3. DESIGN APPROACH

Awake-Pilot aims to address the issue of accidents caused by driver fatigue by continuously monitoring driver behavior and promptly issuing an alert whenever drowsiness is detected within the driver. This is done to enhance driver safety through real-time monitoring of fatigue within the user, and once signs of drowsiness are detected, Awake-Pilot immediately provides an alert through vibration or sound, depending on the degree of drowsiness. To achieve this, the Awake-Pilot Team has done comprehensive research with careful analysis to evaluate various design options, system requirements, and hardware and software integrations. Essential requirements considered include continuous real-time eyelid detection and facial monitoring, reliability in varying lighting conditions, and promptness in efficient and effective multimodal alerts. Major constraints that were considered were economic limitations of a budget of $1,000 and safety constraints ensuring the alerts are effective, yet upholding driver safety at the highest level. Adhering to industry standards such as ISO 16750-2, IEEE 1857, and ISO 26262 influenced the design approach, ensuring the highest reliability, safety, and interconnectivity between subsystems. The following sections delve into the chosen design solution, specifying the reason behind system design decisions, subsystem configurations, and component selections, demonstrating how Awake-Pilot effectively meets the defined project requirements and constraints.

3.1. Design Options

Multiple design options were considered in the development of the Awake-Pilot. When considering the design of the subsystems, two primary solutions were evaluated for the Drowsy Driver Detection and Alert System. Each solution was thoroughly assessed based on system performance, implementation feasibility, cost, power requirements, and adherence to relevant standards. After careful evaluation, the following sections outline the considered design options, and the chosen solution, highlighting their benefits, limitations, and the rationale for the final selection based on its reliability and ability to meet all key constraints.

3.1.1. Design Option 1

The first approach the team explored involved using radars and motion sensors to monitor drowsiness symptoms. This design would use a combination of a heart rate sensor, accelerometer, and grip pressure sensor to detect changes in physical state, such as slower heart rate variability, head tilts, or reduced grip strength on the wheel. A microcontroller would interpret the data and trigger a buzzer or vibration motor if drowsiness indicators were present. While this method offered advantages like lower cost, reduced power consumption, and no dependence on lighting, it lacked the level of accuracy needed. The system would also rely heavily on consistent sensor placement and individual calibration, which could be difficult to manage in practical use. Given these limitations and the goal of developing a more effective and versatile solution, the team decided not to move forward with this option.

3.1.2. Design Option 2

The other design option considered is a camera-based system combined with computer vision, machine learning, and radar sensing to detect signs of driver drowsiness. A camera mounted on the dashboard captures real-time footage of the driver's face, which is analyzed using a trained machine learning model, typically a convolutional neural network (CNN). This model monitors key indicators of fatigue, such as slow or frequent blinking, long eye closures, yawning, and head nodding. To improve accuracy and compensate for limitations caused by poor lighting or obstructions, a radar sensor is also integrated into the system to detect micro-movements such as head nods or subtle posture shifts. The processing is handled by an embedded computing platform, such as the NVIDIA Jetson Nano, which can run the model and sensor fusion logic efficiently. When drowsiness is detected, the system activates alerts such as vibrations or audio signals to wake the driver. The team chose this solution for its high accuracy, multimodal sensing capabilities, and ability to detect subtle fatigue-related behavior. Although it requires more processing power and careful integration, the benefits in terms of reliability and real-time performance make it the best fit for our project.

3.2. System Overview

On a base level, the Awake-Pilot takes data from a camera and a radar and processes it for changes in body and facial movements indicating drowsiness, and if any are found, it outputs auditory and vibration alerts to wake the user. Figure 3-1 shows a black box diagram of how the device works. The only input required by the user is to power the device on, and the Awake-Pilot takes care of the rest

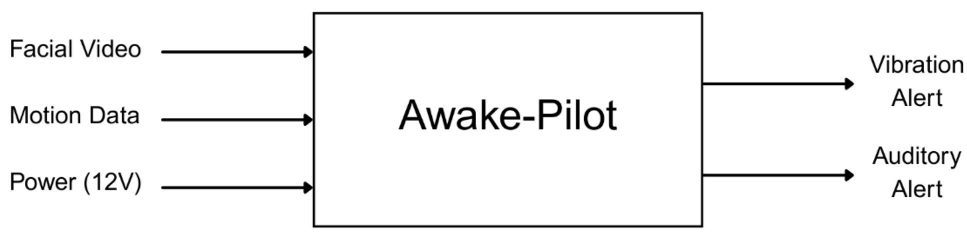

Fig. 3-1: Awake-Pilot Basic Overview (Level 0)

Figure 3-2 shows a more in-depth overview of the Awake-Pilot's design and the subsystem compatibility of all three subsystems and how each system works in tandem for the device to function, which is all powered by the user's car's auxiliary port. The camera and radar are the two main components for gathering detection data, which allows for the buzzer and vibration kit to be used to alert the user. The microcontroller processes the detection data from the radar and camera, which is then output to the alert system to alert the driver.

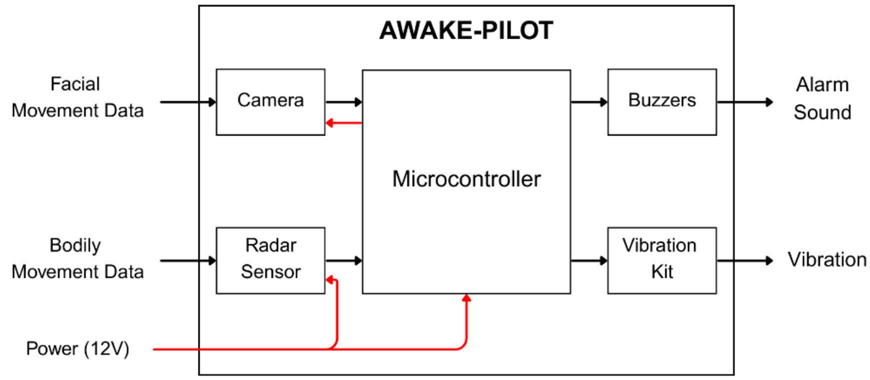

Fig. 3-2: Awake-Pilot Functionality (Level 1)

When the system powers on, the camera continuously monitors the driver's facial movements for signs of drowsiness, such as prolonged eye closure or nodding, while the radar sensor monitors the driver for any changes in bodily movements, breathing, and heart rate patterns. Both these inputs are then processed by the microcontroller in real time. If drowsiness is detected, a signal is sent to both the motor and sound systems, which allows for the vibration kit to buzz and an alarm to sound, alerting the driver. This closed-loop interaction between sensing, processing, and alerting systems ensures a quick and effective response.

3.2.1. Microcontroller

Several microcontrollers were considered in order to achieve the desired functionality for the Awake-Pilot. To efficiently control all aspects of the device, it was important to consider a microcontroller with a significant amount of RAM and camera and radar support. Table 3-1 shows the specifications of the options considered.

Table 3-1: Microcontroller Options

Model	**GPU**	**RAM**	**Power Draw**	**Real-Time Vision Capability**
Requirements	**Dedicated AI-accelerator**	**4 GB**	**≤ 10 W Peak, < 2 W Idle**	**High-Level Visual Processing**
NVIDIA Jetson Nano [1]	128-core CUDA GPU	4 GB	5-10W	Excellent
Raspberry Pi 4B [2]	VideoCore VI (no AI)	4 GB	2.5-7W	Moderate
NXP i.MX 8M Plus [3]	2.3 TOPS NPU	2 GB	3-5W	Good

The Jetson Nano was selected for its strong GPU support, enabling parallel processing of video frames using deep learning and classical vision algorithms. It is the best balance of processing power, low power consumption, and affordability. Compared to the Raspberry Pi 4B, the Jetson Nano offers significantly better performance in running GPU-accelerated models required for facial behavior analysis. The NXP i.MX 8M Plus, while energy-efficient and equipped with a neural processor, would make it more difficult to develop the required software due to limited software integration support and higher complexity.

3.3. Subsystems

The Awake-Pilot incorporates three subsystems, each with its own unique contribution to the overall functionality of providing immediate alerts once driver fatigue is detected. The subsystems are as follows:

1. **Imaging Processing Subsystem** – Continuously captures real-time video and monitors the driver's facial and eye movement for the data to be processed on the Jetson Nano through a custom drowsiness detection algorithm.
2. **Radar Subsystem** – Uses radar sensing technology to monitor bodily changes in the driver for signs of fatigue, adding additional support to the visual detection provided by the imaging processing subsystem.
3. **Alert Subsystem** – Allows for multimodal alerts to be issued to the driver through vibrations and buzzers whenever signs of fatigue are detected, exceeding the limit needed for an alert.

These three subsystems all work in tandem with each other, providing accurate and real-time detection and reliable alerts to reduce the risk of drowsy driving and improve overall road safety. The following sections detail the approach taken into consideration in the design and integration of each subsystem.

3.3.1 Image Processing

The image processing subsystem consists of three main components: the camera, the OpenCV image processor, and a custom real-time drowsiness detection algorithm accelerated by the GPU on the microcontroller. The system is controlled by a Python program interface. Awake-Pilot begins its image processing as soon as the device is powered on, and the driver is detected within the seat. The flowchart in Figure 3-3 illustrates the system hierarchy.

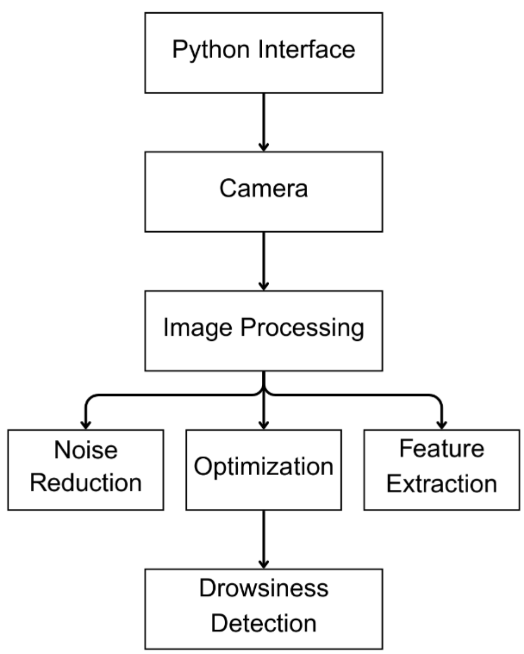

Fig. 3-3: Image Processing Flowchart

Upon system startup, the Python interface initializes the camera using the CSI port, enabling high-frame-rate video capture at 1080p. Real-time video frames are continuously captured and passed to the OpenCV processing pipeline. OpenCV is used for image preprocessing, which includes grayscale conversion, histogram equalization, Gaussian blur, and adaptive thresholding. These steps enhance image quality, remove noise, and isolate key facial features for analysis. After preprocessing, face and eye regions are extracted using Haar cascades or a lightweight deep learning model like a MobileNet-SSD. Through the integration of all these key features, the system is able to track eye status (open or closed) and head position in real time.

The detection logic runs a time-based analysis of the driver's eye state. If the eyes remain closed for a threshold period (e.g., 1.5 seconds) or if a repeated head-nodding pattern is detected, the Python script flags this as a drowsiness event. This information is relayed immediately to the alert subsystem, which activates both a buzzer and seat vibrations to alert the driver.

Several camera modules were considered for real-time video capture under variable lighting conditions. Table 3-2 compares the shortlisted options and highlights the selected camera.

Table 3-2: Camera Options

Model	**Megapixels**	**Compatibility**	**Driver Support**	**Lighting Requirement**
Requirements	**≥ 5 MP**	**Universal or CSI interface**	**Plug-and-play**	**Operates reliably in typical vehicle cabin lighting**
Logitech C270 [4]	5	Universal (USB/UVC)	Excellent	Ambient light
Raspberry Pi Camera Module V2 [5]	8	Raspberry Pi (CSI)	Moderate	Good lighting needed
Arducam IR Module [6]	5	CSI (Jetson/Pi only)	Limited	Low-Light optimized

The Logitech C270, as shown in Figure 3-4, was selected for its broad compatibility, plug-and-play USB support, and reliable performance in typical indoor and cabin lighting conditions. With built-in support through the UVC (USB Video Class) standard, the C270 operates seamlessly with Jetson Nano and most Linux distributions, eliminating the need for custom drivers or CSI interface tuning.

Fig. 3-4: Logitech C270 Camera [7]

Although the Raspberry Pi Camera Module V2 offers higher resolution, it is limited to boards with a native CSI interface and lacks flexibility in system design. The Arducam IR camera, while useful in dark environments, introduces additional complexity, such as IR lighting and power management. Given that the intended operating environment is an illuminated vehicle cabin, these features were not necessary and would have added to the system cost and development time.

The Python-based detection script benefits from OpenCV's extensive support for real-time video processing, facial detection, and easy integration with machine learning libraries. Unlike traditional OCR systems, this subsystem is optimized for behavioral analysis rather than text extraction. Common OpenCV functions used include;

- **cv2.cvtColor() -** to convert the image to grayscale
- **cv2.equalizeHist() -** to enhance contrast
- **cv2.GaussianBlur() -** to reduce image noise
- **cv2.CascadeClassifier() -** for face and eye detection
- **cv2.threshold() -** for binarization in low-light preprocessing

The use of Python, combined with Jetson Nano's GPU acceleration, allows for a flexible, maintainable, and highly efficient pipeline suitable for real-time in-vehicle monitoring.

In summary, the image processing subsystem of Awake Pilot uses a Jetson Nano microcontroller and a Logitech C270 camera to capture and analyze driver behavior in real time. This configuration ensures high accuracy in detecting signs of drowsiness while meeting the budget and power constraints of an in-vehicle embedded system.

3.3.2. Radar

To ensure proper and accurate results of chest movement data, the radar subsystem of the Awake-Pilot uses a radar sensor module to execute signal processing that filters and normalizes reflection signals on a real-time fatigue-detection algorithm. The interface initializes the radar parameters on start-up and immediately extracts bodily movement data to be executed on the Jetson Nano. The workflow of operations is shown in the radar flowchart in Figure 3-5.

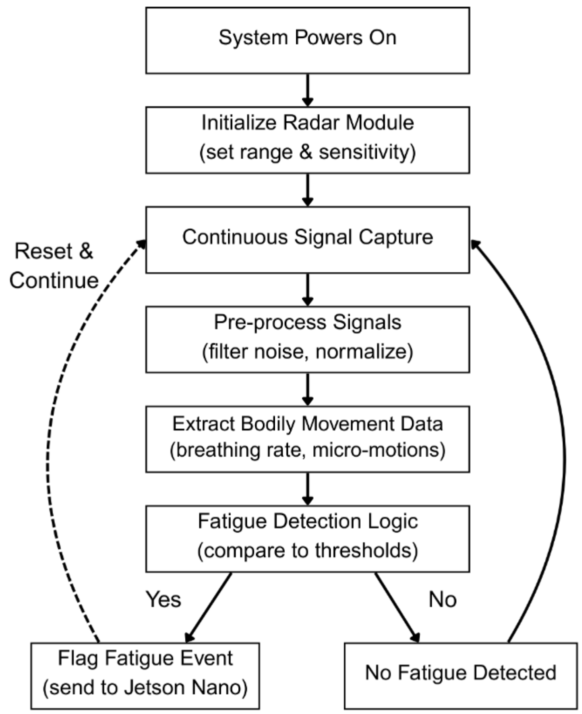

Fig. 3-5: Radar System Flowchart

When considering options for the radar, the team chose three viable options as shown in Table 3-3. There are many parameters that have gone into determining the chosen radar, such as operating frequency, motion detection, interface, and microcontroller compatibility, as well as the software tools available.

Table 3-3: Radar Options

Product	**Radar Type**	**Operating Frequency**	**Interface**	**MCU**	**Micro-Motion Detection**	**Software Tools**
Requirements	**Pulsed Coh. or mmWave FMCW**	**≥ 60 GHz**	**USB-C / high-speed digital**	**On-board MCU**	**Mandatory**	**SDK + GUI**
XE125 [8]	Pulsed Coh. Radar	60 GHz	USB-C	Integrated STM32L4	Yes	SDK + GUI
RCWL-0516 [9]	CW Doppler	3.2 GHz	Digital OUT	No	No	None
Infineon BGT24LTR11 [10]	FMCW / Doppler	24 GHz	Analog I/Q	Limited	Limited	DSP + MCU req

Based on the high-quality pulse coherent radar technology, which makes it possible to accurately detect micro-motions like breathing and minor body shifts essential for tracking driver drowsiness, the XE125 radar (Figure 3-6) is the most appropriate choice the team has decided on. The RCWL-0516 is a low-cost Doppler radar intended for basic motion detection, which means it is not deep or precise enough for physiological monitoring needs to handle real-time capabilities. Although the Infineon BGT24LTR11 has more sensing potential than the RCWL-0516, its need for extra signal processing disqualifies it has as an option needed for quick development and integration. All factors considered, the XE125 offers the best mix of optimum functionality, usability, and development support required for applications including intelligent fatigue detection.

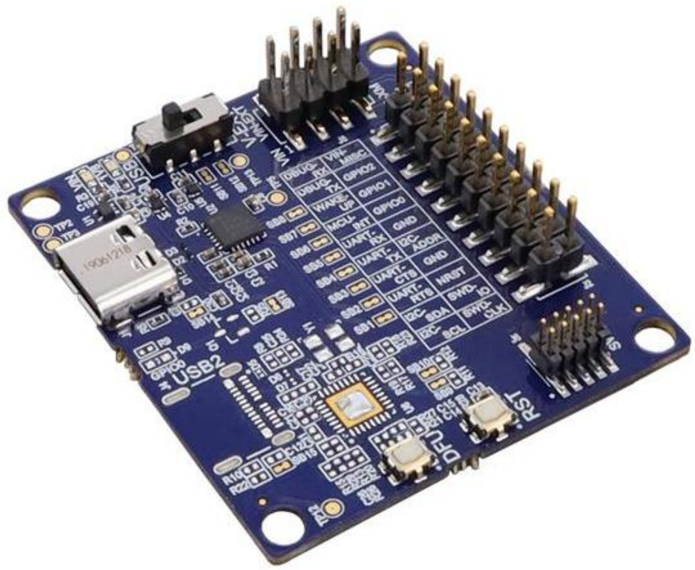

Fig. 3-6: XE125 Radar [11]

The radar subsystem consists of a single XE125 radar device, which allows for the detection of fatigue to be accurately and reliably monitored by the smallest bodily changes associated with the driver's upper chest movement rate. With the Acconeer’s A121 pulsed radar technology, the XE125 is able to detect chest movement in connection with the breathing rate and subtle micro-movements of the upper body. Measurement of these vital signs and movement is essential for the early detection of driver fatigue. In a normal driver, the most common fatigue-related symptom is a change in breathing rate and body movement, which is easily detectable with the software of the XE125 radar.

The XE125 radar is the best option due to the micro-motion sensor that can detect the smallest changes in breathing rate and movements of the upper body, along with the software tools that can be used for full integration with the other subsystems.

3.3.3. Alert

The alert subsystem for the Awake-Pilot consists of a vibration kit and a noise kit, which are embedded in a seat cushion. The kits are triggered by valid detections through a microcontroller connected by USB, powered by the car's auxiliary port, causing significant stimuli for the driver.

The vibration kit for the alert subsystem is required to operate with a high enough power supply and high RPM to provide sufficient vibration to awaken the user. The selected options and their specifications are shown in Table 3-4 below.

Table 3-4: Vibration Kit Options

Product	**Operating Voltage**	**Speed (RPM)**	**Cost**
Requirements	**3-5V**	**≥ 3000 RPM**	**<$20**
USB 3-Speed Vibration Motor [12]	5 V	3000-4500 RPM	$18.77
Analog Ceramic Piezo Vibration Kit [13]	3-5 V	2000-4000 RPM	$6.59
Uxcell Vibration Motors [14]	12 V	4000 RPM	$13.79

The USB 3-Speed Vibration Motor, as shown in Figure 3-7, is the selected product the team has decided on due to its specifications. While more expensive than our other options, it provides a high RPM, resulting in an efficient alert. It also utilizes a USB cord, which is compatible with the Jetson Nano.

Fig. 3-7: USB 3-Speed Vibration Motor [15]

The noise kit for the alert subsystem must be inexpensive and is required to operate with an efficient power supply and not exceed a certain threshold of decibels to prevent hearing loss. The selected options and their specifications are shown in Table 3-5 below.

Table 3-5: Noise Kit Options

Product	**Operating Voltage**	**Specs**	**Cost**
Requirements	**3-5 V**	**90 dB**	**<$15**
Active Piezo Electronic Buzzers [16]	3-24 V	90 dB	$5.49
Tatoko Electronic Buzzer Alarms [17]	3-24 V	80 dB	$9.89

Piezo Icstation Buzzer Alarm [18]	12 V	100 dB	$11.99

The team selected the Active Piezo Electronic Buzzers, as shown in Figure 3-8, due to acceptable noise levels and lower cost. The purchase also includes 3 buzzers, leaving room for error and testing. The Tatoko Electronic Buzzer Alarms proved to be too expensive for weaker specifications, while the Piezo Icstation Buzzer Alarm outputs too high a decibel level at 100 dB.

Fig. 3-8: Active Piezo Electronic Buzzers [19]

The alert subsystem should prove cheap and safe to manufacturers and users. Its simple design and quality components will provide an efficient alarm to keep the user vigilant; all while being slotted into an after-market seat cushion that will both be comfortable and easy to install.

3.4. Level 2 Prototype Design

Looking ahead to Design II, software integration compatibility will ensure all subsystems will be interconnected and provide proper functionality. Along with this, the Awake-Pilot will be installed in a shell for visual aesthetics purposes. The device will then be placed on a makeshift driver's seat, created using woodwork, to allow for testing, and for any user to sit and interact with the device. An installed alert subsystem will be included in a seat cushion, as well as a mock steering wheel will be placed on the makeshift driver's seat to provide a proper demonstration of the device in action, which will allow for any modifications to be taken for accessibility and accuracy of the device.

3.4.1. Level 2 Diagram

As shown in Figure 3-9, the Level 2 design for Awake-Pilot will consist of a Jetson Nano used to process fatigue-related detection data that is fed to the camera and radar, which is then sent to an alert system to awake the user.

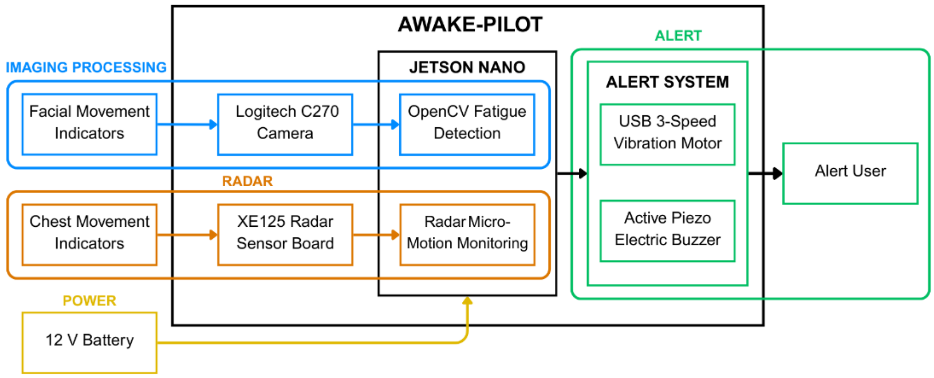

Fig. 3-9: Diagram for Awake-Pilot (Level 2)

Our Level 2 design shows how the Awake-Pilot recognizes fatigue in a user and processes the data detected through the XE125 radar and Logitech C270 camera. This data then feeds the detection into the Jetson Nano, which is powered through a USB cable that is connected to the vehicle's auxiliary port, powered by the car's 12-volt battery. The Jetson Nano registers the input data and outputs to the alert system, triggering a vibration and noise alert to wake the driver.

Awake-Pilot is designed to be a safe, affordable, and efficient device to wake drivers to prevent drowsiness-related incidents. The Level 2 design provides an overview of what the team intends to improve regarding the device's communication and system interconnectivity.

In summary, the Awake-Pilot combines the integrations of camera-based vision, radar sensing, and multimodal alerts in a tight-knit, low-power system to provide dependable, real-time fatigue monitoring and detection while upholding driver and road safety at its highest concern. Each subsystem was chosen and incorporated to meet demands for precision, reliability, power, cost, and ease of installation. The device is easy to operate and understand, as evidenced by the clear explanation of each subsystem and its components, and its straightforward plug-and-play design, allowing drivers to only need to power it on for continuous assurance in safety against drowsy driving.

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