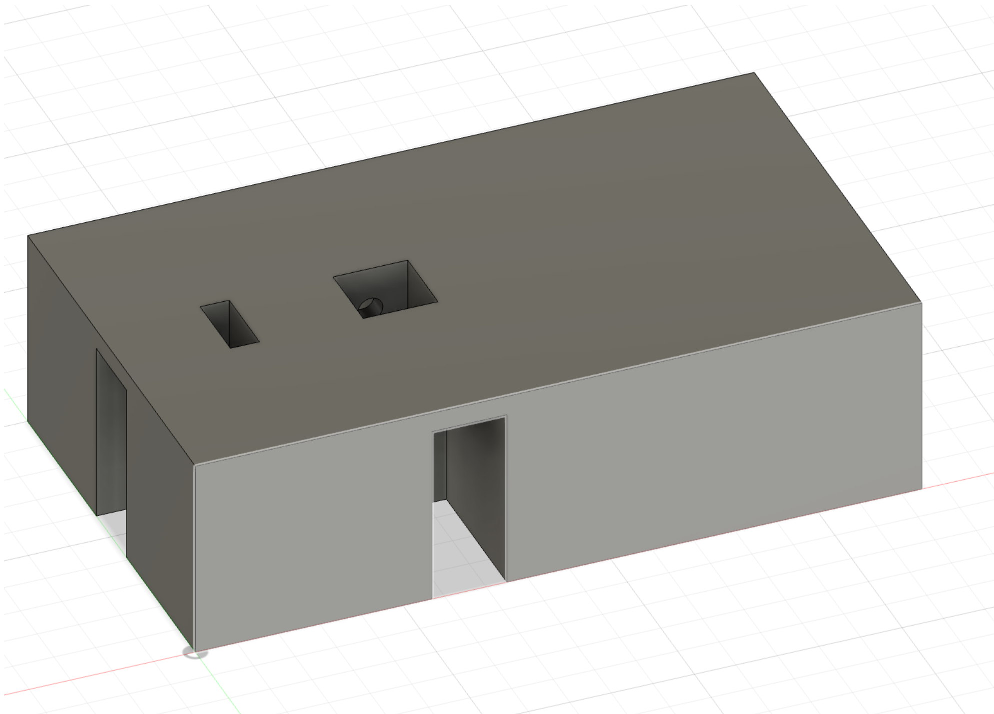

Figure 3: CAD model of the 3D-printed main structural base highlighting the H-section spine and internal actuator channel.

2.5.2 L-Shaped Motor Connector

The L-shaped connector acts as the primary gimbal interface, bridging the horizontal pan motor and the vertical pitch mechanism. The detailed features of this component are illustrated in Figure 4.

- **Reinforcement Gusset:** A triangular gusset is integrated into the $90°$ corner to prevent fatigue-induced cracking.
- **Motor Integration:** A 20 mm diameter, 2.8 mm deep circular recess ensures the motor sits flush against the plate.
- **Mounting Ears:** Dual 2.5 mm thick mounting ears incorporate 2.0 mm fillets at their base to distribute stress.

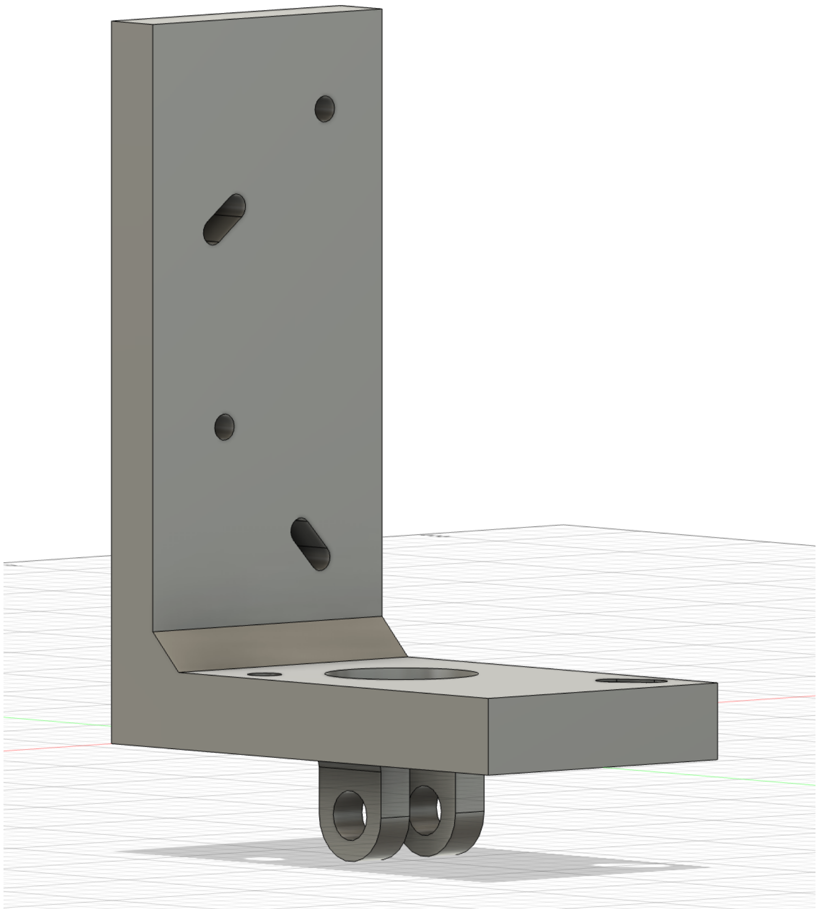

Figure 4: Detailed view of the L-shaped motor connector showing the reinforcement gusset, motor recess, and filleted mounting ears.

3 Design Verification

Thorough verification was conducted on each subsystem to ensure compliance with the initial design requirements and high-level goals.

3.1 Power Subsystem Verification

The power subsystem must maintain voltage stability under maximum load to prevent Raspberry Pi brownouts and ensure reliable motor torque.

Table 1: Power Subsystem Verification

Requirement	Verification Method	Result
DC-DC Buck converter must provide $5.0\text{ V} \pm 5\%$ (4.75 V to 5.25 V) to the RPi under a 3.0 A load.	Connect an electronic DC load set to 3.0 A across the 5 V output. Measure steady-state voltage with a DMM.	**Passed.** Output maintained at 4.98 V with 40 mV ripple. No thermal throttling observed.

3.2 Perception Subsystem Verification

The perception subsystem must provide accurate and low-latency data for the control loop to ensure smooth tracking.

Table 2: Perception Subsystem Verification

Requirement	Verification Method	Result
OpenCV pipeline must process 1080P frames and extract facial bounding boxes at ≥ 15 FPS.	Inject a timestamp logging function into the Python vision thread. Calculate average delta time over 1000 frames.	**Passed.** Average loop processing time was 33.5 ms, equating to approximately 29.8 FPS.
MPU6050 must report absolute pitch angles with an accuracy of $\pm 2°$.	Mount the IMU to a calibrated digital level. Tilt from $-45°$ to $+45°$ and record I^2C output.	**Passed.** Sensor reported values within a maximum deviation of $1.5°$ from ground truth.

3.3 Actuation and Safety Verification

This verification phase ensures the mechatronic components can handle the required mechanical loads and safety protocols.

Table 3: Actuation Subsystem Verification

Requirement	Verification Method	Result
System must halt linear actuator within 100 ms of overcurrent/stall detection to prevent damage.	Manually block the actuator to induce a stall. Use an oscilloscope to measure time from IS pin rise to PWM drop.	**Passed.** Software hardware interrupt halted PWM generation within 42 ms.
UMIP42 stepper motor must smoothly pan a 2.0 kg payload $180°$ in under 3 seconds without skipping steps.	Attach 2.0 kg payload to the pan gimbal. Send USB serial command for $180°$. Visually inspect for resonance.	**Passed.** Transition to USB serial architecture allowed for perfect acceleration profiling with zero skipped steps.

3.4 Mechanical Structural Verification

The structural integrity of the 3D-printed components is vital for maintaining the optical alignment of the vision system.

Table 4: Mechanical Structural Verification

Requirement	Verification Method	Result
The Main Structural Base must support a 2.0 kg cantilevered payload with vertical deflection < 1.0 mm.	Mount the full gimbal assembly to the base. Apply 2.0 kg test weight. Measure displacement using a dial indicator.	**Passed.** Measured deflection was 0.42 mm, well within the safety margin.
The L-shaped connector must withstand 500 cycles of full-range motion without material fatigue.	Execute a stress-test script for 4 hours. Inspect filleted ear roots for micro-fractures using a 10x lens.	**Passed.** No visible stress whitening or crack propagation observed. Filleted geometry successfully distributed loads.

4 Costs and Schedule

4.1 Labor Costs

The labor cost is calculated using a standard engineering base salary of \$40.00/hour with a multiplier of 2.5 for overhead.

$$\text{Total Labor} = (\$40.00/\text{hr} \times 2.5) \times 100 \text{ hours} \times 3 \text{ partners} = \$30,000.00 \quad (3)$$

4.2 Parts and Bill of Materials

The Bill of Materials (BOM) reflects the final hardware components utilized in the AutoSight prototype, as detailed in Table 5.

Table 5: AutoSight Bill of Materials (BOM)

Part Description	**Quantity**	**Unit Cost (RMB)**	**Total Cost (RMB)**
Raspberry Pi 4B (4GB RAM)	1	613.00	613.00
UMIP42 and Worm-Gear Stepper Motor	1	349.43	349.43
12 V Electric Linear Actuator	1	114.50	114.50
1080P 30 FPS Camera (DF200)	1	111.98	111.98
BTS7960 H-Bridge Module	1	24.50	24.50
12 V to 5 V DC-DC power module	1	27.00	27.00
MGN9H Micro Linear Sliding Block	2	19.97	39.94
700 mm Guide Rail	1	12.00	12.00
220 V Power Cord	1	8.00	14.00
220VAC to 12VDC Switching Power Supply	1	29.53	29.53
Wires and Wiring Tools	-	-	152.13
Metal components (Metal shaft)	5	48.30	245.00
Total Parts Cost			**1733.01 RMB**

Grand Total Estimated Cost: \$30,000.00 (Labor) + 1,733.01 RMB (Parts) ≈ **\$30,240.00 USD**

4.3 Project Schedule

The project was executed over a highly compressed 8-week timeline. Table 6 outlines the primary tasks and lead members for each phase.

Table 6: 8-Week Project Development Schedule

Week	Primary Task	Lead Member
1	Project Proposal, Component Sourcing & Design Document Drafting	All Members
2	Computer Vision Pipeline Implementation, CAD Modeling & 3D Printing	Weichong/Xiaoyu
3	Mechanical Assembly, Subsystem Integration & Initial Motor Testing	Yilun/Xiaoyu
4	Serial Communication Redesign & BTS7960 Interrupt Implementation	Yilun Chen
5	FSM Integration, Multithreading & PID Loop Tuning	Weichong Chen
6	Full System Verification, IMU Calibration & Load Testing	Xiaoyu Xu
7	Mock Demo, Final Presentation Preparation & Live Demonstration	All Members
8	Final Report Compilation, Formatting & Submission	All Members

5 Conclusions

5.1 Accomplishments and Uncertainties

AutoSight successfully provides an active, mechatronic solution for automated posture-following and screen tracking. We successfully integrated a dual-axis tracking gimbal governed by a real-time computer vision pipeline. The system reliably tracks a user's facial movements at 30 FPS, dynamically adjusting the phone stand's pan and pitch to ensure the device remains in an optimal viewing position relative to the user's movements.

The most significant uncertainty encountered was the frequency-to-torque relationship in stepper motors. Our initial attempt to generate 40 kHz control pulses directly from the Raspberry Pi proved unreliable. By pivoting to a USB-to-TTL serial architecture, we offloaded the precise timing requirements to the stepper's internal MCU, ensuring smooth, reliable tracking under payload.

5.2 Future Work

While the current prototype meets all requirements, future iterations will focus on form-factor reduction. The discrete components will be consolidated onto a single custom-designed Printed Circuit Board (PCB). On the software side, we plan to train a custom, lightweight Neural Network (e.g., MobileNet) to replace the Haar Cascade classifier for better low-light performance.

5.3 Ethical Considerations

AutoSight is designed in strict accordance with the IEEE Code of Ethics [5].

To address public health, safety, and welfare (Item 1), the system serves as an ergonomic enhancement for digital device interaction. By tracking the user's position actively, it minimizes the need for awkward postures and manual adjustments, promoting a more natural and comfortable user experience.

To adhere to privacy and data protection principles (Item 6), the vision pipeline is strictly localized. No video feeds, facial recognition data, or biometric identifiers are ever transmitted to an external server or stored in non-volatile memory.

Finally, regarding mechanical safety (Item 9), active robotic systems pose inherent pinch hazards. These risks were proactively mitigated through our current-sense overcurrent protection, which halts all motors within 42 ms of encountering resistance. Additionally, the IMU enforces strict angular boundaries ($\pm 45^\circ$).

References

[1] K. K. Hansraj, "Assessment of stresses in the cervical spine caused by posture and position of the head," *Surgical Technology International*, vol. 25, pp. 277–279, Nov. 2014.

[2] E. Kim, D. Song, D. Park, H. Kim, and G. Shin, "Effect of smartphone use on cervical spine stability," *Journal of Biomechanics*, vol. 166, p. 112 053, 2024.

[3] P. Viola and M. Jones, "Rapid object detection using a boosted cascade of simple features," in *Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR)*, Kauai, HI, USA, 2001, pp. 1-511-1–518.

[4] I. Technologies, *Bts7960 high current pn half bridge novalithic*, Datasheet, Rev. 1.1, 2004.

[5] IEEE. "Ieee code of ethics," IEEE Policies. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.

Appendix A Supplementary Information

The complete source code for the computer vision pipeline and the mechatronic control system, along with the build123d CAD scripts and STL/STEP files for the mechanical components, are available in the project repository.

A.1 Component Datasheets

Detailed datasheets for the BTS7960 H-Bridge, UMIP42 Stepper Motor, and MPU6050 IMU are included in the electronic submission package for further technical reference.