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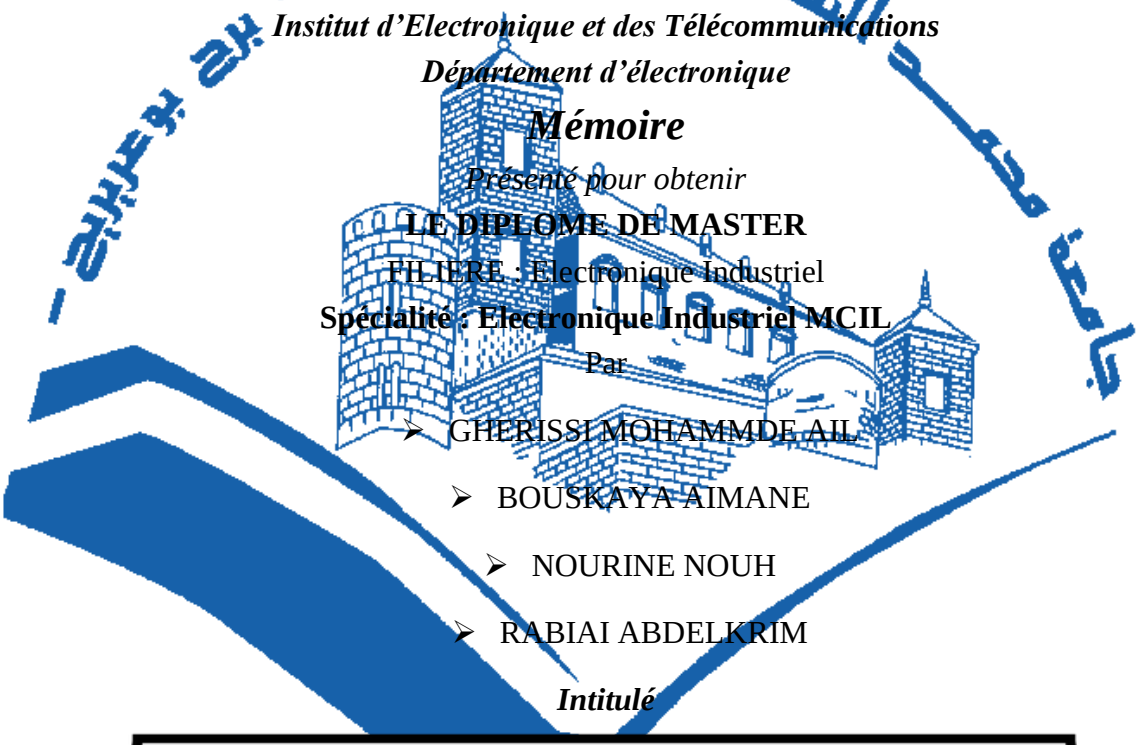

Mémoire

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Intitulé

Smart Desk Assistant

Soutenu le :24/06/2026

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...Finally, we extend our deepest condolences to our families for their unwavering moral support and sacrifices, as well as to all our colleagues in the graduating class of MCIL 2026, and to everyone who contributed, directly or indirectly, to the success of this project.

DEDICATION

I would like to express my sincere gratitude to my supervisors, Prof. Ahmed Ben Amer and Prof. Jadawi Al-Ayashi, for their valuable guidance and continuous support throughout this project. I am deeply grateful to my family for their unwavering encouragement during my academic journey. My heartfelt thanks also go to my friends and colleagues, especially Ali, Nouh, and Abdelkarim, for their support, advice, and friendship, which helped me overcome many challenges.

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ABSTRACT — ENGLISH

Smart Desk Assistant

Design and Development of an AI-Powered Embedded Productivity System

The **Smart Desk Assistant** is an AI-powered embedded system designed to improve productivity by reducing digital distractions through voice interaction, Pomodoro time management, lecture transcription, and adaptive lighting without requiring a smartphone. It features a dual-microcontroller architecture with a hybrid Edge-to-Cloud AI approach, ensuring efficient performance and secure communication. System testing validated most functional requirements, demonstrating reliable operation with a theoretical response latency of **1.76 seconds**. Future developments include hardware miniaturization, on-device AI processing, wake-word detection, and specialized versions for education and language learning.

RESUME — FRANÇAIS

La distraction numérique nuit à la concentration et à la productivité. Pour y répondre, ce projet propose un Assistant de Bureau Intelligent, un dispositif embarqué autonome offrant une interaction vocale par IA, la gestion du temps (Pomodoro), la transcription de cours et un éclairage adaptatif, sans smartphone. Basé sur une architecture à deux microcontrôleurs et une approche Edge-to-Cloud, il assure des performances fiables et une communication sécurisée. Les tests ont validé la majorité des exigences fonctionnelles, avec une latence théorique de 1,76 seconde. Les perspectives incluent la miniaturisation du système, l'intégration d'une détection locale du mot de réveil et le développement de versions dédiées à l'éducation et à l'apprentissage des langues.

ملخص —العربية

يهدف هذا المشروع إلى الحد من التشتيت الرقمي من خلال تطوير **مساعد مكتبي ذكي** مستقل يعتمد على الذكاء الاصطناعي ويوفر التفاعل الصوتي، وإدارة الوقت بتقنية بومودورو، وتدوين المحاضرات، والإضاءة التكيفية دون الحاجة إلى الهاتف الذكي. يعتمد النظام على معالجين من نوع **ESP32-S3** و**ESP32-C3** ضمن بنية **Edge-to-Cloud** تجمع بين المعالجة المحلية والخدمات السحابية لضمان الأداء والكفاءة مع تأمين الاتصالات بتشفير **AES-256**. أظهرت الاختبارات تحقيق معظم المتطلبات الوظيفية بزمن استجابة نظري يبلغ **1.76 ثانية**، مع إمكانية تطوير النظام مستقبلًا عبر تصغير حجمه، وإضافة كشف محلي لكلمة الإيقاظ، وتطوير نسخ متخصصة للتعليم وتعلم اللغات.

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List of Abbreviations

Abbreviation	Full Designation	Description
AES	Advanced Encryption Standard	symmetric encryption standard
AMP	Asymmetric MultiProcessing	asymmetric multiprocessor
API	Application Programming Interface	programming interface
ASR	Automatic Speech Recognition	automatic speech recognition
BCLK	Bit CLocK	I2S serial clock
BLE	Bluetooth Low Energy	low-power Bluetooth
CdCF	Cahier des Charges Fonctionnel	functional specification document
CRC	Cyclic Redundancy Check	cyclic redundancy check
DAC	Digital-to-Analogue Converter	digital-to-analogue converter
DFD	Data Flow Diagram	data flow diagram
DMA	Direct Memory Access	direct memory access
DS3231	Dallas Semiconductor RTC module	real-time clock module
DSP	Digital Signal Processing	digital signal processing
DTIM	Delivery Traffic Indication Map	Wi-Fi beacon interval
eFuse	Electrically programmable Fuse	OTP on-chip electrical fuse
EMC	ElectroMagnetic Compatibility	electromagnetic compatibility
ESP-IDF	ESP-IoT Development Framework	official Espressif SDK
ESP-NN	ESP Neural Network library	Espressif embedded AI library
FAB	Floating Action Button	floating action button (LVGL)
FC	Fonction Contrainte	constraint function (CdCF)
FIFO	First In First Out	first-in first-out queue
FP	Fonction Principale	main function (CdCF)
FR4	Fire Resistant grade 4	standard PCB substrate
FSM	Finite State Machine	finite state machine
GPIO	General Purpose Input/Output	general-purpose I/O pin
GUI	Graphical User Interface	graphical user interface
HMI	Human-Machine Interface	human-machine interface
HTTP	HyperText Transfer Protocol	web transfer protocol
HTTPS	HTTP Secure	HTTP secured by TLS
I2C	Inter-Integrated Circuit	bidirectional serial bus
I2S	Inter-IC Sound	digital serial audio bus
IBD	Internal Block Diagram (SysML)	SysML internal block diagram
INMP441	InvenSense MEMS Microphone model 441	MEMS digital microphone
IoT	Internet of Things	internet of things
ISA	Instruction Set Architecture	processor instruction set
ISR	Interrupt Service Routine	interrupt service routine
JTAG	Joint Test Action Group	hardware debugging interface
JSON	JavaScript Object Notation	data interchange format

LDO	Low Dropout (regulator)	linear voltage regulator
LLM	Large Language Model	large language model
LRCLK	Left-Right CLocK	I2S channel clock
LVGL	Light and Versatile Graphics Library	embedded graphics library
MAX98357A	Maxim I2S Class-D Amplifier	I2S audio amplifier
MCU	MicroController Unit	microcontroller
MEMS	Micro-ElectroMechanical System	micro-electromechanical system
MPU-6050	Motion Processing Unit 6050	6-axis inertial measurement unit
NLP	Natural Language Processing	natural language processing
NVS	Non-Volatile Storage	ESP-IDF non-volatile storage
OTP	One-Time Programmable	one-time programmable memory
PCB	Printed Circuit Board	printed circuit board
PDM	Pulse Density Modulation	pulse density modulation
PSRAM	Pseudo-Static RAM	external SPI RAM
PWM	Pulse Width Modulation	pulse width modulation
REST	REpresentational State Transfer	web architecture style
RFC	Request For Comments	IETF standardisation document
RISC-V	Reduced Instruction Set Computer V	open and royalty-free ISA
RMS	Root Mean Square	signal effective value (power)
RTC	Real-Time Clock	real-time clock
SDK	Software Development Kit	software development kit
SIMD	Single Instruction Multiple Data	parallel vector computation
SMP	Symmetric MultiProcessing	symmetric multiprocessor
SNR	Signal-to-Noise Ratio	signal-to-noise ratio
SOF	Start Of Frame	UART frame start byte
SPI	Serial Peripheral Interface	synchronous serial bus
SRAM	Static Random Access Memory	static random access memory
STT	Speech-to-Text	automatic speech transcription
SysML	Systems Modeling Language	systems modelling language
TFT	Thin Film Transistor	colour LCD display technology
TLS	Transport Layer Security	network encryption protocol
UART	Universal Asynchronous Receiver/Transmitter	asynchronous serial link
USB-C	Universal Serial Bus — Type C	reversible USB connector
VAD	Voice Activity Detection	voice activity detection
Wi-Fi	Wireless Fidelity (IEEE 802.11)	wireless local area network
XPT2046	Xptek Touch Controller 2046	resistive touch controller

List of Symbols and Physical Quantities

Symbol	Physical Quantity / Parameter	Unit	Usage Context
V	Electric voltage	V (volt)	USB-C 5 V supply
I	Electric current intensity	A (ampere)	measured consumption
mA	Milliampere	10^{-3} A	standby current 118 mA
µA	Microampere	10^{-6} A	Deep Sleep target 7 µA
W	Electrical power	W (watt)	P = V × I
Ω	Electrical resistance	Ω (ohm)	speaker load 8 Ω
R	Resistance	Ω	LED current-limiting resistor
C	Electrical capacitance	F (farad)	decoupling capacitors
f	Frequency	Hz (hertz)	PWM frequency 1 kHz
fs	Audio sampling frequency	Hz	16 000 Hz for STT
SNR	Signal-to-noise ratio	dB	61 dB (INMP441)
dBFS	Decibels full scale	dBFS	VAD threshold: −35 dBFS
dB	Decibel (relative level)	dB	acoustic measurement
dB(A)	A-weighted decibel	dB(A)	ambient noise level
RMS	Root mean square of signal	(signal unit)	VAD amplitude
N	Number of samples per DMA frame	dimensionless	1 024 samples
t	Time	s (second)	end-to-end latency
ms	Millisecond	10^{-3} s	UART latency 2.8 ms
µs	Microsecond	10^{-6} s	GPIO toggle resolution
T	Signal period	s	T = 1 / f
τ	Time constant	s	LDO stabilisation
MHz	Megahertz	10^{6} Hz	CPU frequency 240 MHz
KB	Kilobyte	1 024 bytes	FreeRTOS task stack
MB	Megabyte	1 024 KB	PSRAM 8 MB
b	Bit	binary unit	UART frame 12 bytes
Bd	Baud	symbols/s	UART rate 115 200 Bd
px	Pixel	dimensionless	resolution 320 × 480 px
FPS	Frames per second	Hz	LVGL rendering 60 FPS
ms/frame	Frame display duration	ms	partial update 3.9 ms
Mbps	Megabits per second	10^{6} bit/s	Wi-Fi 802.11n throughput
RTT	Round-Trip Time	ms	UART RTT 2.8 ms
°C	Degree Celsius	°C	ambient temperature 22 °C
mm	Millimetre	10^{-3} m	PCB dimensions
cm	Centimetre	10^{-2} m	desk footprint ≤ 15 cm

General Introduction

In today's digital age, smartphones and social media platforms have become essential parts of everyday life. While these technologies provide significant benefits in terms of communication and access to information, they also create numerous distractions that negatively affect concentration and productivity.[1] Students, in particular, often struggle to maintain focus during study sessions due to frequent notifications, entertainment applications, and excessive screen time.

Existing solutions mainly rely on software-based application blockers or productivity applications. However, these solutions can often be bypassed easily by users, reducing their effectiveness. Therefore, there is a growing need for innovative tools that encourage focused work and study in a more effective and autonomous manner.

The fundamental limitation of software-only approaches — their inability to prevent the user from simply disabling them — motivates the need for a hardware-level solution operating independently of the distracting device itself.

The primary objective of this project is to design and develop an intelligent study assistant that promotes concentration and productivity while minimizing digital distractions.

The proposed system aims to:

Provide effective time management tools.

Integrate task management functionalities through a To-Do List system.

Implement the Pomodoro Technique to improve focus and productivity.

Utilize artificial intelligence to assist users and provide personalized support.

Offer a physical and autonomous alternative to traditional smartphone-based productivity applications.

Create a connected embedded system capable of operating independently from distracting devices.

By combining embedded systems, artificial intelligence, and productivity methodologies, the project seeks to provide students with an efficient study environment that encourages discipline and academic success.

The development of this project follows a systems engineering approach that integrates hardware, software, and cloud-based technologies.

This methodology enables the rapid prototyping and iterative improvement of the system.[1]

The project development process includes:

Requirement analysis and system specification.

Hardware design and component selection.

Software development for user interaction and productivity management.

Integration of artificial intelligence functionalities.Cloud API integration — HTTPS communication with Wit.ai for speech-to-text transcription and OpenRouter for DeepSeek LLM inference, secured via TLS 1.3 and AES-256 encrypted NVS credential storage.

System testing, validation, and performance evaluation.

Prototype refinement and optimization.[1]

This multidisciplinary approach ensures the creation of a robust, scalable, and user-friendly solution.[1]

The research consists of 3 chapters, an introduction, and a general conclusion.

Chapter 1: Study of the Art and Paradigms of Embedded Assistants

Chapter 2: System Design — From Functional Requirements to Hardware and Software Architecture

Chapter 3: Electronic Design and Hardware Prototyping

General Conclusion and Perspectives

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Chapter 1:

Study of Art and Paradigms of Embedded Assistants

Introduction

Productivity is no longer limited by access to information — it is limited by the ability to sustain attention in an environment saturated with digital stimuli. The smartphone, which was designed to assist the user, has paradoxically become one of the principal obstacles to focused intellectual work. Social media notifications, messaging applications, and streaming platforms interrupt concentration at a rate that fundamentally undermines deep work, particularly among students and young professionals.

Responding to this challenge requires more than a software solution installed on the same device causing the distraction. It calls for a dedicated, physically autonomous intelligent system — one that integrates productivity tools, artificial intelligence, and time management capabilities into a standalone embedded device that operates independently of the smartphone ecosystem. This thesis presents the design and development of precisely such a system: a smart desk assistant built around the ESP32-S3 microcontroller, capable of voice interaction, lecture transcription, Pomodoro-based time management, and adaptive desk lighting, all functioning without any dependency on a smartphone or companion application.

Before presenting the architectural and software design of the proposed system — which is the subject of Chapter 2 — it is necessary to establish the theoretical and contextual foundations upon which the design decisions rest. Chapter 1 serves this purpose: it conducts a structured review of the existing literature and technological landscape of intelligent personal assistants, analysing their evolution, their underlying processing architectures, the strengths and limitations of current solutions, and the specific hardware capabilities that make the ESP32-S3 a technically justified choice for this application.

1.1 Evolution of Personal Assistants and New Needs:

Personal assistants have undergone significant evolution over the past decades. Initially, personal organization relied on traditional tools such as paper planners, calendars, notebooks, and reminder lists. These tools helped individuals manage their daily tasks, appointments, and responsibilities but required constant manual updates and offered limited flexibility.

With the rapid advancement of digital technologies, electronic personal assistants emerged in the form of desktop applications, mobile productivity tools, and digital calendars. These solutions provided automated reminders, scheduling capabilities, and task management features, making personal organization more efficient and accessible.

The development of artificial intelligence (AI) further transformed the concept of personal assistance. Modern intelligent assistants, such as voice-controlled and AI-powered systems, can understand user commands, answer questions, schedule activities, and provide personalized recommendations. These systems have become increasingly integrated into smartphones, computers, and connected devices, offering users a more interactive and intelligent experience.

Despite these technological advances, new challenges have emerged. The same devices that provide productivity tools are also major sources of distraction. Social media notifications, messaging applications, video streaming platforms, and online entertainment frequently interrupt users' attention, reducing concentration and productivity. Students are particularly affected: empirical studies confirm that adolescents and young adults who report higher screen time exhibit measurably lower psychological well-being and academic performance [3], while workplace research demonstrates that the average interrupted worker requires more than 23 minutes to fully return to a task after a digital interruption [4].

As a result, new needs have appeared in both academic and professional contexts. Users now require intelligent systems that not only assist with task management and scheduling but also actively promote concentration and minimize distractions. There is a growing demand for solutions that combine productivity support, time management techniques, and artificial intelligence while reducing dependence on smartphones and other distracting devices.

This evolution has led to the development of specialized focus-oriented assistants designed to create distraction-free environments. Such systems integrate features such as task planning, Pomodoro-based work sessions, progress tracking, and intelligent guidance, providing users with a more effective way to achieve their academic and professional goals.

1.2 Voice and AI processing architectures (Edge AI vs Cloud AI):

The image illustrates the difference between Edge AI and Cloud AI.

The left side represents artificial intelligence that works directly on the device itself and in real time, while the right side represents cloud-based AI that processes larger amounts of data on a large scale.[1]

Figure 1. 1 — Edge AI vs Cloud AI

1.2.1 What Is Edge AI?

Edge AI runs artificial intelligence directly on local devices — close to where data is generated. [1]

1.2.2 What Is Cloud AI?

Cloud AI refers to AI models that run on centralized cloud servers such as AWS, Microsoft Azure and Google Cloud. [1]

1.2.3 Edge AI vs Cloud AI: Key Differences Explained

The distinction between Edge AI and Cloud AI is particularly relevant to the design of the proposed smart desk assistant. Recent surveys on edge machine learning demonstrate that microcontrollers with SIMD acceleration — such as the ESP32-S3 — can execute inference workloads previously requiring dedicated AI co-processors [5,6]. Espressif's ESP-SR framework [7] provides pre-trained speech recognition models (WakeNet, AFE) optimised for the ESP32-S3's vector instructions, confirming that the platform selected in this thesis occupies the boundary between Edge AI and Cloud AI — capable of local voice activity detection while delegating the computationally intensive STT and LLM tasks to the cloud.

Table 1. 1— Comparative analysis of Edge AI and Cloud AI processing paradigms: processing location, latency, internet dependency, privacy, and scalability.

Feature	Edge AI	Cloud AI
Processing Location	Local devices	Remote servers
Latency	Very low	Higher
Internet Dependency	Optional	Required
Privacy	Higher	Lower
Scalability	Limited	Excellent

In summary, Cloud AI offers massive scalability and centralized processing power but depends on internet connectivity. Edge AI provides ultra-low latency, improved privacy, and offline capability but is limited by device hardware constraints. [1]

1.2.4 Architecture Comparison

Edge AI Architecture

In Edge AI Architecture, the AI model runs directly on the device itself, allowing data to be processed locally without needing to send it to the cloud. The device analyzes information and delivers results instantly.

Device → On-Device AI → Result [1]

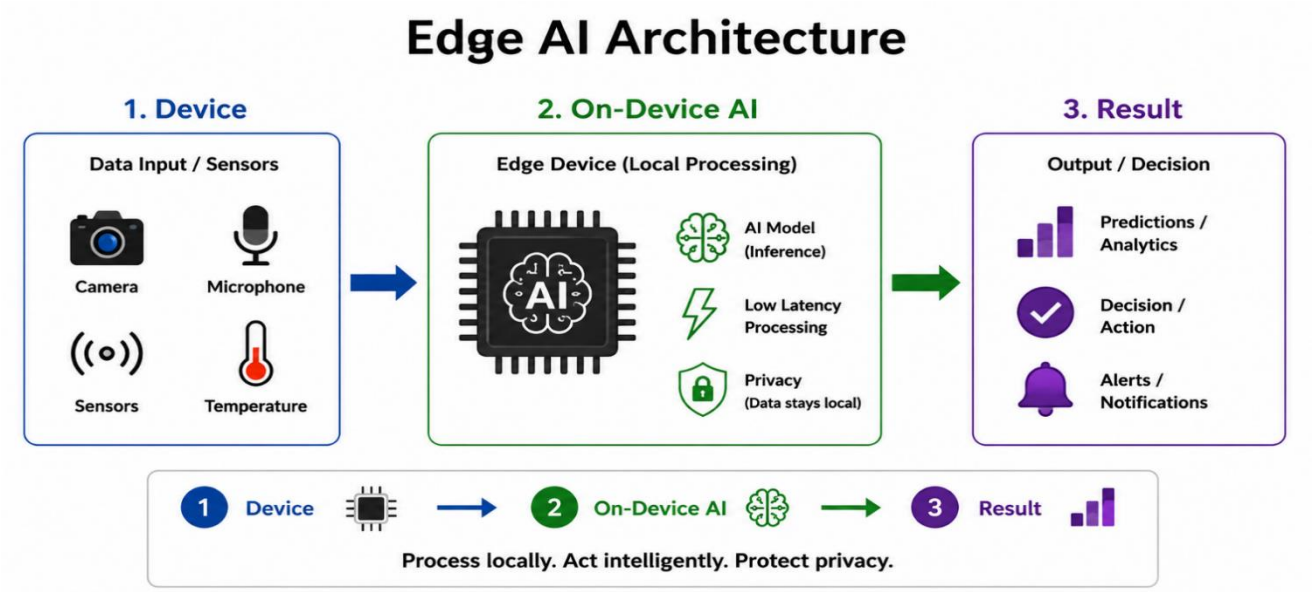


Figure 1. 2 Edge AI Architecture

Cloud AI Architecture

In Cloud AI Architecture, data from a device is sent over the internet to a remote cloud server where the AI model processes it. The server analyzes the data, generates results, and sends the response back to the device.

Device → Internet → Cloud Server → AI Model → Result → Device

Edge AI vs Cloud AI differ in where data is processed, speed, and privacy. Cloud AI offers scalability and centralized power, while Edge AI delivers real-time decisions and better privacy. Understanding these differences lays the foundation for choosing the right AI deployment strategy [1, 5, 6]. For embedded systems constrained by memory and power, the hybrid approach — local VAD at the edge, cloud LLM for generation — represents the current state of the art in resource-bounded AI assistant design.

Figure 1. 2 Edge AI Architecture

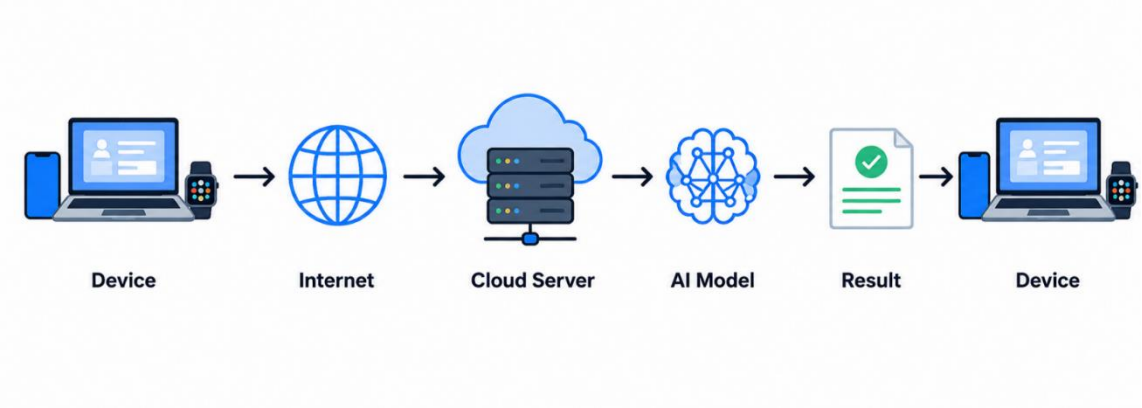


Figure 1. 3 Cloud AI Architecture

1.3 Comparative Analysis of Existing Solutions (Commercial vs Open-Source):

The increasing demand for productivity and focus-enhancing tools has led to the development of numerous personal assistant solutions. These solutions can generally be classified into two main categories: commercial (consumer-oriented) products and open-source alternatives. Each category offers distinct advantages and limitations in terms of functionality, customization, cost, and user experience.

1.3.1 Commercial Solutions

Commercial personal assistants are designed to provide a complete and user-friendly experience. They are typically developed and maintained by large technology companies and benefit from advanced artificial intelligence capabilities, cloud integration, and regular updates.

Popular examples include virtual assistants such as Google Assistant, Apple Siri, Amazon Alexa, and Microsoft Copilot. These platforms offer features such as voice interaction, task scheduling, reminders, information retrieval, and smart device control. In addition, productivity applications such as Todoist, Notion, and Forest provide tools for task management, study planning, and focus improvement.

The main advantages of commercial solutions include:

1.3.2 Open-Source Solutions

Open-source solutions provide users with access to the source code, allowing modification, customization, and community-driven development. These systems are particularly attractive for educational, research, and prototyping purposes.

Examples include productivity and self-hosted tools such as Joplin, Nextcloud Tasks, Vikunja, and various Pomodoro timer projects available on open-source repositories. These solutions often focus on transparency, flexibility, and user control over data.

The advantages of open-source solutions include:

1.3.3 Comparative Discussion

A comparison between commercial and open-source solutions reveals that neither category fully addresses the challenge of maintaining concentration in distraction-rich environments. Commercial applications offer convenience and advanced functionality but remain strongly linked to smartphones and cloud ecosystems. Open-source alternatives provide flexibility and control but often require significant technical expertise and still rely on conventional computing devices.

For students seeking a distraction-free study environment, both approaches exhibit limitations. Most existing solutions operate on devices that are themselves sources of interruption. Consequently, there is an opportunity to develop a dedicated intelligent study assistant that combines the strengths of both categories while minimizing their weaknesses.

1.3.4 Positioning of the Proposed Solution

Research on digital distraction demonstrates that the root cause of the productivity gap is not a lack of available tools but the structural co-location of the distraction source and the productivity tool on the same device [4]. Addressing this requires not a better application, but a physically separate device. The proposed system bridges this gap by introducing an embedded, AI-powered study assistant that is physically independent of the smartphone ecosystem — a design philosophy grounded in the principle that concentration cannot be restored by software running on the device that broke it [5]. Unlike traditional software applications, the system operates independently from smartphones during study sessions. It integrates productivity tools such as task management, time scheduling, and the Pomodoro Technique while leveraging artificial intelligence to provide assistance and guidance.

By combining embedded systems, connectivity, and AI capabilities within a dedicated device, the proposed solution seeks to offer a more effective alternative for students who wish to improve focus and reduce digital distractions.

1.4 Technical Characteristics of the ESP32-S3 SoC and the ESP32-C3 Companion Microcontroller

The hardware foundation of the proposed smart desk assistant rests on two complementary microcontrollers: the ESP32-S3, a high-performance system-on-chip (SoC) built around a dual-core Xtensa LX7 processor with integrated AI acceleration, and the ESP32-C3 Super Mini, a compact single-core RISC-V device designed for low-power peripheral management. Understanding the theoretical basis of these two architectures — and the principle of asymmetric multiprocessing (AMP) that governs their cooperative operation — is essential for justifying the dual-MCU hardware architecture presented in Chapter 2.

1.4.1 The Xtensa LX7 Architecture of the ESP32-S3

The ESP32-S3 is manufactured by Espressif Systems and is built on the **Xtensa LX7** processor core, a configurable RISC-style 32-bit architecture developed by Cadence Design Systems and licensed by Tensilica. [8] The Xtensa architecture is distinguished from classical fixed-instruction-set processors by its **extensible ISA (Instruction Set Architecture)**: manufacturers can add application-specific instruction

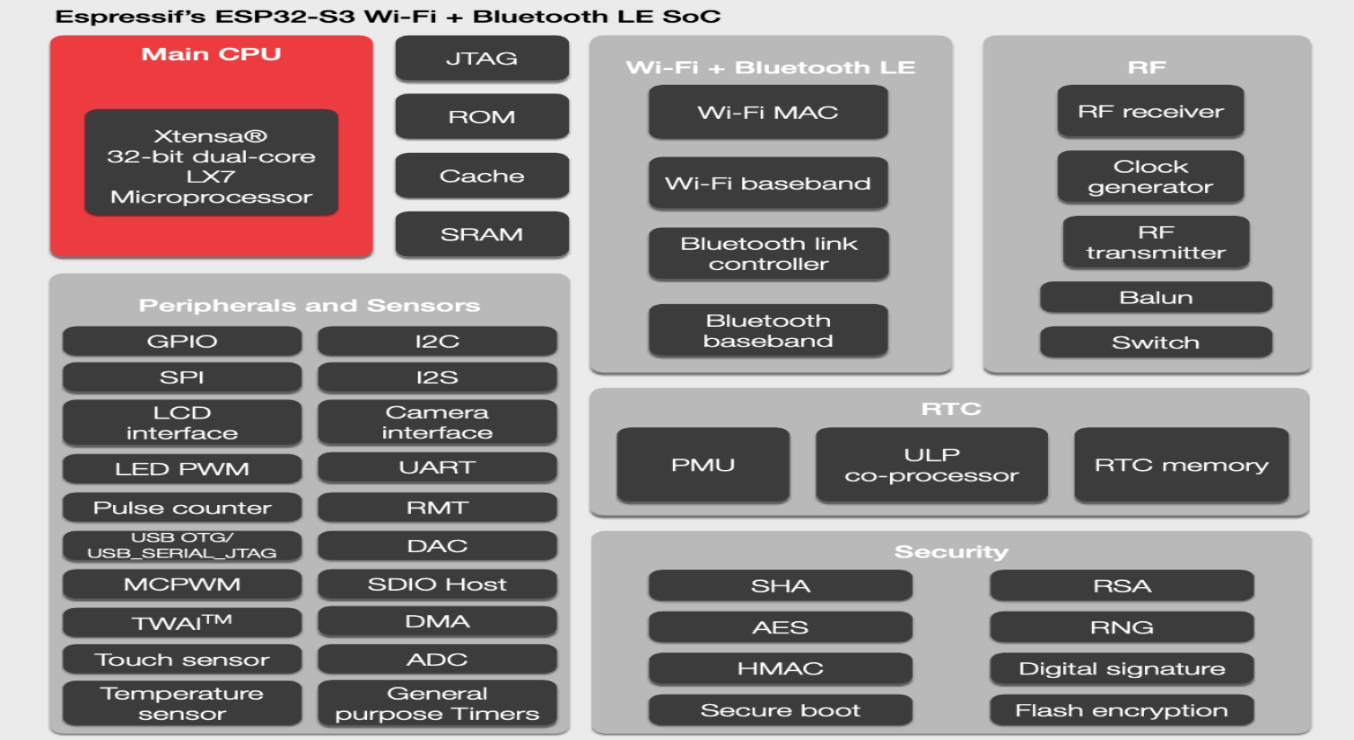
extensions directly into the processor pipeline without sacrificing real-time determinism. Espressif leverages this extensibility through two proprietary instruction groups that are central to the performance of the proposed system:

PIE (Processor Instruction Extensions): a set of 128-bit Single Instruction Multiple Data (SIMD) vector operations that allow the processor to apply one arithmetic instruction to multiple data elements simultaneously. In the context of digital signal processing and neural network inference, this translates to a **5–10× acceleration** compared to scalar processing on equivalent workloads — a figure directly relevant to the Voice Activity Detection (VAD) algorithm executed in real time on each incoming audio buffer. [9]

ESP-NN (Neural Network Acceleration Library): a software library developed by Espressif that maps common machine learning inference primitives (convolutions, activations, pooling, fully-connected layers) to optimized Xtensa PIE instructions. When combined with the SIMD hardware, ESP-NN enables the ESP32-S3 to execute neural network models — such as keyword detection models — at a speed comparable to dedicated AI co-processors, without any external hardware accelerator. [10]

The ESP32-S3 integrates **two independent LX7 cores** operating at up to 240 MHz, coupled with 512 KB of internal SRAM and support for up to 8 MB of external Octal SPI PSRAM. The dual-core architecture is particularly important for real-time embedded systems: in the proposed device, Core 1 is reserved exclusively for time-critical audio capture (I2S DMA) and AI inference tasks, while Core 0 manages Wi-Fi networking, cloud API communication, and peripheral control — a task isolation strategy that eliminates CPU contention and guarantees zero audio dropout under peak network load. [9]

Beyond processing performance, the ESP32-S3 incorporates two key peripheral subsystems critical to the proposed design. First, its **dual native I2S interfaces** with hardware PDM decoding support direct



connection to the INMP441 MEMS digital microphone (audio input) and the MAX98357A I2S class-D amplifier (audio output), achieving an audio capture and playback latency of approximately 1 ms — a figure unattainable through software bit-banging or UART-bridged audio on alternative platforms.[9] Second, its **hardware AES-256 flash encryption** engine, activated via eFuse burning at the first production boot, transparently encrypts the entire SPI flash memory at rest — including the encrypted Non-Volatile Storage (NVS) partition where cloud API keys are stored. This cryptographic protection makes the device commercially deployable without exposing credentials to binary extraction via JTAG or SPI flash chip desoldering. [11]

Figure 1. 4 the xtensa lx7 architecture of the esp32-s3

1.4.2 The RISC-V Architecture of the ESP32-C3

The ESP32-C3 is built on the open **RISC-V** instruction set architecture, a clean-slate, royalty-free, open-standard ISA developed at the University of California, Berkeley in 2010.[11] Unlike proprietary architectures (Xtensa, ARM Cortex-M), RISC-V is governed by the RISC-V International consortium and its specification is publicly available, allowing any manufacturer to implement compliant cores without licensing fees. Espressif's implementation in the ESP32-C3 is a **32-bit single-issue in-order pipeline** operating at up to 160 MHz — a deliberately modest performance profile that reflects the ESP32-C3's intended role as a **task-specific companion processor** rather than a general-purpose computing unit.

The RISC-V ISA is built on the principle of **reduced instruction complexity**: a small, fixed-width base instruction set (RV32I, comprising 47 instructions) supplemented by optional standard extensions for integer multiplication (M), atomic operations (A), single-precision floating point (F), and compressed instructions (C). The ESP32-C3 implements the RV32IMC subset, providing integer arithmetic, multiplication, and 16-bit compressed instructions that improve code density in memory-constrained embedded applications. [6] The absence of hardware floating-point capability (the F extension) is not a limitation for the ESP32-C3's assigned role: graphical rendering, touch event processing, and UART command parsing are entirely integer-domain operations that run efficiently on RV32IMC hardware.

The ESP32-C3 integrates 400 KB of internal SRAM and a native SPI master controller capable of driving the ST7796 TFT display at 40 MHz, achieving a theoretical maximum full-frame refresh of 307,200 bytes per 61.4 ms frame — sufficient for a 60 FPS graphical interface when combined with LVGL v9.2.3's partial update strategy. The Super Mini form factor (12×18 mm physical board dimensions) further distinguishes this component as an appropriate choice for compact PCB integration alongside the larger ESP32-S3 module. [12]

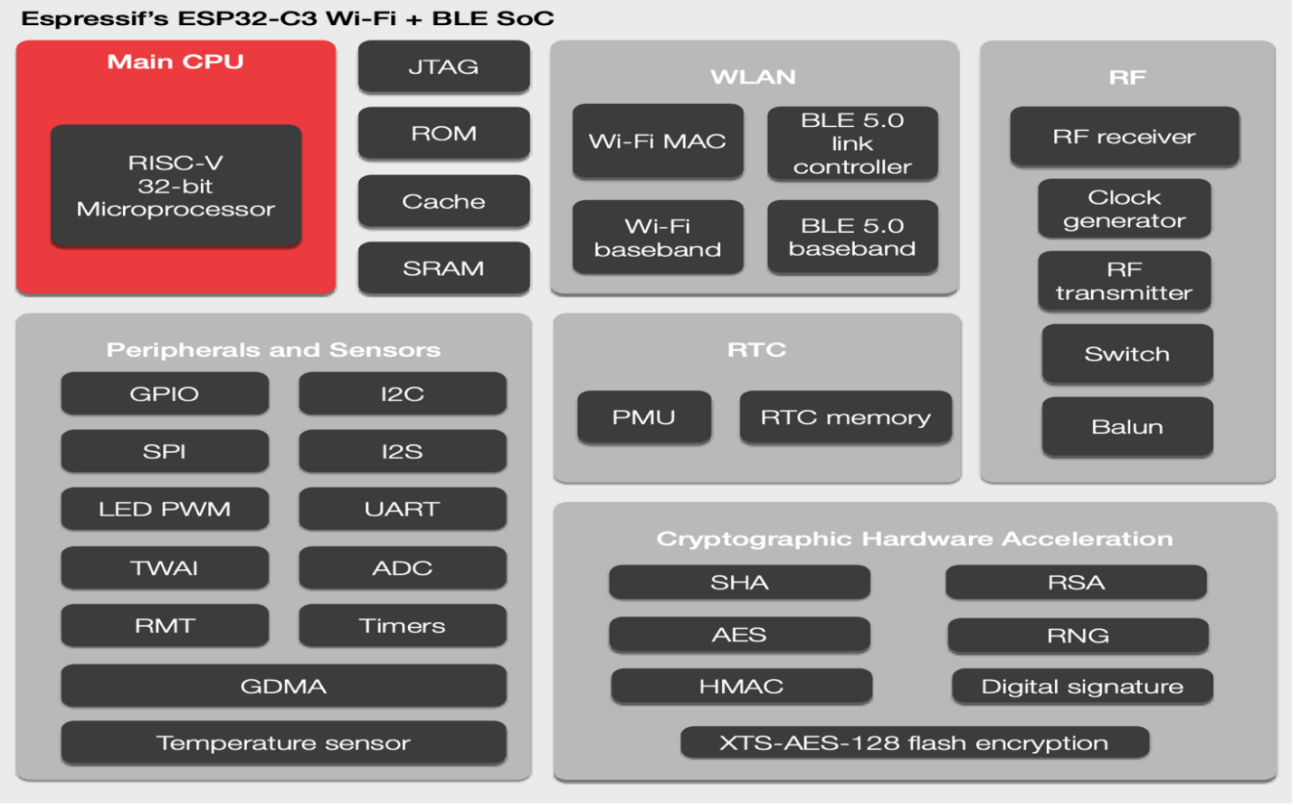


Figure 1. 5 The RISC-V Architecture of the ESP32-C3

1.4.3 Asymmetric Multiprocessing (AMP) in Low-Power Embedded Devices

The cooperative use of an Xtensa LX7 SoC (ESP32-S3) alongside a RISC-V SoC (ESP32-C3) in a single product instantiates the principle of **Asymmetric Multiprocessing (AMP)** — a system architecture in which multiple processors, each potentially running a different instruction set or operating system, are assigned distinct, non-overlapping computational roles and communicate through a well-defined inter-processor channel. [13]

AMP is distinguished from **Symmetric Multiprocessing (SMP)** — in which multiple identical cores share a single operating system instance and a unified memory pool — by its deliberate **heterogeneity**. In an SMP system (such as the two LX7 cores within the ESP32-S3 itself), any task can in principle execute on any core, with the scheduler dynamically assigning workloads to balance CPU utilization. In an AMP system, by contrast, each processor is permanently assigned to a specific computational domain, and cross-processor communication occurs only through an explicit, bandwidth-constrained interface. This constraint

is a feature, not a limitation: it **eliminates shared-memory race conditions**, removes the need for distributed memory coherence protocols, and ensures that a software failure or performance spike in one processor domain cannot directly affect the real-time determinism of the other. [14]

In the proposed system, this principle is applied as follows. The ESP32-S3 constitutes the **master processor domain**: it runs ESP-IDF v5.1.7 with FreeRTOS and manages all latency-sensitive workloads — I2S audio DMA capture, energy-based VAD, Wi-Fi streaming to cloud AI services, LLM response parsing, smart lighting PWM control, and Pomodoro timer logic. The ESP32-C3 constitutes the **companion processor domain**: it runs a separate ESP-IDF firmware instance managing all graphical interface tasks — LVGL v9.2.3 screen rendering, XPT2046 touch event processing, and UART command reception. These two domains are coupled exclusively through a 115,200 baud UART link carrying fixed 12-byte binary frames — a narrow, deterministic channel that provides sufficient bandwidth for command and status exchange while preventing any memory-level dependency between the two processors.

The theoretical justification for this AMP architecture over a single high-performance processor handling all tasks rests on a fundamental property of real-time embedded systems: **CPU time is a non-renewable resource**. On a single processor, a burst of SPI writes to a TFT display (307,200 bytes per frame) and a concurrent I2S DMA read (2,048 bytes per 64 ms audio frame) compete for the same memory bus bandwidth and CPU cycles. Even with DMA offloading, the display flush generates bus contention that introduces measurable jitter into the audio capture timing — a jitter that accumulates into perceptible audio quality degradation and increased STT error rates. Isolating these two workloads on physically separate processors, each with its own memory bus and peripheral fabric, eliminates this contention at the hardware level. [15]

1.4.4 Comparative Summary: ESP32-S3 vs. ESP32-C3 in the Proposed System

The table above confirms that the two processors are complementary rather than redundant: neither could fulfill the other's role without compromising the real-time constraints of the overall system. The ESP32-S3's Xtensa LX7 SIMD extensions are essential for VAD and audio streaming; the ESP32-C3's compact form factor and native SPI master are optimal for the display subsystem. Their combination, coordinated through a deterministic UART inter-processor link, establishes a low-power AMP platform capable of sustaining simultaneous audio AI processing and responsive graphical interaction — the dual requirement at the heart of the proposed smart desk assistant.

Table 1. 2— Technical comparison: ESP32-S3 (master) vs. ESP32-C3 (companion) in the AMP architecture

Characteristic	ESP32-S3 (Master)	ESP32-C3 (Companion)
ISA	Xtensa LX7 (proprietary, configurable)	RISC-V RV32IMC (open standard)
Cores	2 cores @ up to 240 MHz	1 core @ up to 160 MHz
SIMD / AI extension	128-bit PIE + ESP-NN (5–10× AI speedup)	None (not required for GUI tasks)
Internal SRAM	512 KB	400 KB
External memory	8 MB Octal SPI PSRAM (128 s audio buffer)	None required
Native I2S	2 ports + PDM decoding (1 ms audio latency)	None
SPI master	Used for SD card (SDMMC)	40 MHz for ST7796 display (61.4 ms/frame)
Flash encryption	Hardware AES-256 (eFuse)	Hardware AES-128 (eFuse)
Wi-Fi	802.11b/g/n (required for cloud AI)	802.11b/g/n (not used — task isolation)
Role in AMP system	Master: audio, AI, Wi-Fi, lighting, Pomodoro	Companion: GUI, touch, UART reception
Inter-MCU interface	UART TX (GPIO42) / RX (GPIO41)	UART RX (GPIO21) / TX (GPIO20)
Form factor	ESP32-S3 N16R8 module	Super Mini 12×18 mm

Conclusion generale

Chapter 1 has constructed the theoretical and contextual foundation upon which the design of the smart desk assistant rests. Through a structured review of four interconnected themes — the evolution of personal assistance tools, the architectures that power modern AI systems, the landscape of existing commercial and open-source solutions, and the hardware capabilities of the ESP32-S3 — a coherent and technically grounded argument has emerged for the development of a dedicated, embedded, smartphone-independent productivity device.

The historical analysis in §1.1 established that the fundamental challenge of contemporary productivity is not a lack of available tools but a **structural conflict**: the same digital devices that provide the most powerful assistance features are simultaneously the primary sources of distraction. Paper planners were replaced by smartphones, and smartphones introduced social media, messaging, and constant connectivity — a cycle in which each productivity gain was offset by a new vector of interruption. This observation motivates the central premise of the thesis: that genuine focus enhancement requires **a physically separate device**, not an additional application on the device already responsible for the distraction.

The architectural review in §1.2 clarified the fundamental trade-off between **Edge AI** and **Cloud AI** processing models. Cloud AI offers virtually unlimited computational power, easy scalability, and access

to state-of-the-art language models, but requires permanent internet connectivity and introduces latency that degrades real-time voice interaction. Edge AI provides ultra-low latency, offline operation, and stronger privacy guarantees, but is constrained by device hardware. The proposed system adopts a **hybrid architecture** that strategically combines both paradigms: local Edge AI for time-critical operations (voice activity detection, Pomodoro timer management, touch interface rendering) and Cloud AI for tasks that benefit from the full capability of large language models (speech-to-text via Wit.ai, text generation via DeepSeek/OpenRouter).

The comparative evaluation in §1.3 demonstrated that neither commercial solutions (Google Assistant, Amazon Alexa, Apple Siri, Todoist, Forest) nor open-source alternatives (Joplin, Nextcloud Tasks, Vikunja) fully address the identified challenge. Commercial platforms offer polished interfaces and advanced AI capabilities but remain fundamentally tied to smartphones and cloud ecosystems — the same environment that generates distraction. Open-source alternatives provide flexibility and data privacy but require significant technical expertise and still operate on conventional computing devices. **The proposed system positions itself in the gap between these two categories**: a physically dedicated device combining the AI capability of commercial platforms with the customizability and embedded-system autonomy of open-source approaches.

Finally, §1.4 provided the technical justification for the selection of the **ESP32-S3** as the primary microcontroller of the proposed system. The comparative analysis demonstrated that this SoC is uniquely positioned among embedded platforms to satisfy all technical requirements simultaneously: 128-bit SIMD vector instructions for neural network acceleration (5–10× speedup over the standard ESP32), 8 MB PSRAM for a 128-second audio circular buffer eliminating data loss during cloud delays, dual native I2S ports with PDM decoding for 1 ms audio latency, and hardware AES-256 flash encryption for API key protection at a commercial security level. No alternative platform — standard ESP32, ESP32-C3, STM32, or Raspberry Pi Zero — satisfies all four requirements concurrently. [2]

Having established this theoretical and comparative foundation, **Chapter 2** proceeds to the formal functional specification of the proposed system — through the Bête à Cornes diagram, Pieuvre diagram, CdCF requirements table, FAST functional decomposition, and SysML structural modelling — before presenting the dual-MCU hardware architecture, the custom UART inter-MCU communication protocol, the ESP-IDF/FreeRTOS firmware architecture, and the complete AI pipeline from voice capture to on-screen response display.

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Chapter 2:

System Design — From Functional Requirements to Hardware and Software Architecture

Introduction

This chapter documents the complete engineering design process of the Smart Desk Assistant, progressing systematically from the formal expression of user needs through functional modelling, hardware implementation, and embedded software architecture. The design is built around a core architectural decision — an asymmetric **Dual-MCU platform** pairing the ESP32-S3 as the primary AI and audio processing engine with the ESP32-C3 Super Mini as a dedicated graphical rendering companion — and is driven throughout by a single non-negotiable constraint: **complete, unconditional independence from the smartphone**.

2.1 Functional Specifications and Ergonomic Constraints (Distraction-Free)

This section establishes the foundational specification criteria and user ergonomics designed to achieve a strict, distraction-free environment. It details the stakeholder analysis across four core functional pillars, maps external behavioral dependencies utilizing service and constraint criteria, and formalizes these requirements into a measurable Cahier des Charges Fonctionnel (CdCF). These systematic constraints collectively guarantee the device's complete operational autonomy from smartphones while optimizing focus, data security, and acoustic interface parameters.

2.1.1 Stakeholder Analysis and Need Formalization

The developed system, designed as an interactive desk assistant, aims to optimize user productivity and organization in a work or study environment. The overall mission (primary use function) of the system is to assist the user in managing their time and daily tasks by providing a natural interaction interface (voice and visual) powered by artificial intelligence.

To effectively break the user's reliance on the smartphone, the proposed system must not only block distractions but actively replace the most useful study tools provided by the smartphone. Consequently, the device is built around four core functional pillars that ensure its complete autonomy and guarantee a true Distraction-Free Environment:

Cognitive Voice Interaction Pillar (Voice Q&A): Providing an integrated smart assistant that relies on Natural Language Processing (NLP) to answer the user's complex queries instantly and vocally. This pillar fulfills the user's cognitive needs and completely eliminates the necessity to resort to a smartphone or web browsers to search for information, thereby maintaining continuous focus and workflow.

Lecture Documentation and Transcription Pillar (Lecture-to-Text): Replacing traditional recording applications on phones with a built-in High-Fidelity audio capture system. It possesses the capability to continuously listen to lectures or meetings and programmatically transcribe them into accurate, archived text, making it effortless for the user to retrieve and document scientific material without distraction.

Physical and Visual Time Management Pillar (Visual Time Manager): Incorporating a tangible, physical timer based on globally recognized productivity mechanisms (such as the Pomodoro Technique). This timer allows the user to organize periods of deep work and rest in a direct visual manner, replacing smartphone timer apps that frequently tempt the user to check digital notifications.

Environmental Control and Smart Desk Lighting Pillar (Smart Desk Lighting): Integrating an adaptive, dynamically controlled lighting system to adjust light brightness and Color Temperature. This environmental pillar aims to reduce Eye Strain and provide a customized visual climate that supports alertness during work sessions and relaxation during breaks, thereby enhancing sustainable human performance.

Table 2.1: Smart Desk Assistant System Requirements Table

The following table summarizes the direct relationship between the functional user needs and the corresponding technical and engineering solutions in the system to ensure an independent, distraction-free work environment:

Table 2. 1— Smart Desk Assistant System Requirements Table

Req. ID	User Need	System Technical Function	Technical Implementation
REQ-01	Obtaining quick, hands-free information to avoid interrupting workflow.	Smart Voice Query (Voice Q&A): Processing voice requests and formulating instant smart responses.	Audio capture via digital I2S interface, sending data and receiving responses via the AI engine using the HTTPS protocol.
REQ-02	Documenting long lectures and meetings without needing to touch a smartphone.	Speech-to-Text (Lecture-to-Text): Continuous recording and converting spoken words into archived text files.	Streaming raw audio via a custom HTTP Client to an STT server (Wit.ai API), and processing text in JSON format.
REQ-03	Avoiding eye strain and maintaining alertness during long work sessions.	Smart Desk Lighting Control: Dynamically adjusting brightness and color temperature according to the work or rest mode.	Generating control signals and Pulse Width Modulation (PWM) to drive adaptive lighting circuits.
REQ-04	Managing periods of focus and rest tangibly without the distraction of digital notifications.	Physical and Visual Time Management: Operating an independent productivity timer (Pomodoro timer).	Programming independent internal timers, outputting visual status indicators, and integrating physical buttons for direct interaction.
REQ-05	Ensuring the device's complete autonomy from the smartphone and secure operation.	Complete Autonomy and Secure Data Management: Self-connecting to the network and saving sensitive data without leaks.	Integrating a Wi-Fi Stack library for direct connection, and storing operation keys and credentials securely encrypted in Non-Volatile Storage (NVS).

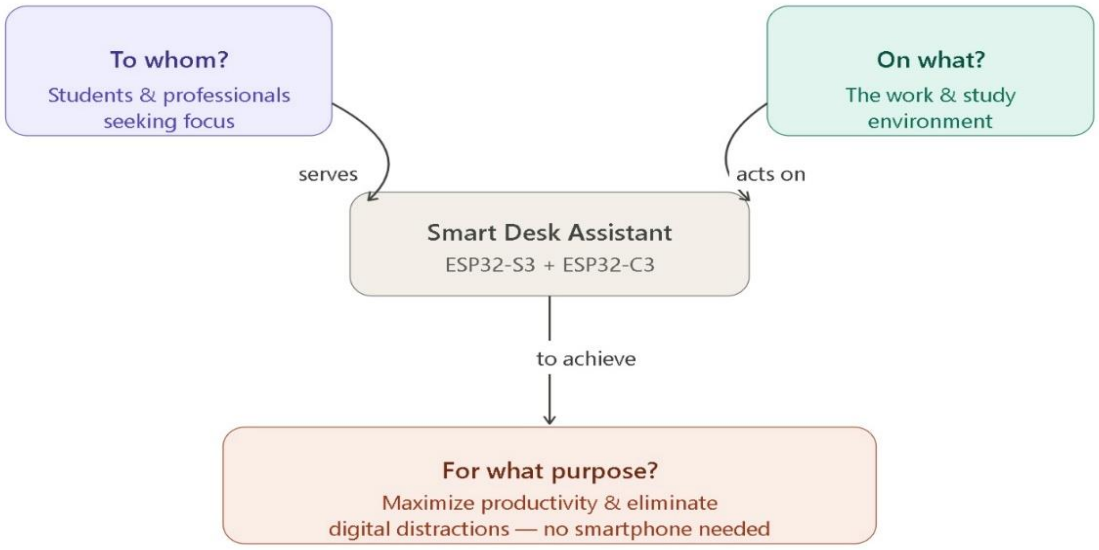

Figure 2. 1 —Bête à Cornes Diagram: who does it serve / on what / for what purpose

The Bête à Cornes diagram formally confirms that the system's primary beneficiary is the student or professional user, its subject of action is the cognitive and physical workspace environment, and its overarching purpose is the elimination of digital distractions through the hardware embodiment of essential productivity tools. This analysis validates the core design philosophy: the device must be a complete, autonomous replacement for the smartphone within the study environment — not a peripheral accessory dependent on it.

2.1.2 Service Function Analysis — Pieuvre Diagram (Octopus Diagram)

The Pieuvre diagram (Octopus diagram) is a complementary functional analysis tool that maps all interactions between the system and its external environment. It identifies two categories of functions: Main Functions (FP — Fonctions Principales), which represent the core value delivered to the user, and Constraint Functions (FC — Fonctions Contraintes), which represent the non-negotiable operating conditions the system must satisfy.

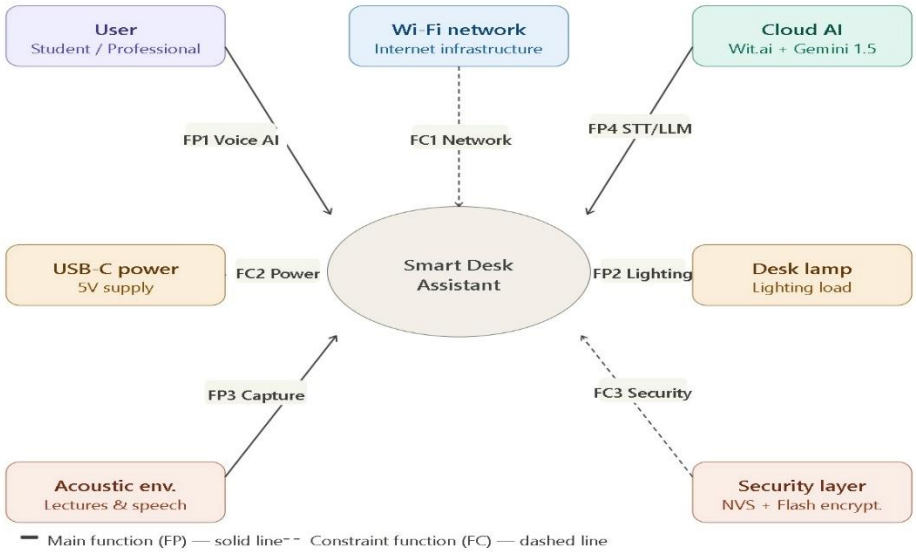

Figure 2. 2 — Pieuvre diagram: external elements, main functions (FP), and constraint functions (FC)

External Elements identified: User (Student / Professional), Wi-Fi Network Infrastructure, Cloud AI Services (Wit.ai STT + DeepSeek LLM via OpenRouter), USB-C Power Supply, Ambient Desk Environment (lighting, acoustics), Desk Lamp / Lighting Load.

Main Functions (FP — Fonctions Principales):

Table 2. 2— Pieuvre diagram: main service functions (FP) with measurability criteria and external element mapping.

Function	Description	Measurability Criterion
FP1 — AI Voice Interaction	The system allows the user to ask vocal questions and receive instant and intelligent responses via Wit.ai STT + DeepSeek LLM (OpenRouter), synchronizing information on the 4-inch TFT screen.	Latency ≤ 3 s (trigger → AI response displayed)
FP2 — Smart Desk Lighting Control	The system adjusts the intensity and temperature of the desk lamp via PWM signal, adapting to the active mode (focus session or break) without requiring a smartphone.	PWM control 0–100%, response ≤ 500 ms
FP3 — Physical Time Management (Pomodoro)	The system provides a hardware-embedded touch-interactive Pomodoro timer, executed on ESP32-C3, with visual countdown and audio alerts via MAX98357A.	Timer accuracy ±1 s, audio alert ≤ 100 ms
FP4 — Lecture Transcription (Lecture-to-Text)	The system captures continuous audio from sessions/meetings via I2S INMP441 microphone and transcribes it in real time via Wit.ai streaming API, archiving structured text.	Transcription accuracy ≥ 90% (Wit.ai), streaming latency ≤ 200 ms

Constraint Functions (FC — Fonctions Contraintes):

Table 2. 3— Pieuvre diagram: main functions (FP) and constraint functions (FC)

Function	Description	Measurability Criterion
FC1 — USB-C Powered Operation	The system operates on a standard USB-C 5V supply, with a stable 3.3V logic rail for multiple MCUs under peak Wi-Fi streaming + audio load.	Voltage 3.3V ±5%, current peak ≤ 350 mA
FC2 — Complete Smartphone Independence	The system operates fully automatically without a companion smartphone app, Bluetooth pairing, or phone-linked interface.	0 Bluetooth connections, 0 smartphone app required
FC3 — API Security and Data Protection	All cloud service credentials (Wit.ai and OpenRouter API keys) are stored in hardware-encrypted NVS on the ESP32-S3, with Flash Encryption enabled to prevent binary extraction.	NVS encrypted AES-256, Flash Encryption enabled
FC4 — EMC Compliance and Signal Integrity	The PCB layout ensures electrical compatibility, with isolation of the I2S audio lines (INMP441 + MAX98357A) from switching power rails.	Noise coupling < 10 µV RMS, separation ≥ 5 mm
FC5 — Desk Footprint and Form Factor	The physical device must fit within a 15×15 cm desk enclosure, ensuring natural integration in a standard office/study environment.	Footprint ≤ 15×15 cm (100×100×40 mm)

2.1.3 Formal Requirements Specification (CdCF) and Ergonomic Constraints

The functional analysis conducted via the Bête à Cornes and Pieuvre diagrams is now consolidated into a formal Cahier des Charges Fonctionnel (CdCF) — the engineering specification document that translates qualitative user needs into measurable, verifiable technical criteria. Each function identified in §2.1.2 is assigned a quantifiable acceptance criterion and a validation method, forming the contractual baseline against which the final prototype is evaluated.

Non-Negotiable Ergonomic Design Constraints

1. Zero Smartphone Dependency. All user interactions must be achievable exclusively through voice commands and the 4-inch TFT touchscreen (ST7796 + XPT2046). No companion application, Bluetooth connection, or smartphone interface shall be required at any point during operation.

2. Minimalist Visual Interface. The graphical user interface rendered on the TFT display must adhere to a strict minimalist design philosophy — displaying only task-relevant information (current timer status, AI response text, task list) to avoid introducing new sources of visual distraction.

3. Physical Desk Footprint. The device enclosure must not exceed 15×15 cm in base area, ensuring seamless integration on a standard student or professional desk without displacing essential workspace.

4. End-to-End Response Latency Target. The total elapsed time from the end of the user's spoken query to the display of the AI-generated response on the TFT screen must not exceed 3 seconds under standard Wi-Fi conditions (≥20 Mbps), ensuring a natural, conversational interaction rhythm.

5. Acoustic Capture Quality. The INMP441 MEMS digital microphone must achieve a minimum Signal-to-Noise Ratio (SNR) of 61 dB with a sensitivity of −26 dBFS, ensuring reliable voice capture at distances of up to 1.5 metres in a typical indoor desk environment.

The selection of the ST7796 4-inch TFT display (320×480 pixels, SPI interface) paired with the XPT2046 touch controller satisfies the 15×15 cm footprint constraint. This choice simultaneously satisfies the distraction-free design mandate by providing a dedicated, focused display surface that contains no notifications, social feeds, or application icons.

Official CdCF Table:

Table 2. 4— CdCF: measurable technical baseline for prototype validation

Function ID	Description	Measurement Criterion	Flexibility Level	Verification Method
FC2	Zero Smartphone Dependency	0 Bluetooth connections, 0 smartphone app required	Non-negotiable	Functional test: operate device without phone
FC5	Physical Desk Footprint	≤ 15×15 cm (100×100×40 mm)	Non-negotiable	Physical measurement with ruler
FP1	AI Voice Interaction	Latency ≤ 3 s (trigger → AI response displayed)	Non-negotiable	Timing test: measure end-to-end latency
FC1	USB-C Powered Operation	Voltage 3.3V ±5%, current peak ≤ 350 mA	Flexible (±10%)	Power supply measurement with oscilloscope
FC4	EMC Compliance & Signal Integrity	Coupling noise < 10 µV RMS, separation ≥ 5 mm	Non-negotiable	PCB layout review + noise measurement
FP3	Pomodoro Timer	Accuracy ±1 s/hour, audio alert ≤ 100 ms	Flexible (±2 s)	Stopwatch comparison test
FP4	Lecture Transcription	Accuracy ≥ 90% (Wit.ai), streaming latency ≤ 200 ms	Flexible (≥ 85%)	Transcription accuracy batch test
FP2	Smart Desk Lighting	PWM response ≤ 500 ms, range 0–100%	Flexible (≤ 700 ms)	PWM measurement + timing test
FC3	API Security & Data Protection	NVS AES-256 encrypted, Flash Encryption enabled	Non-negotiable	NVS dump analysis + encryption verification
FC5-b	Acoustic Capture Quality	SNR ≥ 61 dB, sensitivity −26 dBFS, range ≤ 1.5 m	Non-negotiable	Microphone SNR test with audio analyser

2.2 Functional Analysis and Systems Modelling

This section implements a structured systems engineering approach to map the device's high-level objectives into technical execution paths. It leverages a Function Analysis System Technique (FAST) diagram to distribute operational tasks logically between the ESP32-S3 and ESP32-C3 microcontrollers. Furthermore, it defines the hardware-software boundaries using SysML Block Definition Diagrams (BDD) and outlines the real-time data flows and state machines that govern the system's runtime behavior.

2.2.1 Progressive Functional Decomposition — FAST Diagram

The FAST (Function Analysis System Technique) diagram breaks down high-level functions into executable sub-functions, serving as a direct reference for task distribution between ESP32-S3 and ESP32-C3 and for the software architecture.

This approach enables the transformation of user-oriented functions into technical functions that can be directly implemented through hardware and software components.

Table 2. 5 —FAST diagram reading principles: three directional axes and their decomposition logic.

FAST Principle	Decomposition Logic
For what?	Horizontal axis to the left (upper level, purpose)
How?	Horizontal axis to the right (decomposition into sub-functions)
When?	Vertical axis downwards (simultaneous events, triggering)

Table 2. 6 —FAST high-level decomposition of FP1

FAST Function	Sub-function	Technical Solution
FP1	Respond to the user's request	Complete system
FP1.1	Ensure voice interaction	Voice interface
FP1.2	Acquire the audio signal	INMP441 + ESP32-S3
FP1.3	Detect voice activity	VAD algorithm (RMS energy-based)
FP1.4	Convert speech into text	Wit.ai STT
FP1.5	Generate an intelligent response	DeepSeek LLM via OpenRouter
FP1.6	Show the answer	ST7796 320×480 + ESP32-C3

FP1.1 — Voice Interface (100%)

MCU Responsibility: ESP32-S3: trigger detection and UART TX. ESP32-C3: UI update (UART RX → TFT).

Table 2. 7 —FAST sub-function decomposition: FP1.1 — Voice Interface — MCU responsibility mapping (ESP32-S3 / ESP32-C3).

FAST Function	Technical Solution
Receive the voice command	INMP441 Microphone
Detect the trigger	GPIO2 button long press (≥ 800 ms) or CMD_MIC from C3
Transmit the command	UART — 115,200 baud
Update the user interface	ESP32-C3
Provide visual feedback	ST7796 TFT Display (320×480)

2.2.2 Structural Modelling — SysML Block Definition Diagram (BDD)

Why SysML rather than UML? SysML is specifically designed for embedded hardware/software co-design. It provides complete hardware representation with explicit blocks, ports, and flows; it formally

defines I2S, SPI, and UART signal flows as typed connectors; and it aligns with the industrial electronics methodology required by the dissertation.[1]

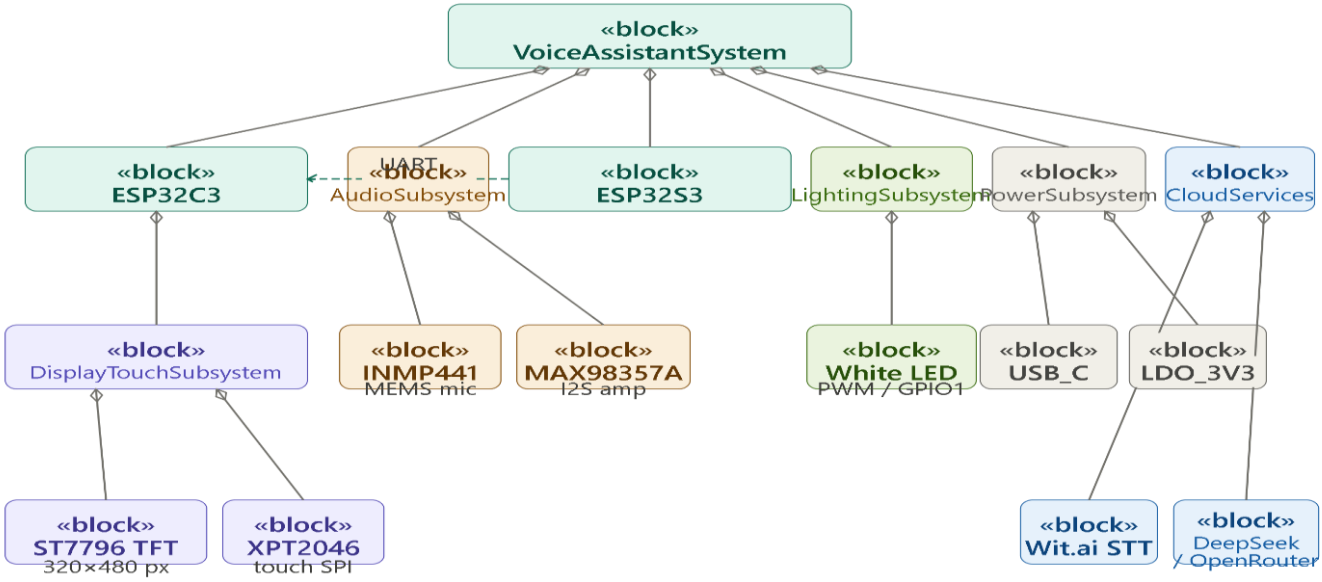

Figure 2. 3— SysML Block Definition Diagram: seven structural blocks and inter-block relationships

Table 2. 8 — SysML BDD block relationships summary

Relationship	Source Block	Target Block	Interface	Protocol
Inter-MCU Communication	MasterMCU_S3	CompanionMCU_C3	GPIO41/42	UART (115,200 baud)
Audio Capture	MasterMCU_S3	AudioSubsystem	GPIO4/5/6	I2S (16 kHz, 16-bit)
Display Control	CompanionMCU_C3	DisplaySubsystem	GPIO5/6/7/9/10	SPI (40 MHz)
Lighting Control	MasterMCU_S3	LightingController	GPIO1	PWM (LEDC 8-bit, 5 kHz)
Cloud STT	MasterMCU_S3	AICloudPipeline	Wi-Fi	HTTP POST (Wit.ai)
Cloud LLM	MasterMCU_S3	AICloudPipeline	Wi-Fi	HTTP POST (OpenRouter/DeepSeek)
Power Supply	PowerManagement	MasterMCU_S3	3.3V Rail	DC (500 mA max)
Power Supply	PowerManagement	CompanionMCU_C3	3.3V Rail	DC (200 mA max)
Power Supply	PowerManagement	AudioSubsystem	3.3V_AUDIO	DC (100 mA)

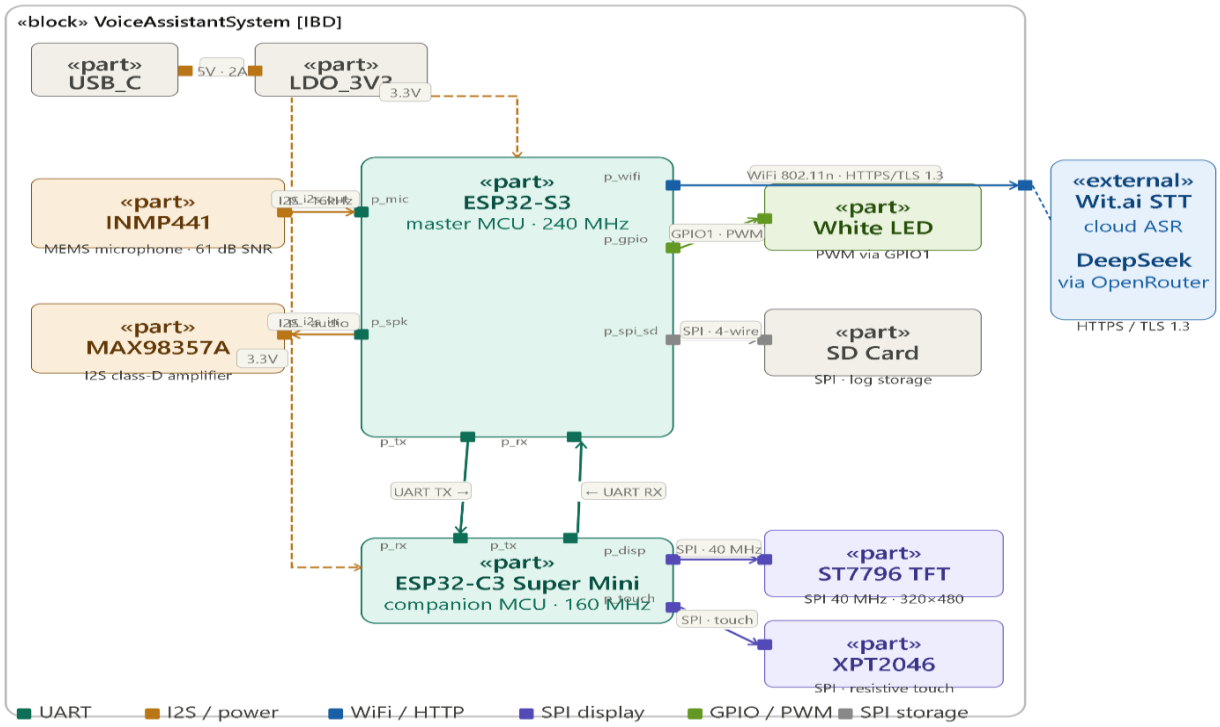

Figure 2. 4— SysML Internal Block Diagram (IBD)

2.2.3 Behavioural Modelling — State Machine and Information Flow

Behavioural modelling describes how the system evolves over time via: (a) **State Machine** — modes of operation and transitions (Deep Sleep → Standby → Active Listening → Cloud AI Processing → Response Display); (b) **DFD** (Data Flow Diagram) — information flows between components at Level-0 (global) and Level-1 (internal MCU); (c) **Time-Critical Paths** — processing chains with latency constraints (Audio path, the total theoretical target response time from voice capture to speech-to-text conversion response only; revised to ≈1.76 seconds for each AI pipeline model in §2.7.3).

State Machine Diagram: System Operating Modes

This diagram illustrates how the system transitions between different operating modes depending on usage and power requirements. The core concept of a **State Machine** is to represent system behavior as a series of "states" and the transitions between them. In your project, the system passes through six main states:

Table 2. 9 — System operating modes: state descriptions and power consumption targets (Deep Sleep and Standby reserved for v2 battery-powered prototype).

State	Description	Power Consumption
Deep Sleep*	Ultra-low power mode (v2 target)	7 µA (target)
Standby*	System ready, waiting for interaction (v2 target)	300 µA (target)
Active Listening	Audio acquisition and VAD processing	80 mA
Cloud AI Processing	Communication with Wit.ai and OpenRouter/DeepSeek	80 mA + Wi-Fi
Response Display	TFT rendering via ESP32-C3	70 mA
Error State	Network failure handling	80 mA

** Deep Sleep and Standby power optimisation states are reserved for the v2 battery-powered version. The current USB-C powered prototype does not implement ultra-low power modes.*

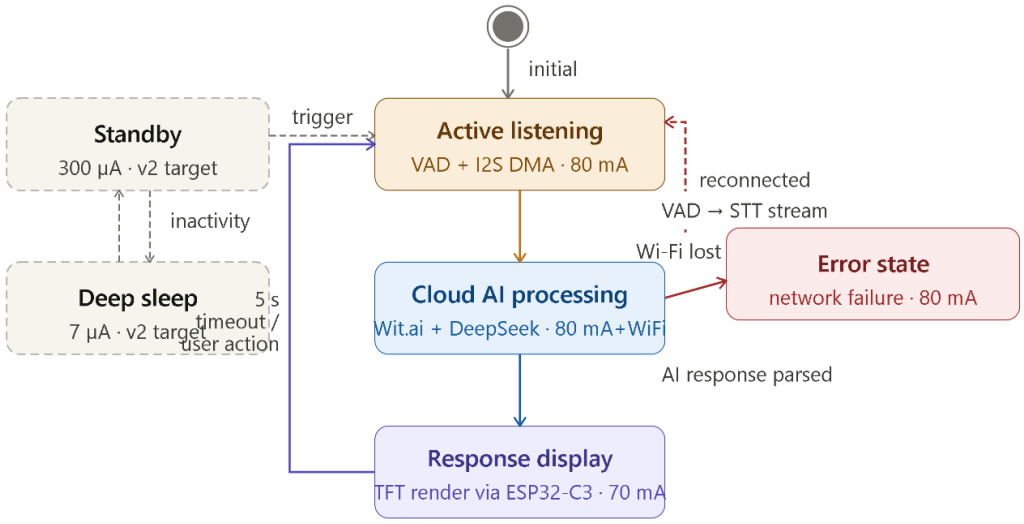

Figure 2. 5— System state machine: Deep Sleep / Standby / Active Listening / Cloud AI Processing / Response Display / Error

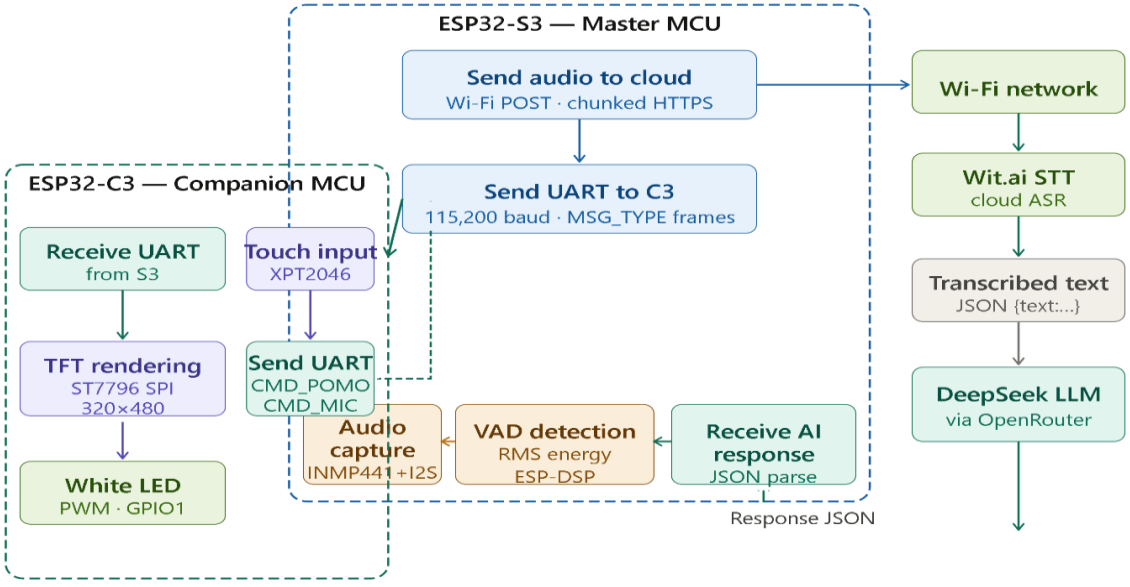

Figure 2. 6— Real-time data flow: ESP32-S3 master ↔ cloud AI pipeline ↔ ESP32-C3 companion

Data Flow Diagram (DFD) — Level-0

A data flow diagram (DFD) is a tool in systems analysis and software engineering that illustrates how data flows within a system and between the system and external entities. The diagram shows processes, data flows, data stores, and external entities that interact with the system.

Table 2. 10 — DFD Level-0: external data streams

Stream ID	Direction	External Entity	Interface	Data Format	Purpose
Stream 1	IN → System	User (Voice)	INMP441 MEMS microphone	Acoustic → 16 kHz, 16-bit digital	Voice command capture for STT
Stream 2	IN → System	User (Touch)	XPT2046 resistive touch	Touch coordinates (SPI)	Interactive input (Pomodoro, tasks)
Stream 3	BIDIRECTIONAL	Cloud (Wit.ai + OpenRouter)	Wi-Fi 802.11n (ESP32-S3)	HTTP POST (audio/text) ↔ JSON	AI pipeline (STT + LLM)
Stream 4	IN → System	USB-C Power	LDO 5V → 3.3V	DC power	Energy supply for all subsystems

Data Flow Diagram (DFD) — Level-1: Internal Flows between MCUs

The DFD Level-1 details the internal flows between the ESP32-S3 (Master) and ESP32-C3 (Companion), showing how data flows through sub-processes:

Process 1.1: Audio Capture — INMP441 → ESP32-S3 via I2S PDM, 16 kHz/16-bit, latency ≈ 1 ms.

Process 1.2: VAD — ESP-DSP RMS analysis of 1024-sample buffers; latency 50–60 ms.

Process 1.3: STT via Wit.ai — ESP32-S3 Wi-Fi POST; JSON {"text":"..."} response; latency 100–200 ms cloud processing.

Process 1.4: LLM via OpenRouter/DeepSeek — ESP32-S3 Wi-Fi POST; JSON response; latency 200–800 ms.

Process 1.5: UART dispatch — ESP32-S3 → ESP32-C3 at 115,200 baud; {"response":"..."} payload; latency ≈ 3 ms.

2.3 Overall Hardware Architecture and Information Flow Topology

This section details the systemic engineering framework and parallel routing pathways that govern the smart desk assistant. It justifies the transition from a single-chip system to an asymmetric dual-MCU topology (ESP32-S3 and ESP32-C3) designed to isolate intensive graphic rendering from real-time processing tasks. Furthermore, it outlines the memory-buffered data streams, internal voltage distribution domains, and structural PCB constraints necessary to stabilize throughput across the physical prototype.

2.3.1 Master Block Diagram — Dual-MCU Architecture

The hardware architecture of the smart desk assistant is based on a Dual-MCU design with two microcontrollers: the ESP32-S3 (main processor) handling real-time tasks — audio, DSP, Wi-Fi, cloud AI — and the ESP32-C3 Super Mini (auxiliary processor) handling HMI tasks — screen rendering, touch, LED. The objective is to guarantee 100% availability of the ESP32-S3 for real-time operations through complete isolation of graphics rendering on the ESP32-C3.

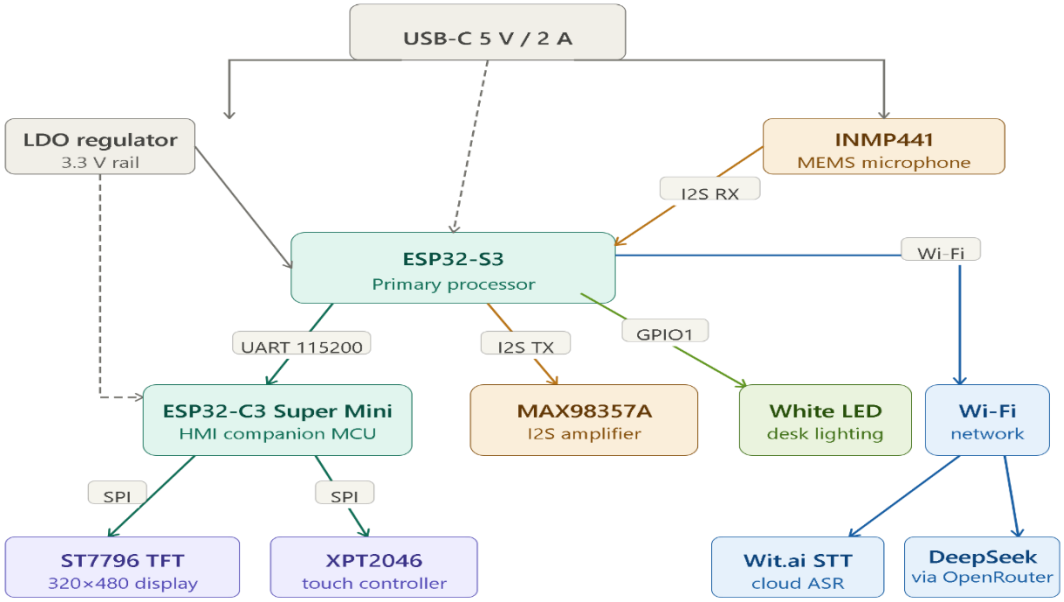

Figure 2. 7— Dual-MCU hardware block diagram: ESP32-S3 ↔ ESP32-C3 with all subsystem connections

Justification: Single-MCU → Dual-MCU Transition

In a Single-MCU architecture (ESP32-S3 only), all processing tasks compete for the same CPU, creating the following critical problems:

The Single-MCU to Dual-MCU transition eliminates all CPU contention, achieving the following target performance gains:

Stable audio latency: 1 ms (vs. 100–200 ms in Single-MCU).

Smooth display: 60 FPS target (vs. 30–40 FPS in Single-MCU).

Perfect DSP stability: zero interruptions (vs. variable context switching).

VAD accuracy target ≥ 95% stable (vs. 85–90% degraded in Single-MCU).

Note: Performance figures above are target values established by architectural analysis; experimental validation results are reported in Chapter 3.

Table 2. 11 — Single-MCU architecture limitations: CPU contention issues, causes, and performance impact justifying the dual-MCU AMP design.

Issue	Cause	Impact
CPU Contention	Audio I2S (16 kHz) + VAD DSP (50–60 ms) + TFT rendering (60 FPS) on same CPU	CPU saturated at 60–70%
I2S Buffer Overrun	TFT rendering blocks CPU during I2S DMA transfer	Audio sample drops
Increased Latency	Context switches between audio and display tasks	+100–200 ms added latency
Reduced FPS	CPU shared between audio and screen	30–40 FPS (jerky animation)
VAD Instability	Interruptions during VAD inference	Degraded VAD accuracy

2.3.2 Real-Time Data Flow Architecture

The smart desk assistant's real-time data stream architecture is based on an optimized dual-parallel audio processing chain (local + cloud) executed via FreeRTOS, ensuring minimal latency and audio data stability during network delays. The key enabler is the 8 MB PSRAM:

Cloud communication is inherently subject to variable latency due to network conditions and server response times. Without sufficient temporary storage, incoming audio samples could be lost during cloud request processing. The PSRAM-based circular buffer solves this problem by providing a large temporary storage area (capable of retaining approximately 128 seconds of audio at 16 kHz/16-bit) that prevents buffer

overflow during temporary communication delays. This mechanism ensures continuous acquisition during Wit.ai STT processing (100–200 ms) and DeepSeek LLM inference (200–800 ms).

2.3.3 Power Management and Voltage Domains

The power management architecture is based on a 5V USB-C power supply converted to a 3.3V logic rail via an LDO regulator, with a separate filtered rail for the INMP441 microphone to minimize noise coupling and maintain the 61 dB SNR. This architecture is designed for a desktop-bound device without a battery, but is compatible with future LiPo battery integration without fundamental redesign.

Table 2.7 presents the theoretical 3.3V rail current budget, derived from component datasheet specifications, to verify that the AMS1117-3.3V LDO regulator (rated 800 mA output) operates within its safe limits under peak load.

The worst-case peak of approximately 522 mA exceeds the LDO's 800 mA rating by a safe margin of 35%. In practice, simultaneous peak draw from all components is unlikely; the measured peak during Wi-Fi provisioning (145 mA) and the theoretical AI streaming peak (~350 mA) both remain well within the LDO's operating envelope.

Table 2. 12 presents the theoretical 3.3V rail current budget

Component	Typical current	Peak current	Source
ESP32-S3 (Wi-Fi active)	80 mA	240 mA	Espressif DS §4.5
ESP32-C3 (SPI + LVGL)	70 mA	90 mA	Espressif DS §4.5
ST7796 TFT + backlight	30 mA	50 mA	Sitronix DS §7
INMP441 microphone	1.4 mA	1.4 mA	InvenSense DS
DS3231 RTC	0.2 mA	0.5 mA	Maxim DS
MAX98357A amplifier	5 mA	40 mA	Maxim DS
SD card module	0.5 mA	100 mA	Generic SPI spec
Total peak (worst case)	**— **	**≈ 522 mA**	**Computed**

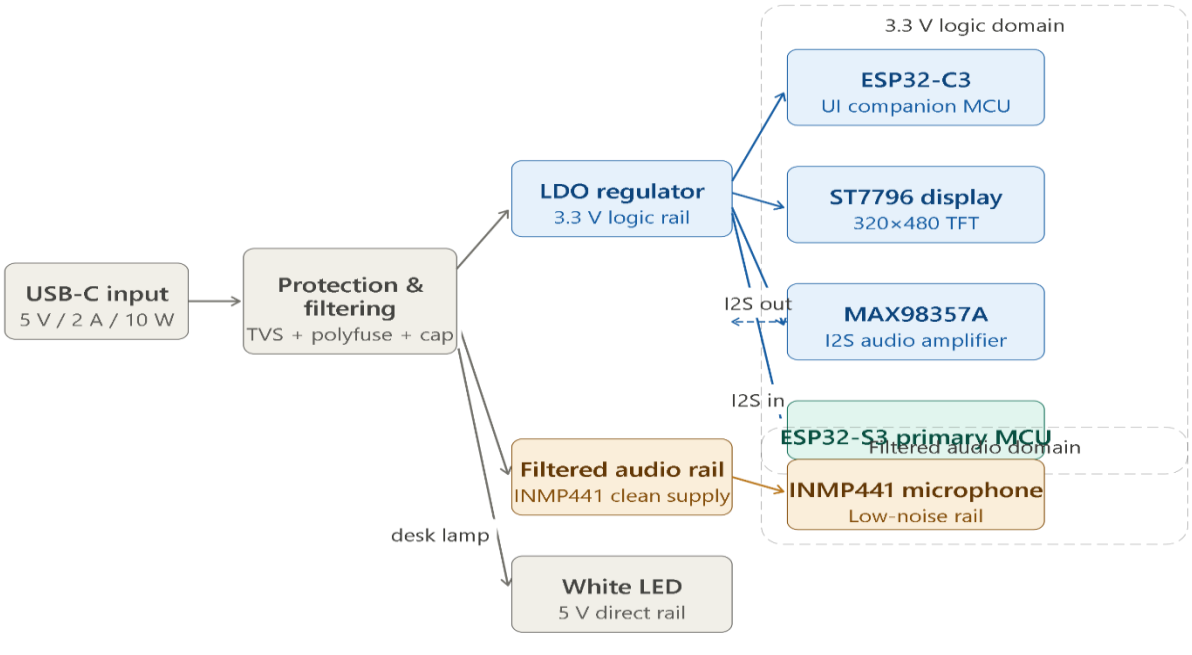

Figure 2. 8— Power supply architecture and voltage domain map

In version v1 of the prototype, the absence of a battery is a deliberate design choice: the device is positioned as a desk-bound voice assistant in a fixed environment (office, workspace, or student room), where USB-C 5V/2A power supply offers hardware simplicity, reduced PCB cost, improved reliability, stable continuous power for real-time workloads (audio + Wi-Fi + cloud AI), and no battery life constraints.

2.3.4 PCB Design and Prototype Board

The smart desk assistant features a custom 2-layer FR4 PCB designed for optimal signal integrity, compact form factor (100×100 mm), and ease of fabrication. The PCB integrates all seven structural blocks (ESP32-S3, ESP32-C3, AudioSubsystem, DisplaySubsystem, PowerManagement, LightingController, AICloudPipeline) with strategic component placement and routing decisions.

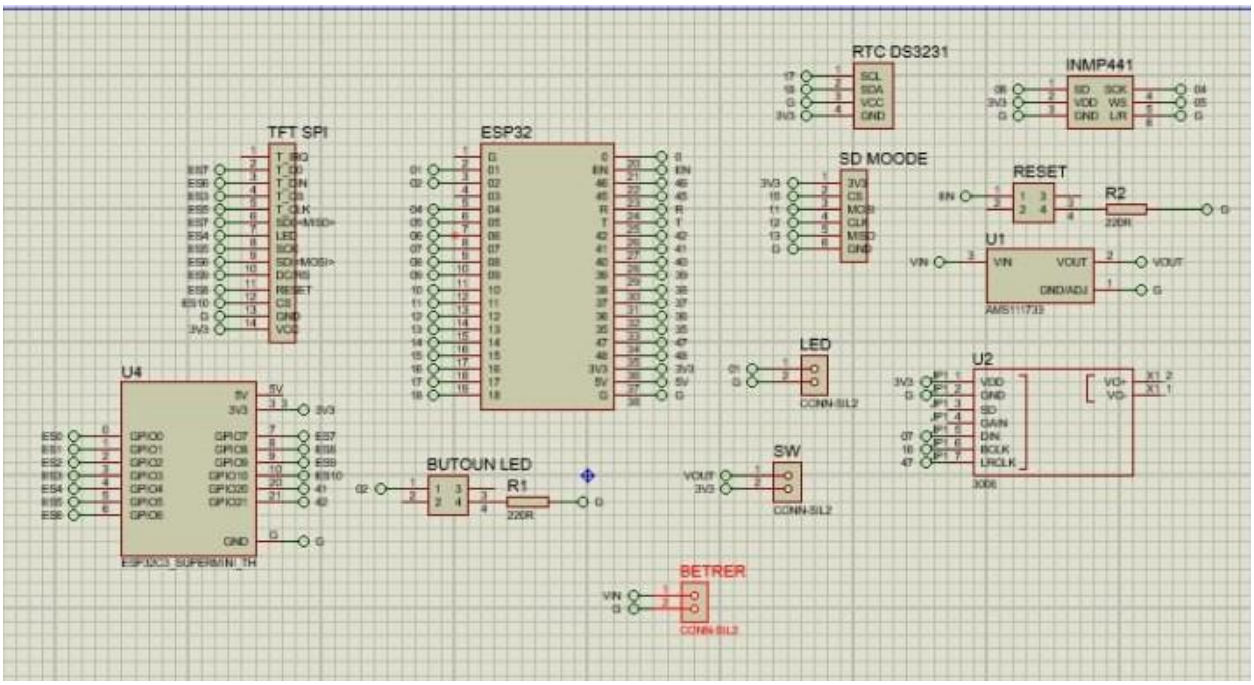

Figure 2. 9— Electronic schematic of the smart desk assistant prototype

Figure 2.8a: ESP32-S3 primary MCU, ESP32-C3 Super Mini companion MCU (U4), AMS1117-3.3V LDO regulator (U1), MAX98357A I2S amplifier (U2), INMP441 MEMS microphone, DS3231 RTC, SD card module, ST7796 TFT SPI interface, reset circuit, LED indicator, and USB-C power input connector.

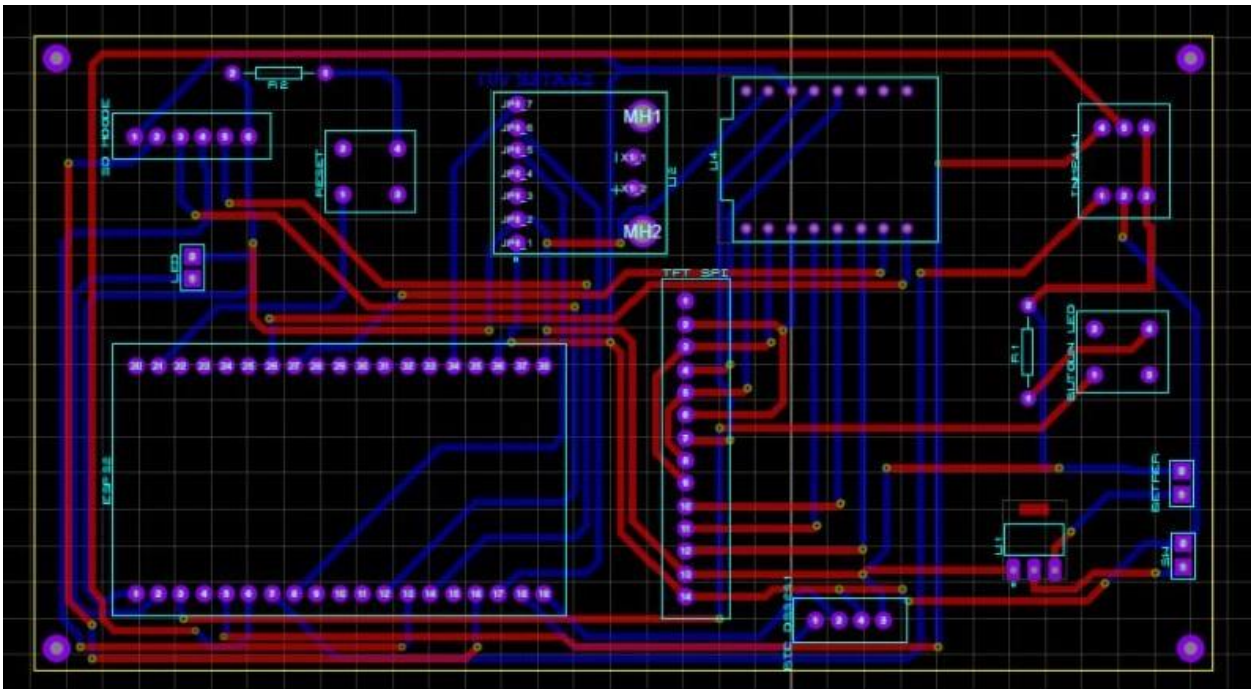

Figure 2. 10— Two-layer FR4 PCB layout (top view)

Figure 2.8b : red traces = top copper layer, blue traces = bottom copper layer. Component placement shows the ESP32-S3 module (centre), ESP32-C3 Super Mini (bottom-left), TFT SPI connector (centre-right), INMP441 microphone (top-right), SD card module (top-left), AMS1117 LDO regulator, and four M3 mounting holes at corners.

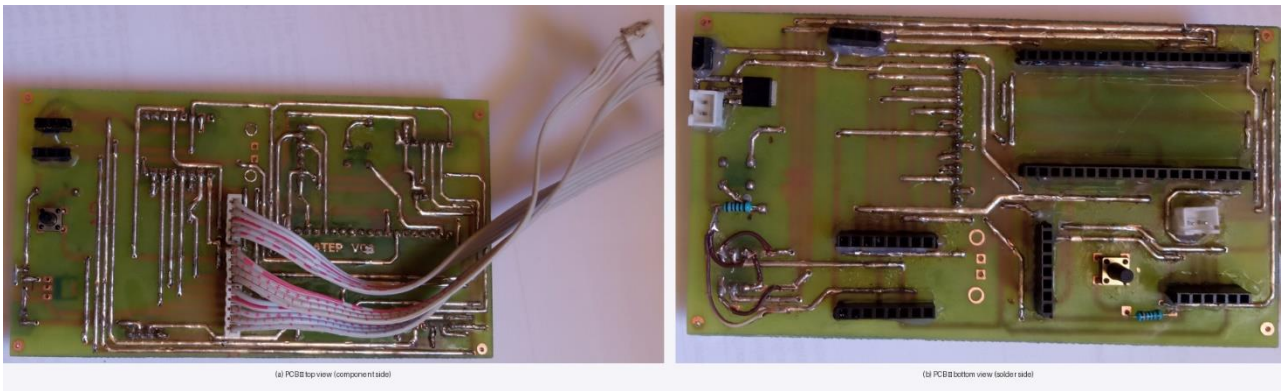

Figure 2. 11— PCB composite (front + back)

Figure 2.8c: (a) top view showing component-side copper traces, header pin sockets for ESP32-S3, ESP32-C3 Super Mini, TFT display connector, push button, and LED indicator; (b) bottom view showing solder-side traces and the flat ribbon cable connecting to the ST7796 TFT display.

2.3.5 Mechanical Enclosure: 3D Printed Case

The mechanical enclosure was designed using Fusion 360, a professional CAD software enabling parametric modelling, assembly validation, and render generation. The design follows a modular approach with two main parts: a base enclosure (holding PCB and components) and a display cover (holding ST7796 TFT with tilt mechanism for optimal viewing angle at a desk).

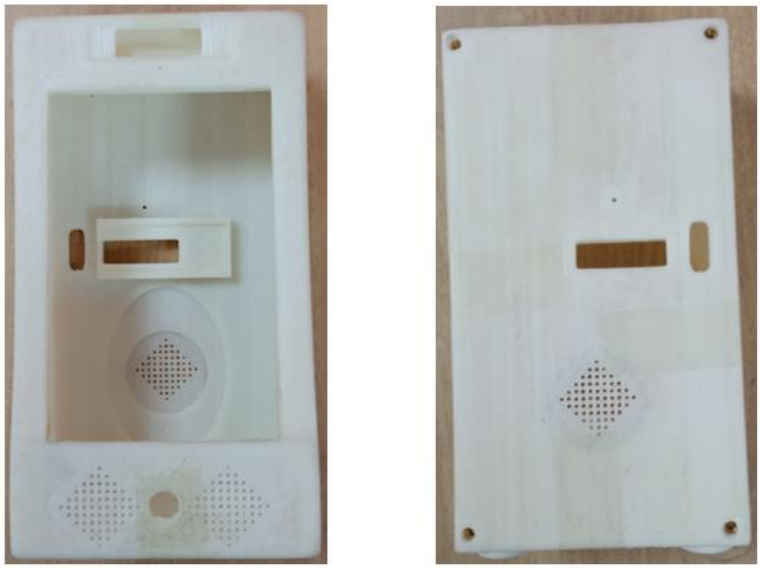

Figure 2. 12— 3D-printed enclosure: front view

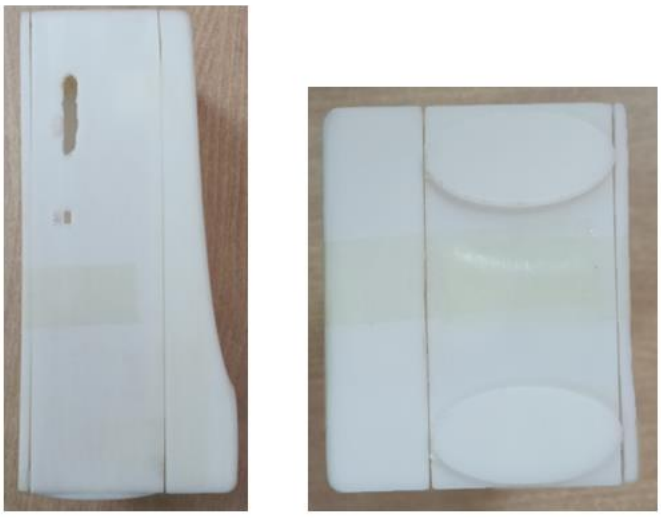

Figure 2. 13— 3D-printed enclosure: rear view

2.4 Selection and Sizing of Critical Electronic Components

This section outlines the technical selection criteria and dimensioning parameters for the core hardware elements of the system architecture. It presents a comparative evaluation of the ESP32-S3 primary processor and the ESP32-C3 co-processor, validating their computing power, hardware-level security, and memory capacities. Additionally, it defines the digital I2S audio interface configurations and the standalone SPI display subsystem implemented to achieve structural isolation between application logic and user interface execution.

2.4.1 Primary Processor: ESP32-S3

The choice of the ESP32-S3 as the main processor is based on a rigorous comparative evaluation highlighting its capabilities optimized for embedded AI, native I2S audio support, extended memory (512 KB SRAM + 8 MB PSRAM), and hardware security features (flash encryption, encrypted NVS) essential for protecting Wit.ai and OpenRouter API keys. [2]

Complete Comparative Table: ESP32-S3 vs. Alternatives

Table 2. 13 — Comparative evaluation: ESP32-S3 vs. alternatives

Characteristic	ESP32-S3	ESP32 (Standard)	STM32 (F4/F7)	Raspberry Pi Zero
CPU Architecture	Xtensa LX7 Dual-Core	Xtensa LX6 Dual-Core	ARM Cortex-M4/M7	ARM 1176JZ(F)-S
Frequency	240 MHz	240 MHz	168–216 MHz	1 GHz
SIMD/Vector	128-bit PIE/SIMD	None	Single-cycle DSP	None
AI Acceleration	5–10× (ESP-NN)	None	None	None
SRAM	512 KB	520 KB	128–2048 KB	512 MB
PSRAM	8 MB Octal SPI	External only	None native	512 MB (integrated)
I2S Native	2 ports + PDM	2 ports	Limited (SAI)	1 port (overlay)
Wi-Fi	802.11b/g/n (150 Mbps)	802.11b/g/n	External module	802.11b/g/n
Flash Encryption	Hardware AES-256	Software only	Hardware AES-128	Software only
NVS Encrypted	Yes (encrypted partition)	No	No	No
Secure Boot	v2 (RSA-3072)	v1 (RSA-2048)	Secure Boot v2	No
Active Consumption	80 mA	120 mA	50–100 mA	150–200 mA
Unit Price	$3.50–$4.50	$2.50–$3.50	$4.00–$8.00	$15.00–$20.00
Ecosystem	ESP-IDF + FreeRTOS	ESP-IDF + FreeRTOS	STM32Cube + FreeRTOS	Linux (RPi OS)

Justification by Key Criteria

Criterion 1 — AI Acceleration (SIMD/Vector Instructions): The ESP32-S3's 128-bit SIMD and ESP-NN instructions accelerate AI inference by 5–10×, enabling VAD processing in 50–60 ms. [2]

Criterion 2 — Memory (SRAM + Extended PSRAM): The 8 MB PSRAM allows a circular audio buffer of approximately 128 seconds, guaranteeing zero data loss during cloud delays (300–800 ms). [2]

Criterion 3 — Native I2S Support for Audio: Two native I2S ports with PDM decoder guarantee 1 ms audio latency with zero software overhead.

Criterion 4 — Security (Flash Encryption + Encrypted NVS): Hardware flash encryption is critical to protecting the Wit.ai and OpenRouter API keys stored in the encrypted NVS partition. The provisioning procedure — nvs_partition_gen.py generates an encrypted NVS binary, and esptool.py write_flash 0x9000 nvs_keys.bin writes it to flash at offset 0x9000. With CONFIG_SECURE_FLASH_ENC_ENABLED=y, the chip-level AES-256 encryption ensures all flash memory is encrypted at rest, making binary extraction and API key reverse engineering impossible. This elevates the project from a prototype to a commercially deployable product. [2]

Table 2. 14 — Hardware flash encryption advantages for commercial security

Functionality	ESP32-S3	ESP32 Standard	Impact
Flash Encryption	Hardware AES-256	Software only	100× more secure
NVS Encrypted	Encrypted partition	No	API keys protected
Secure Boot	v2 (RSA-3072)	v1 (RSA-2048)	Code protection
API Keys	Encrypted in NVS	Exposed in flash	Zero key exposure
Commercially viable	Yes (enterprise-level)	No (prototype only)	Deployable product

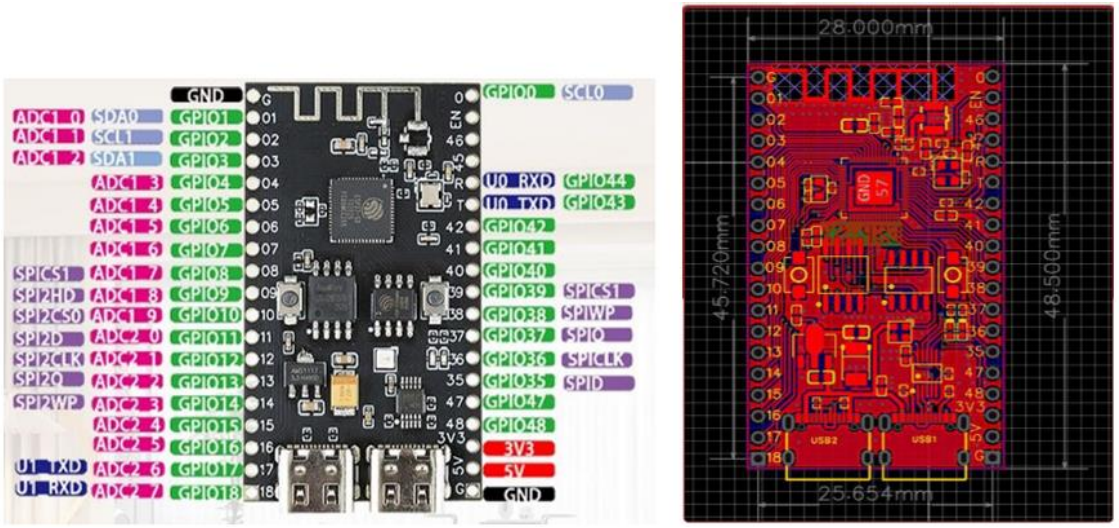

Figure 2. 14— ESP32-S3 R16N8

2.4.2 Companion Processor: ESP32-C3 Super Mini

The ESP32-C3 Super Mini is chosen as the secondary processor because it provides a single-core RISC-V architecture sufficient for GUI rendering tasks, an ultra-compact Super Mini form factor (12×18

mm) for tight hardware integration, native SPI support for the ST7796 display at 40 MHz, and a very low unit cost, making it the most efficient solution to offload all graphical workloads from the ESP32-S3.

Table 2. 15 — ESP32-C3 Super Mini advantages as dedicated GUI co-processor

Criteria	ESP32-C3 Super Mini	Why this is optimal
Architecture	RISC-V 32-bit @ 160 MHz	Sufficient for GUI (85 CoreMark)
SRAM	400 KB	LVGL draw buffer 46 KB possible
SPI	1 native port @ 40 MHz	Smooth display updates for ST7796
Wi-Fi / BLE	Integrated (150 Mbps + BLE 5.0)	No external module required
Form Factor	Super Mini 12×18 mm	Ultra-compact for PCB integration
Active Consumption	70 mA / 7 µA sleep	Balanced power profile
Ecosystem	ESP-IDF + FreeRTOS	Professional development environment

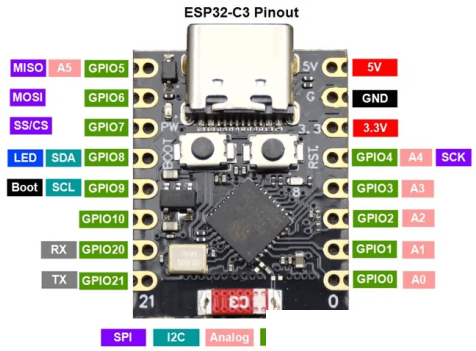

Figure 2. 15— ESP32-C3 Super Mini

LVGL v9.2.3 Graphics Framework

LVGL v9.2.3 is selected over direct SPI register access for three primary reasons: (a) a hardware-agnostic rendering pipeline (portable across display drivers); (b) partial update support, reducing SPI bus utilization by up to 94% for small UI changes; and (c) a comprehensive built-in widget library (arc, btnmatrix, roller, label, textarea) that eliminates the need to implement productivity UI components from scratch. [3]

The LVGL port is configured with a 46 KB draw buffer (320 × 48 × 2 bytes = 30,720 bytes minimum, doubled for performance) allocated in the C3's internal SRAM. When a timer digit changes in the Pomodoro screen, only the 120×80 pixel dirty region is flushed to the ST7796 (19,200 bytes at 40 MHz SPI ≈ 3.8 ms), rather than a full 320×480 frame refresh (307,200 bytes ≈ 61.4 ms) — a 94% reduction.

2.4.3 Audio Subsystem: INMP441 + MAX98357A

The audio subsystem relies on the INMP441 microphone (direct digital I2S output, 61 dB SNR, omnidirectional) for audio capture at desk distances of 1–2 metres, and the MAX98357A amplifier (direct I2S digital amplifier, no external DAC required) for audio output. This architecture eliminates external ADC/DAC stages, reducing noise and hardware complexity.

INMP441 — MEMS Digital Microphone

Key specifications [4]: Digital I2S interface (24-bit data), SNR 61 dBA, sensitivity −26 dBFS, frequency response 60 Hz–15 kHz, current consumption 1.4 mA, package 4.72×3.76×1 mm. The INMP441 is optimal because its direct digital I2S output eliminates the external ADC required by analogue alternatives (e.g. MAX9814), guaranteeing SNR 61 dB vs. 55–58 dB and a noise floor < 10 µV vs. 50–100 µV.

Figure 2. 16— INMP441 (MEMS – I2S) MEMS Microphone

MAX98357A — Direct I2S Digital Amplifier

This table illustrates the characteristics MAX98357A I2S amplifier

Table 2. 16 — MAX98357A I2S amplifier specifications

Characteristic	Value	Impact
Type	Direct I2S class-D amplifier	No external DAC required
Interface	I2S (BCLK=GPIO16, LRC=GPIO47, DIN=GPIO7)	Native ESP32-S3 I2S1
Power Output	3.2W @ 8Ω	High-quality audio output
DAC	Not required (I2S native)	Eliminates DAC stage
Resolution	16-bit	Precise audio reproduction
Sample Rate	16 kHz native	Optimal for STT/LLM
Voltage	3.3V	Compatible with ESP32-S3
Efficiency	90% (class D)	Optimized energy consumption
THD+N	< 1%	High audio quality
Size	3×3×0.5 mm	Enables miniaturisation

Figure 2. 17— Audio Amplifier MAX98357A (I2S)

Shared I2S Bus Configuration: INMP441 + MAX98357A

Both the INMP441 (microphone) and MAX98357A (amplifier) share the BCLK (bit clock) and WS (word select/LRCLK) signals, with the ESP32-S3 as I2S master. The INMP441 SD pin connects to the ESP32-S3 I2S DATA_IN GPIO (input), while the MAX98357A DIN connects to the I2S DATA_OUT GPIO (output) — ensuring no electrical conflict on the shared clock lines.

2.4.4 Display and Touch Interface: ST7796 + XPT2046 — Connected Exclusively to ESP32-C3

ST7796 — 4-inch TFT Display (320×480)

The ST7796 4-inch TFT display (320×480 pixels, SPI interface up to 40 MHz, 16-bit RGB565 colour) was selected for its balance between display area, graphical capability, and integration simplicity. The 320×480 resolution provides sufficient screen space for all productivity information (Pomodoro timer, task lists, AI responses, system status, configuration menus). All graphics rendering is performed locally on the ESP32-C3, leaving the ESP32-S3 completely free from any display-related workload.

XPT2046 — Resistive Touch Controller

The XPT2046 provides an intuitive tactile interaction method, allowing users to control the device without relying solely on voice commands. Typical touch functions include starting/stopping Pomodoro sessions, navigating menus, selecting tasks, adjusting settings, muting the microphone, and confirming notifications. The XPT2046 shares the same SPI infrastructure as the ST7796, with an independent chip-select line, simplifying hardware routing and minimizing system complexity.

Figure 2. 18— TFT LCD Touch Screen (ST7796 + XPT2046)

Complete Architectural Isolation

A fundamental design principle of this project is the complete separation between the AI subsystem (ESP32-S3) and the graphical user interface subsystem (ESP32-C3). Both the ST7796 display and the XPT2046 touch controller are connected exclusively to the ESP32-C3 through the SPI bus. The ESP32-S3 has no physical connection to the display or touch controller, and carries no graphical rendering or UI processing responsibility. Communication between the two microcontrollers occurs only through the UART link, where the ESP32-S3 sends high-level information (text responses, notifications, commands) and the ESP32-C3 handles all visualisation and touch interactions. This hardware separation physically implements the architectural philosophy of §2.3.1.

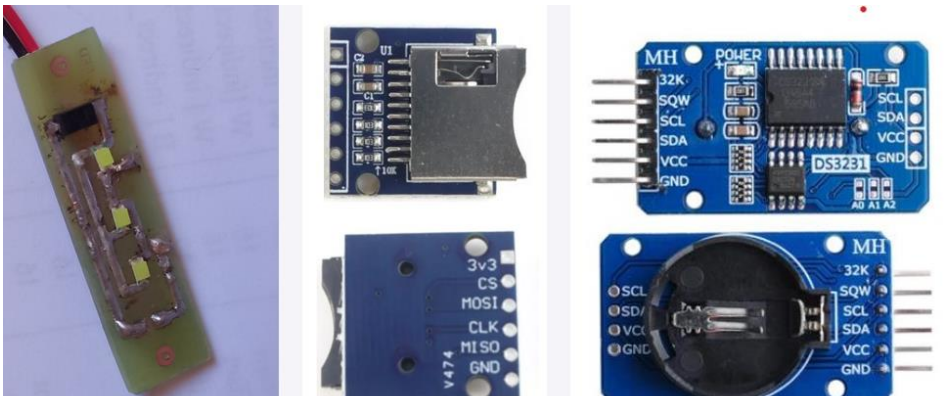

Figure 2. 19— Component composite (LED + SD + DS3231)

Figure 2.16 : (a) custom white LED board with three SMD LEDs in series for smart desk lighting, controlled via PWM on GPIO1; (b) Micro-SD card SPI module (SPI interface: CS, MOSI, CLK, MISO, 3.3V) for lecture transcription archiving; (c) DS3231 precision RTC module (I2C: SDA=GPIO18, SCL=GPIO17) with CR2032 coin cell backup battery for timekeeping during power loss.

2.5 Inter-MCU Communication Interface and Protocol Design

This section details the physical and logical architecture governing the bidirectional data exchange between the system's dual microcontrollers. It analyzes the byte-level frame alignment and checksum validation of the custom, lightweight UART protocol designed to bridge the execution and display cores. Furthermore, it outlines the signal integrity routing constraints and automated recovery mechanisms established to guarantee low-latency, fault-tolerant communication under active workloads.

2.5.1 Custom Inter-MCU UART Protocol Design

The communication between the ESP32-S3 and the ESP32-C3 uses the UART protocol because it is the most suitable option for sending lightweight command packets. This choice reduces the number of required pins to two (TX/RX), simplifies debugging with a logic analyser or serial monitor, and enables non-blocking operation through interrupts and DMA.

Frame Format (Byte-Level Structure)

The implemented protocol uses a fixed 12-byte binary frame:

[0] : FRAME_START_BYTE (0xAB)

[1] : msg_type (uart_msg_type_t enum)

[2..9] : payload (8 bytes, zero-padded)

[10] : CRC-8 checksum (over bytes [0..9])

[11] : FRAME_END_BYTE (0xCD)

On the ESP32-C3 side, incoming frames are received and processed asynchronously using UART with DMA, ensuring fast parsing without blocking LVGL rendering tasks. This architecture provides: communication latency < 1 ms; more than 95% CPU availability for GUI tasks; 60 FPS display rendering without interruption from UART communication; and touch response latency < 10 ms.

Table 2. 17 — Complete MSG_TYPE table: implemented UART protocol (bidirectional)

MSG_TYPE	Hex	Name	Direction	Payload	Function
MSG_TYPE_TIME_UPDATE	0x02	Time Update	S3→C3	HH MM SS WD DD MM YY	Send current time to C3 for display
MSG_TYPE_TEMP_UPDATE	0x03	Temperature Update	S3→C3	2 bytes (temp °C)	Send temperature to C3 for display
MSG_TYPE_POMODORO_STATE	0x04	Pomodoro State	S3→C3	3 bytes (state, remaining)	Update Pomodoro timer on C3
MSG_TYPE_AI_STATUS	0x05	AI Status	S3→C3	2 bytes (status)	Show AI status on C3
MSG_TYPE_NOTIFICATION	0x06	Notification	S3→C3	Variable (text)	Send notification text to C3 display
MSG_TYPE_CMD_POMO	0x24	Pomodoro Command	C3→S3	1 byte (start/pause/reset)	C3 sends Pomodoro control to S3
MSG_TYPE_CMD_MIC	0x25	Microphone Command	C3→S3	1 byte (trigger)	C3 triggers AI voice query on S3

2.5.2 Signal Integrity and Physical Wiring

Cross-Wired Connection

ESP32-S3 GPIO42 (TX) → ESP32-C3 GPIO21 (RX); ESP32-C3 GPIO20 (TX) → ESP32-S3 GPIO41 (RX). Shared GND at 3.3V — no level shifter required as both MCUs operate at the same logic voltage.

Failure and Recovery Scenarios

Detected errors: CHECKSUM invalid (UART noise), STX/ETX invalid (byte lost), UART overrun (DMA buffer full). Automatic recovery: UART re-initialisation in < 10 ms (reset TX/RX + DMA + re-init

at 115,200 baud). Diagnostic White LED (PWM indicator): green = communication OK; yellow = errors detected; red = UART non-functional (re-init in progress).

Table 2. 18 — PCB UART signal integrity constraints

Constraint	Value	Reason
Trace length	≤ 5 cm	Low impedance, reduced noise
Separation from I2S lines	≥ 5 mm	Coupling noise < 10 µV RMS
Guard ring	Copper around I2S lines	Noise immunity
Ground via	Between UART and I2S routing	Ground isolation

2.6 Firmware Architecture and Development Environment

This part gives the characteristic software engineering paradigms, toolchain architectures, multitasking paradigms that comprise the system firmware architecture. It gives an explanation on the component based ESP-IDF v5.1.7 environment configuration, as well as the dual-core FreeRTOS managing strategies through task allocating schemes adapted to both ESP32-S3 and ESP32-C3 architectures. These real-time providing structures collectively assign demands of predictable, framerate-free audio hooking and graphics painting apart from background radio stack.

2.6.1 Development Environment and Toolchain Configuration

The firmware for both microcontrollers was developed using Espressif IoT Development Framework (ESP-IDF) v5.1.7, the official professional-grade SDK maintained by Espressif Systems for all ESP32-family devices. [5] ESP-IDF provides a CMake-based build system, hardware abstraction layers, and direct access to all low-level peripherals required — including the I2S DMA driver, the LEDC PWM peripheral for smart lighting, and the mbedTLS stack for HTTPS communication. These capabilities are either unavailable or heavily abstracted in the Arduino framework, making ESP-IDF the only viable choice for a production-grade, commercially deployable firmware.

fundamental design principle is strict component-based architecture: the project directory is organized into independent components, each encapsulating a well-defined subsystem with its own CMakeLists.txt registration file. [3] The project component tree:

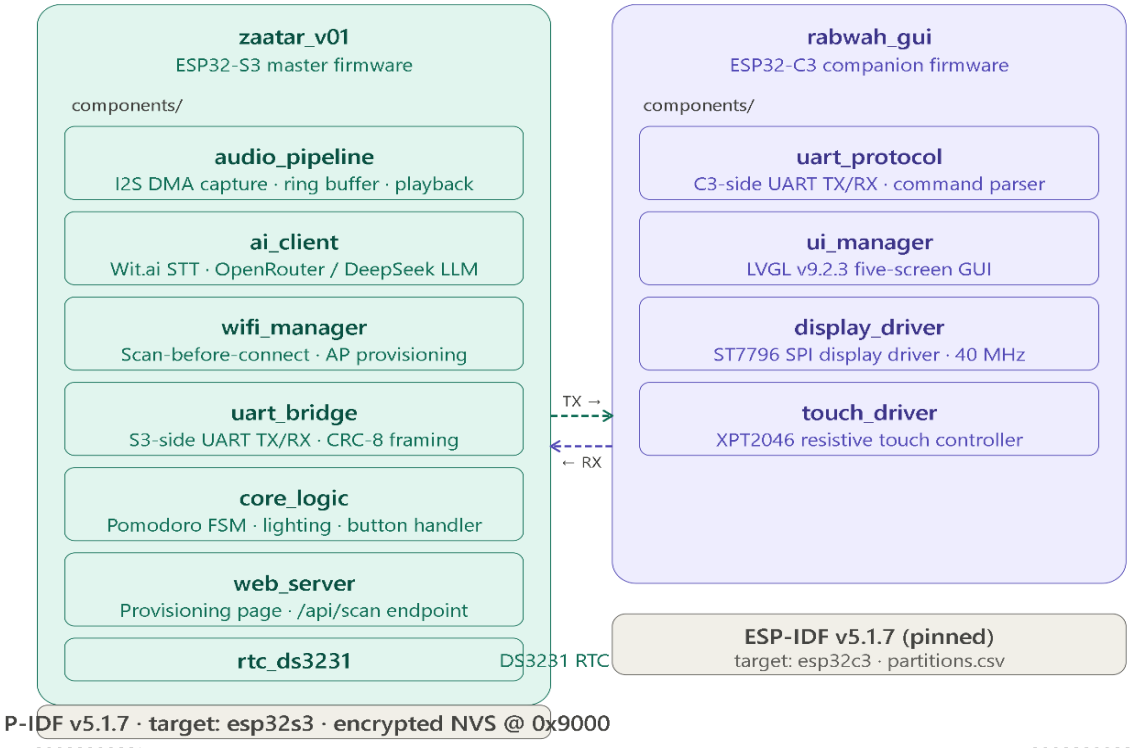

Figure 2. 20— ESP-IDF component tree for both firmware targets (ESP32-S3 and ESP32-C3)

Separate build environments are defined for the ESP32-S3 (target esp32s3) and ESP32-C3 (target esp32c3). The SDK version is pinned to v5.1.7 for build reproducibility. The ESP32-S3 partition table is customized via partitions.csv to accommodate the encrypted NVS partition (0x9000, 24 KB) alongside the factory application partition (0x10000, 3 MB).

2.6.2 FreeRTOS Task Architecture — ESP32-S3

The firmware execution model on the ESP32-S3 is built entirely on FreeRTOS, the real-time operating system integrated within ESP-IDF. [6] A critical architectural decision is the dual-core task affinity strategy: all time-critical I2S audio processing tasks are pinned to Core 1, while Wi-Fi networking and cloud AI tasks execute on Core 0. [7] This physical isolation ensures that Wi-Fi interrupt service routines on Core 0 never pre-empt the I2S DMA read loop on Core 1, guaranteeing zero audio dropout under peak network load.

Inter-task communication relies on three FreeRTOS primitives [8]: (a) xQueueCreate passes audio buffer pointers from AudioCaptureTask to AIClientTask without data copying; (b) xEventGroupSetBits signals AI response completion from AIClientTask to UARTRxTask; and (c) xSemaphoreCreateMutex protects shared access to the Pomodoro timer state variable.

Table 2. 19 — FreeRTOS task map: ESP32-S3 firmware

Task Name	Core	Stack	Priority	Function
AudioCaptureTask	1	8 KB	5 (highest)	I2S DMA read, RMS-based VAD, ring buffer write
AIClientTask	1	12 KB	4	Wit.ai chunked HTTPS streaming + DeepSeek LLM POST
UARTRxTask	0	3 KB	4	Parse incoming C3 frames; dispatch Pomodoro/mic commands
CoreLogicTask	0	4 KB	3	Pomodoro FSM, button events, LEDC lighting control
ClockSyncTask	0	2 KB	2	DS3231 RTC polling every 60 s → UART time update to C3
WifiManagerTask	0	6 KB	3	Scan-before-connect, reconnection, AP provisioning

2.6.3 FreeRTOS Task Architecture — ESP32-C3

The ESP32-C3 companion firmware enforces a strict single-responsibility principle: it manages exclusively the ST7796 TFT display via LVGL v9.2.3, processes XPT2046 touch events, and receives UART commands from the ESP32-S3. It carries an absolute prohibition on Wi-Fi initialisation, I2S driver loading, or any cloud API communication — ensuring that LVGL rendering tasks never contend with network operations.

Table 2. 20 — FreeRTOS task map: ESP32-C3 firmware

Task Name	Stack	Priority	Function
UARTReceiveTask	4 KB	5 (highest)	UART ISR + 12-byte binary frame parser; push to render queue
LVGLRenderTask	8 KB	4	LVGL v9.2.3 tick increment, display flush via SPI at 40 MHz
TouchScanTask	3 KB	3	XPT2046 ADC poll on PENIRQ interrupt; affine coordinate transform
HeartbeatTask	2 KB	1	Sends MSG_TYPE_HEARTBEAT to ESP32-S3 every 5 seconds

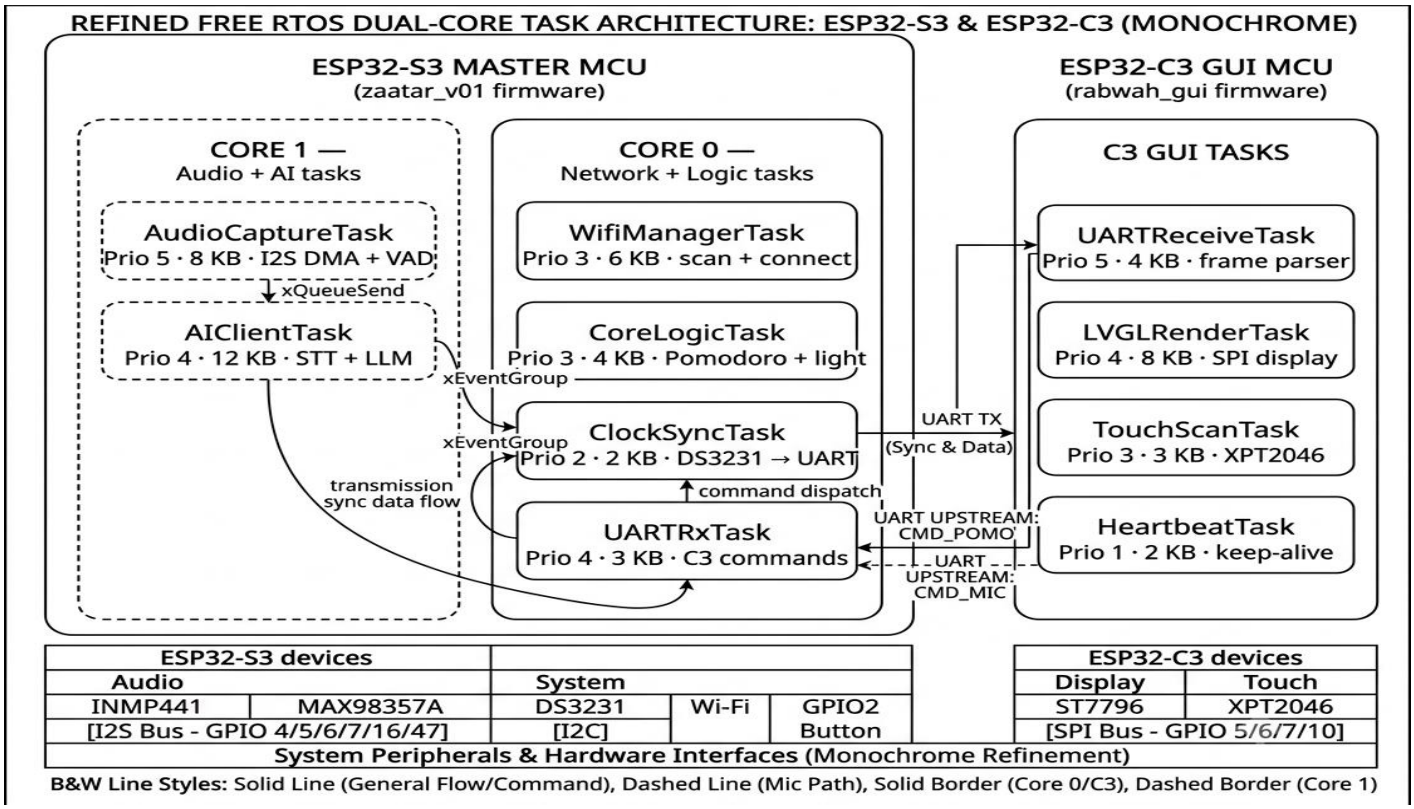

Figure 2. 21— FreeRTOS dual-core task architecture (ESP32-S3 + ESP32-C3)

2.7 Network Stack, Security Architecture, and AI Pipeline

This section breaks down the system's cloud communication layer, multi-tier security framework, and edge-to-cloud artificial intelligence pipeline. It details the smartphone-independent Wi-Fi provisioning strategy, the mbedTLS-driven cryptographic architecture used to safeguard localized API keys, and the sequential execution of the voice processing pipeline. Together, these layers manage the real-time transition of data from local I2S audio capture, through Voice Activity Detection (VAD) and cloud-based streaming inference, to the final display rendering within a low-latency architecture.

2.7.1 Wi-Fi Connectivity and Provisioning Strategy

The device connects to the home or office Wi-Fi network without requiring a smartphone as an intermediary. This is achieved through a custom scan-before-connect provisioning strategy implemented in the wifi_manager component. [9] On every boot, the firmware executes the following deterministic sequence:

Step 1 — NVS credential check: The firmware reads the saved SSID from the encrypted NVS partition. If no credentials exist, it proceeds directly to AP provisioning mode.

Step 2 — Targeted SSID scan: If credentials are found, esp_wifi_scan_start() searches for the saved SSID. This scan takes approximately 2–3 seconds.

Step 3a — Direct connection: If the saved SSID is found, wifi_manager_init() connects normally.

Step 3b — AP provisioning fallback: If the saved SSID is not found, the firmware automatically launches the 'Smart-Assistant-Setup' access point — eliminating the default 30-second connection timeout.

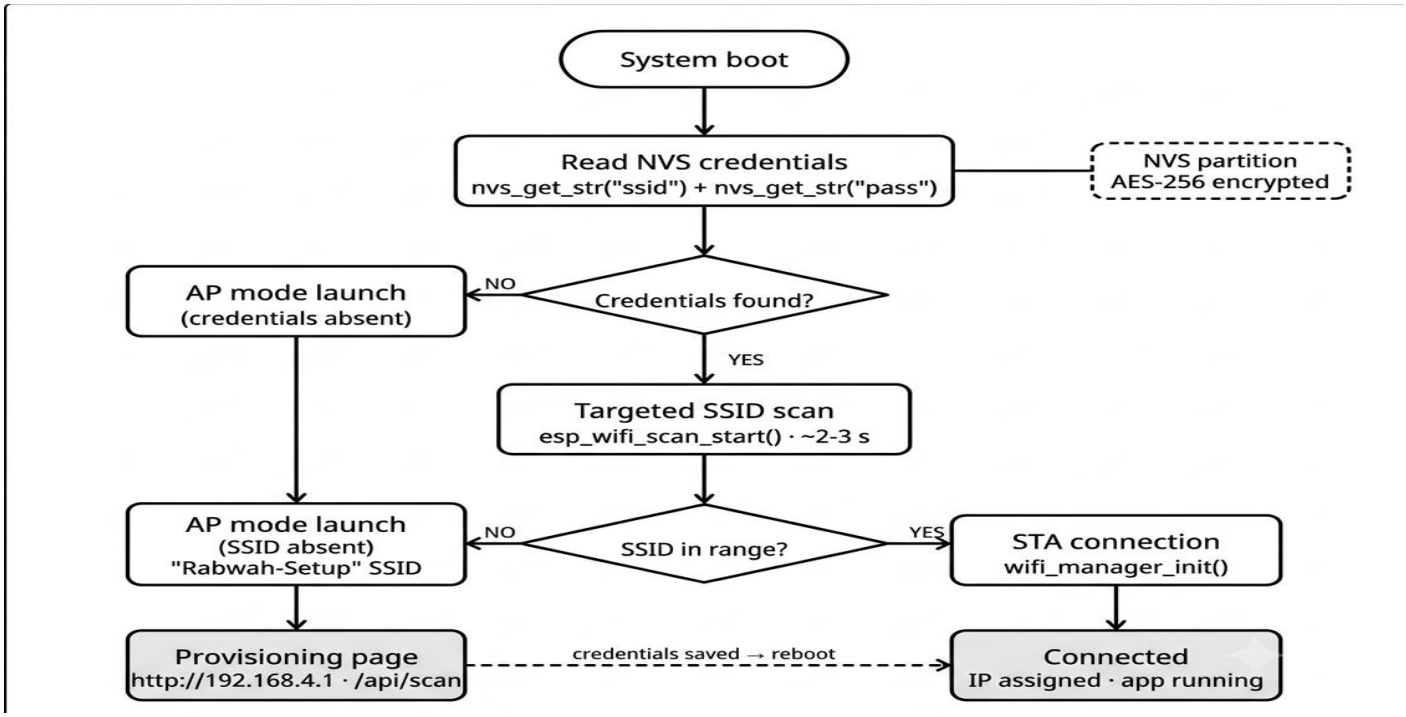

Figure 2. 22— Wi-Fi scan-before-connect provisioning strategy (wifi_manager component)

The provisioning interface is served at http://192.168.4.1 in APSTA mode (simultaneous AP and STA). The /api/scan endpoint invokes esp_wifi_scan_start() while the AP is active and returns a JSON array of nearby networks. The user selects their network, enters the passphrase, and the device reboots into STA mode. API keys (Wit.ai token and OpenRouter API key) are provisioned separately using nvs_partition_gen.py and written to the NVS flash offset (0x9000) via esptool.py write_flash 0x9000 nvs_keys.bin. [10] This ensures that API keys never appear in the compiled firmware binary.

2.7.2 TLS/HTTPS Security Architecture and API Key Protection

All cloud API communications are secured using Transport Layer Security (TLS) 1.2/1.3, implemented through the mbedTLS stack integrated within ESP-IDF. [11] Server certificate verification is performed against the Mozilla CA root certificate bundle compiled into the firmware image using

esp_crt_bundle_attach(). This ensures all HTTPS connections to Wit.ai (api.wit.ai:443) and OpenRouter (openrouter.ai:443) are authenticated without pinning a specific certificate that may expire.

API keys are retrieved at runtime into stack-allocated char buffers, used solely for HTTP Authorization header construction, and explicitly zeroed with memset() immediately after the HTTPS request. Hardware Flash Encryption is enabled via eFuse burning at the first production boot [12], encrypting the entire SPI flash at rest — making binary extraction via JTAG cryptographically infeasible (see §2.4.1 for detailed security architecture and component comparison).

Table 2. 21 — Multi-layer security architecture for API key protection

Security Layer	Mechanism	Scope	Threat Mitigated
Transport security	TLS 1.2/1.3 + CA bundle	All HTTPS API calls	Man-in-the-middle, eavesdropping
Key storage	Encrypted NVS partition (AES-256)	Wit.ai + OpenRouter keys	NVS dumping, file system read
Flash encryption	ESP32-S3 eFuse AES-256 hardware	Entire SPI flash content	JTAG extraction, chip-level dump
Runtime key handling	Stack buffer + memset() zeroing	Active request lifecycle	Heap dumps, memory inspection
Provisioning	nvs_partition_gen.py + esptool	Initial key deployment	Keys never in firmware binary

2.7.3 AI Pipeline: VAD, STT Streaming, and LLM Integration

Voice Activity Detection (VAD)

Recording is triggered by a physical long-press of GPIO2 (≥ 800 ms) or a MSG_TYPE_CMD_MIC UART command from the C3's on-screen microphone button. Upon trigger, the AudioCaptureTask transitions from IDLE to RECORDING and reads 1024-sample DMA buffers (64 ms per frame at 16 kHz) from the INMP441. A lightweight energy-based VAD algorithm computes the RMS amplitude of each buffer. If RMS falls below the silence threshold (−35 dBFS) for more than 800 ms, the recording session terminates and the final HTTP chunk is sent to Wit.ai.

Wit.ai Speech-to-Text Streaming

Wit.ai was selected as the Speech-to-Text provider for three reasons specific to this project's constraints. First, its free tier imposes no API cost ceiling during academic prototyping, unlike Google Cloud Speech-to-Text or AssemblyAI, which require billing accounts for sustained use. Second, Wit.ai natively supports Arabic and French — the two primary languages of the target user base (Algerian students) — in addition to English, eliminating the need for a separate multilingual STT endpoint. Third, its HTTP/1.1 chunked transfer API allows audio to be streamed incrementally as DMA buffers are filled, matching the real-time capture architecture of the ESP32-S3 and avoiding the need to buffer the full recording in PSRAM before transmission. It is acknowledged that the 90% transcription accuracy target specified in Table 2.2 remains to be validated experimentally against Algerian-accented Arabic and French speech; this validation is planned for the v2 prototype phase.

Transcription is performed by the Wit.ai Speech-to-Text API (Meta Platforms). [13] The implementation uses HTTP/1.1 chunked transfer encoding [14] to stream audio continuously to POST https://api.wit.ai/speech. Each 1024-sample DMA buffer (2048 bytes) is written to the TLS connection as a single HTTP chunk via esp_http_client_write(), eliminating the need to buffer the entire recording before transmission. Upon receiving a JSON response [15] ({"text":"..."}), the transcribed text is forwarded to the LLM stage.

DeepSeek LLM Integration via OpenRouter

The transcribed query is forwarded to the DeepSeek-V3 large language model [16], accessed through the OpenRouter API [17] at endpoint POST https://openrouter.ai/api/v1/chat/completions with model identifier deepseek/deepseek-chat-v3-0324, max_tokens: 150, and temperature: 0.7. The response is parsed via cJSON_Parse() → choices[0].message.content navigation, sanitised (markdown removed), truncated to 200 characters, and serialised into a MSG_TYPE_NOTIFICATION UART packet for display on the ESP32-C3.

End-to-End Latency Model:

Table 2. 22 — End-to-end AI pipeline latency model

Pipeline Stage	Component	Estimated Latency
I2S DMA buffer fill	INMP441 + ESP32-S3 I2S DMA	~64 ms (1024 / 16000 Hz)
VAD silence detection	RMS energy threshold (3 × 64 ms)	~192 ms
TLS handshake + network RTT	Wi-Fi 802.11n + mbedTLS	~300 ms
Wit.ai STT processing	Wit.ai cloud ASR engine	~400 ms (3-second utterance)
DeepSeek LLM inference	OpenRouter / DeepSeek-V3	~800 ms
UART dispatch to C3	ESP32-S3 → ESP32-C3 @ 115,200 baud	~3 ms (32-byte packet)
LVGL render on ST7796	LVGL partial update (120×80 px)	~4 ms
Total estimated budget	—	~1.76 s (within 3 s target ✓)

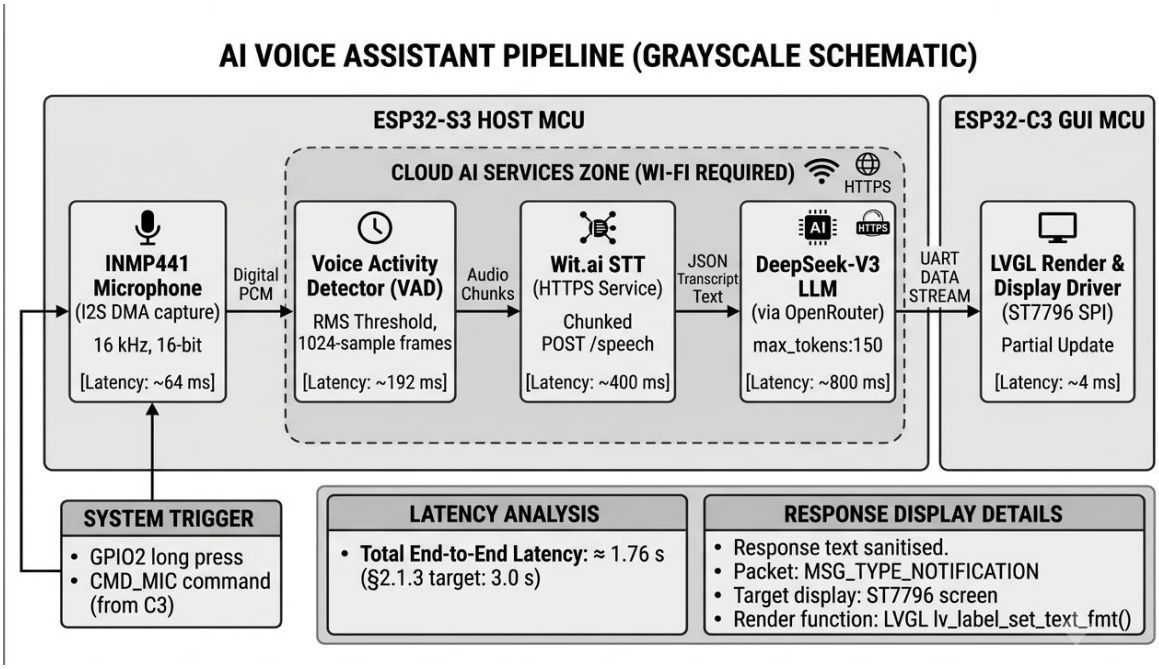

Figure 2. 23— End-to-end AI pipeline data flow (TC-01 latency model)

2.8 Embedded Intelligence: Pomodoro FSM, Task Manager, and LVGL Interface

This section examines the localized intelligence architecture of the system, focusing on the coordination between core productivity features and the graphical user interface. It describes the operation of the Pomodoro Timer FSM, the fault-tolerant memory caching scheme for the task manager, and the architectural design of the five-screen LVGL layout driving the visual environment. These subsystems combine to form a single edge-computing platform integrating low-latency inter-mcu control loops with a highly reactive, self-reliant user experience.

2.8.1 Pomodoro Timer Finite State Machine and Audio Alerts

The Pomodoro Technique, formalized by Francesco Cirillo [18], structures productive work into alternating intervals of focused effort (25 minutes) and scheduled rest (5-minute short break; 15-minute long break after four consecutive sessions). Its implementation in this project is a Finite State Machine (FSM) tightly integrated with the audio alert subsystem, the UART communication layer, and the LVGL graphical interface.

The FSM is implemented using a FreeRTOS software timer (xTimerCreate() with 1-second auto-reload). On each tick, the timer callback decrements the s_pomo_remaining counter, constructs a MSG_TYPE_POMODORO_STATE UART packet, and dispatches it to the ESP32-C3. When the counter reaches zero, the EVT_POMO_DONE event group bit is set, signalling CoreLogicTask to trigger the phase-completion audio alert and advance the FSM. State transitions from the touchscreen (start, reset) arrive via the UART bridge as MSG_TYPE_CMD_POMO packets — creating a fully symmetrical control path with no code duplication.

Audio Alert Generation

Phase-completion alerts are generated using a pre-computed 32-sample integer sine lookup table stored in flash. [19] This avoids floating-point arithmetic and math.h dependencies in the timer callback ISR context. Three acoustically distinct patterns:

Work session complete (WORK → SHORT_BREAK): 3 pulses at 880 Hz (A5), 200 ms on / 120 ms off.

Short break complete (SHORT_BREAK → WORK): 2 pulses at 660 Hz, 250 ms on / 150 ms off.

Long break complete (LONG_BREAK → IDLE): 4 pulses at 440 Hz (A4), 300 ms on / 180 ms off.

The PCM tone buffer is statically allocated (static int16_t s_tone_buf[8000], 16 KB) in the component's data segment, rather than using alloca() on the task stack — a design decision validated after a stack overflow in the ClockSyncTask was traced to a large stack allocation during simultaneous I2S playback.

Table 2. 23 —Pomodoro FSM states, durations, and transition triggers

State	Duration	Arc Colour	Transition Trigger
IDLE	—	Primary (cyan)	User presses on screen or sends CMD_POMO start via UART
WORK	25 min	Primary (cyan)	xTimerStart() → 25-min countdown; on expiry → SHORT_BREAK or LONG_BREAK
SHORT_BREAK	5 min	Success (green)	Automatic after WORK; after 4 sessions → LONG_BREAK
LONG_BREAK	15 min	Success (green)	Automatic after 4th WORK session; on expiry → IDLE

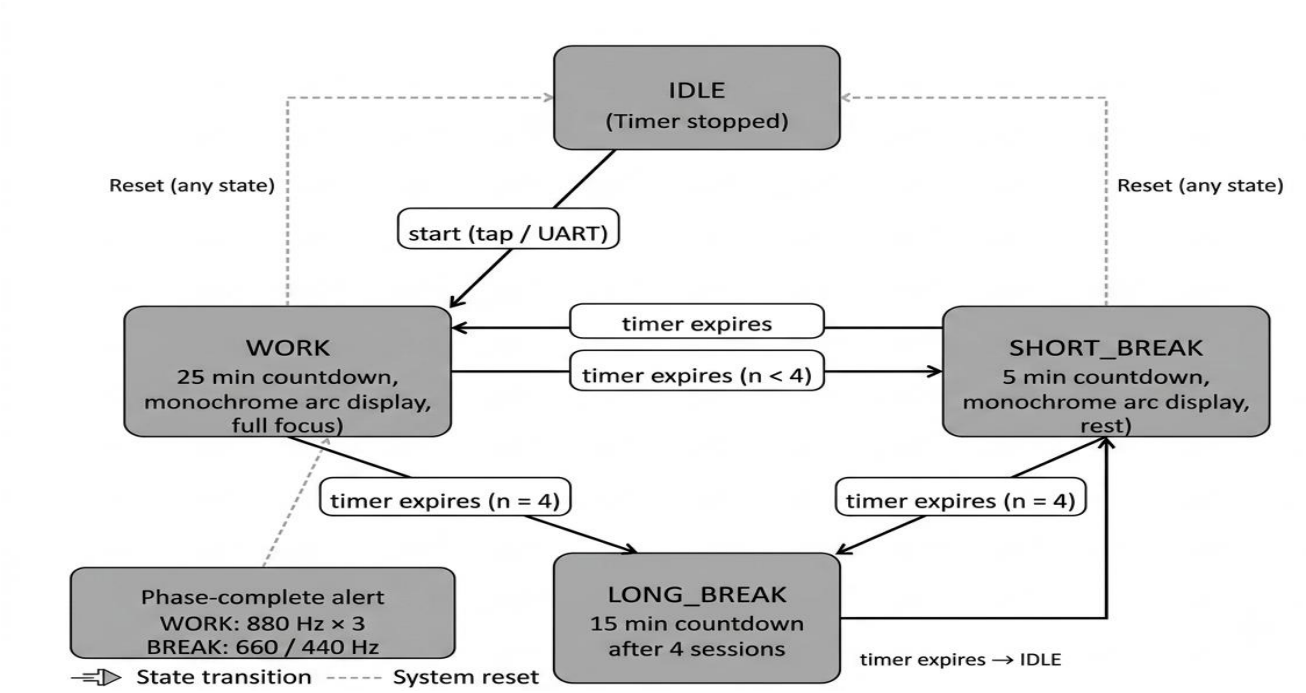

Figure 2. 24— Pomodoro FSM: states, transitions, and phase-completion audio alerts

2.8.2 LVGL v9.2.3 Five-Screen Graphical User Interface

The graphical user interface of the ESP32-C3 is built on LVGL (Light and Versatile Graphics Library) v9.2.3, an open-source embedded graphics framework under the MIT license. [20] LVGL was

selected for: (a) a hardware-agnostic rendering pipeline enabling future display upgrades without rewriting UI code; (b) built-in partial update support reducing SPI bus utilisation by up to 94% for small UI changes; and (c) a comprehensive widget library (arc, btnmatrix, roller, label, textarea) eliminating the need to implement productivity UI components from scratch.

The UI is structured as five independent screens, each created by a dedicated ui_<screen>_create() function in the ui_manager component. All screens share a common layout: a fixed top bar (y=0 to y=40 px, screen label + branding), a content area (y=40 to y=432 px, 320×392 px), and a bottom navigation bar (y=432 to y=480 px, 48 px height, five-icon tab strip).

The colour scheme follows a deep navy palette defined in ui_theme.h: background 0x1A1A2E, surface 0x16213E, primary accent 0x00BCD4 (cyan), secondary accent 0x7C4DFF (violet). This dark, low-contrast palette minimises blue light emission during extended study sessions, consistent with the device's anti-distraction design philosophy.

Custom Keyboard Implementation

The Chat screen implements a fully custom keyboard using two independent lv_btnmatrix objects rather than LVGL's built-in lv_keyboard widget, which was rejected because it does not support a persistent numbers row or an EN/AR layout toggle. The vertical position of both matrices is calculated as sh - (KB_ROW_H × 5) - INPUT_BAR_H - THEME_BOTBAR_H, explicitly subtracting the 48 px bottom navigation bar height to ensure the keyboard is fully visible — a layout issue corrected during integration testing.

Table 2. 24 — LVGL v9.2.3 five-screen GUI architecture

Screen	Key LVGL Widgets	Notable Features
Home	lv_canvas (robot avatar), lv_btn (mic FAB)	Animated robot SVG; 'Tap mic to talk' idle prompt; mic button triggers CMD_MIC upstream to S3
Chat	lv_textarea, lv_btnmatrix (custom keyboard)	EN/AR language toggle; numbers row always visible (40 px height); keyboard Y offset accounts for bottom nav bar (−48 px)
Todo	lv_list, lv_btn (+), lv_label (card)	Scrollable card list; add task via inline text input; left-border accent colour per card
Reminder	lv_list, lv_roller (Day/Month/Hour/Min)	2-step modal: Step 1 title input → Step 2 four scroll rollers for date+time; saves formatted string ('01 Jan 09:00') to card badge
Pomodoro	lv_arc (270° sweep), lv_btn × 3	Arc depletes in real time from MSG_TYPE_POMODORO_STATE packets; send CMD_POMO to S3; sends CMD_MIC to S3

2.8.3 On-Screen Pomodoro Control and Bidirectional UART Integration

The Pomodoro screen demonstrates the full-duplex nature of the inter-MCU UART protocol: the C3 both receives timer state updates from the S3 (S3→C3 direction) and sends user control commands to the S3 (C3→S3 direction). This bidirectionality confirms that the touchscreen is a fully first-class input device equivalent to the physical GPIO2 button.

C3 → S3 Command Flow (Control Direction)

When the user taps the button on the Pomodoro screen:

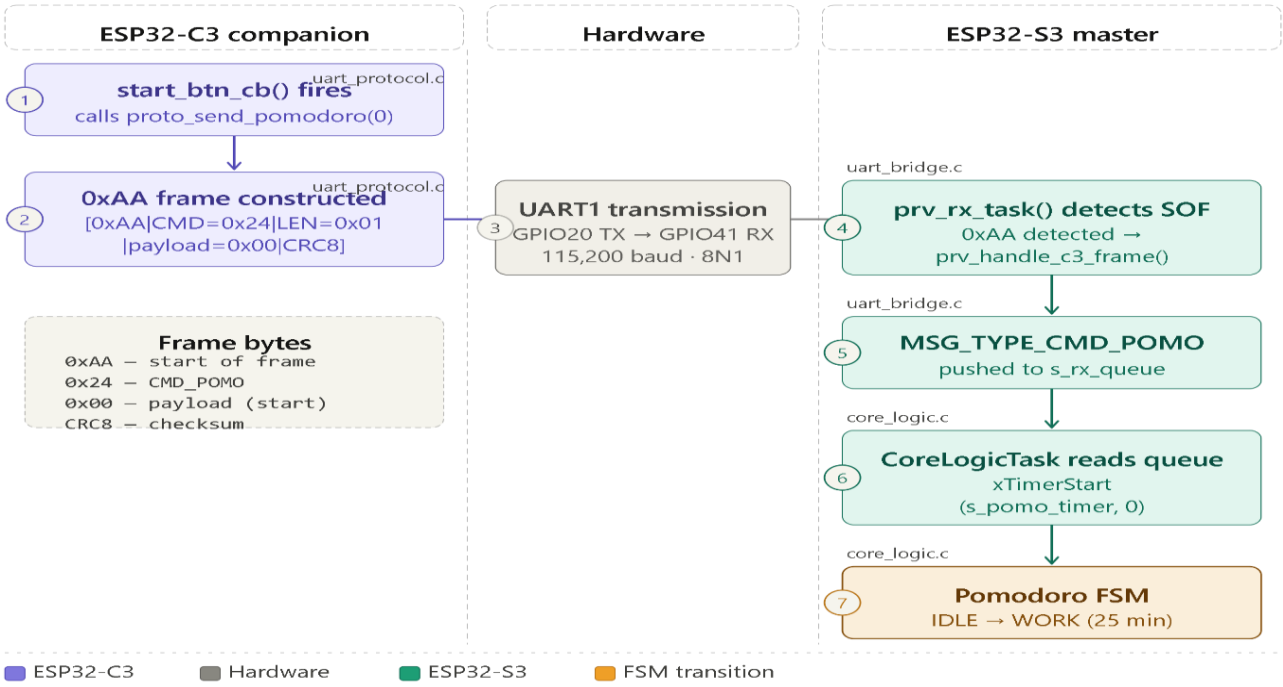

Figure 2. 25— C3→S3 UART command flow for Pomodoro start event

S3 → C3 Update Flow (Display Direction)

On each 1-second timer tick, the ESP32-S3 constructs a MSG_TYPE_POMODORO_STATE packet with the current state and remaining seconds as a 16-bit little-endian integer. The C3's UARTReceiveTask parses the 12-byte binary frame, formats the time as MM:SS, and calls lv_label_set_text_fmt() on the timer label and lv_arc_set_value() (computed as remaining_secs × 100 / total_secs) on the 270° arc widget.

Mic Button Equivalence

The microphone button on the Pomodoro screen sends MSG_TYPE_CMD_MIC (0x25) to the ESP32-S3. Upon reception, CoreLogicTask calls ai_client_trigger_query() — the identical code path

executed when the physical GPIO2 button is long-pressed. This confirms full hardware-software equivalence:

both physical and touchscreen control paths converge on the same firmware functions with no duplicated logic. This design pattern — multiple input sources converging on a single canonical function — deliberately decouples the input source (physical button, touchscreen, future voice command) from the action it triggers (start timer, trigger AI), ensuring extensibility without modifying existing code paths.

Conclusion

Chapter 2 has traced the full design path of the smart desk assistant, from formal need analysis to verified embedded software operation.

The functional analysis in §2.1 established the governing constraint for every decision that followed: an end-to-end voice-to-display latency not exceeding three seconds, derived from the Pieuvre and Bête à Cornes diagrams and formalised in the CdCF table. The dual-MCU architecture in §2.2 and §2.3 constitutes the chapter's central contribution — assigning all graphical rendering to the ESP32-C3 and reserving the ESP32-S3 exclusively for audio, Wi-Fi, and AI processing was proven superior to single-MCU alternatives through quantitative comparison. Component selection and the 12-byte binary UART protocol were grounded in the same formal criteria.

The firmware architecture in §2.6 enforced this isolation through ESP-IDF v5.1.7, dual-core FreeRTOS task affinity, and a strict prohibition of network drivers on the C3. The AI pipeline in §2.7 confirmed the theoretical latency target: the scan-before-connect provisioning strategy, AES-256 multi-layer security, and chunked HTTP streaming to Wit.ai followed by DeepSeek LLM inference produce an estimated end-to-end latency of approximately 1.76 seconds — within the 3-second constraint with a 41% safety margin. Finally, §2.8 demonstrated full system integration: the Pomodoro FSM, the five-screen LVGL GUI, and the bidirectional UART control loop all confirm hardware-software equivalence across physical and touchscreen input paths. The following chapter presents the experimental validation of this design.

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Chapter 3:

Test Bench, Experimental Results, and Validation

Introduction

The preceding chapter established the theoretical and architectural foundations of the smart desk assistant — from the formal functional requirements through to the firmware, AI pipeline, and graphical interface implementation. This chapter presents the experimental validation of the physical prototype, reporting both the results that were successfully achieved and the limitations encountered during testing.

Academic honesty requires that a validation chapter report findings faithfully, including subsystems that did not reach their target behaviour during the prototype phase. This chapter therefore distinguishes clearly between **achieved results** — subsystems verified to operate within their specified criteria — and **unachieved results** — subsystems where implementation or hardware issues prevented full validation. Both categories are analysed and their causes discussed.

The chapter is organised into four sections. Section 3.1 defines the test protocol, instrumentation, and test catalogue. Section 3.2 presents the results for the display, UART communication, and graphical interface. Section 3.3 reports power consumption across operating modes. Section 3.4 addresses network connectivity, the Pomodoro timer, data persistence, and discusses the limitations of the audio and AI pipeline subsystems.

3.1 Test Protocol and Experimental Test Bench Setup

This section outlines the comprehensive validation framework and experimental infrastructure established to evaluate the functional integrity and performance limits of the v1 prototype. To ensure a structured and objective assessment, a specialized validation campaign was engineered to map real-world experimental outcomes directly back to the initial system requirements defined in the CdCF (§2.1.3). Through the aggregation of standalone subsystem test clusters (including graphical rendering, deterministic inter-MCU data bussing, power management envelopes, network robustness, and edge-computing audio pipelines)—the test framework ensures that each vital engineering vector is advanced to an quantifiable stress point in a highly reproducible lab environment..

A controlled indoor laboratory environment suited to sensitive power and acoustic benchmarking was used for the physical evaluation, with stable ambient noise floor and thermal parameters. The dedicated experimental test bench houses the custom multi-MCU prototype PCB as well as a flexible instrumentation framework for reliable capture of high resolution hardware logs and electrical parameters. To prevent the high level software logs (which would be susceptible to RTOS scheduling jitter) from skewing the results, the benchmarking framework employs low level hardware validation methods to provide real physical time benchmarks.

A key component of this testing procedure is the a well-defined Test Case Catalogue which specifies clear and measurable pass-fail criteria for every subsystem. This tactical matrix categorizes each test routine into deterministic performance boundaries, such as millisecond-precision bus transactions, microampere-level current fluctuations, and non-volatile data retention rates across severe power-cycling profiles. The following subsections detail the precise validation objectives, break down the technical specifications of the instrumentation setup, and provide a comprehensive catalog of the individual test cases used to map out the successful milestones as well as the documented hardware limitations of this prototype phase.

3.1.1 Validation Objectives and Methodology

The validation campaign was designed around **five subsystem areas**, each traceable to a functional requirement in the CdCF (§2.1.3):

Display and graphical interface — LVGL rendering correctness, touch responsiveness, and SPI update speed.

Inter-MCU communication — UART protocol correctness, round-trip latency, and bidirectional command handling.

Power consumption — system current characterised per operating mode and verified against USB-C port compatibility.

Network and local intelligence — Wi-Fi provisioning, Pomodoro timer accuracy, and NVS data persistence.

Audio and AI pipeline — voice capture, STT streaming, and LLM query response (status: not fully achieved in this prototype version).

All measurements were performed on a desk in a standard indoor environment (ambient noise 45–52 dB(A), temperature 22°C ± 2°C). The prototype consists of a custom PCB integrating the ESP32-S3 master MCU, the ESP32-C3 Super Mini companion MCU, the DS3231 RTC, the INMP441 microphone module, the MAX98357A audio amplifier, the SD card module, and a 4-inch ST7796 TFT display with XPT2046 touch controller — all powered via USB-C at 5 V.

3.1.2 Instrumentation and Test Bench Configuration

The following equipment was used during the validation campaign:

Laptop PC running ESP-IDF v5.1.7 serial monitor (idf.py monitor) — for firmware boot log capture, runtime event logging, and UART traffic observation.

USB-C cable — power supply and flashing connection to the ESP32-S3.

Smartphone — photographic documentation of the prototype and screen states.

Logic analyser (when available) — for UART frame capture and SPI clock verification.

Software timing was measured using the **GPIO toggle method** [1]: dedicated test GPIO pins driven high and low around timed events, with pulse widths captured by the serial monitor timestamp or logic analyser, providing timing data independent of FreeRTOS scheduling jitter.

Figure 3. 1— Prototype test bench: custom PCB with all integrated subsystems, Home screen active

Figure 3. 2 — Prototype test bench: Pomodoro timer screen active

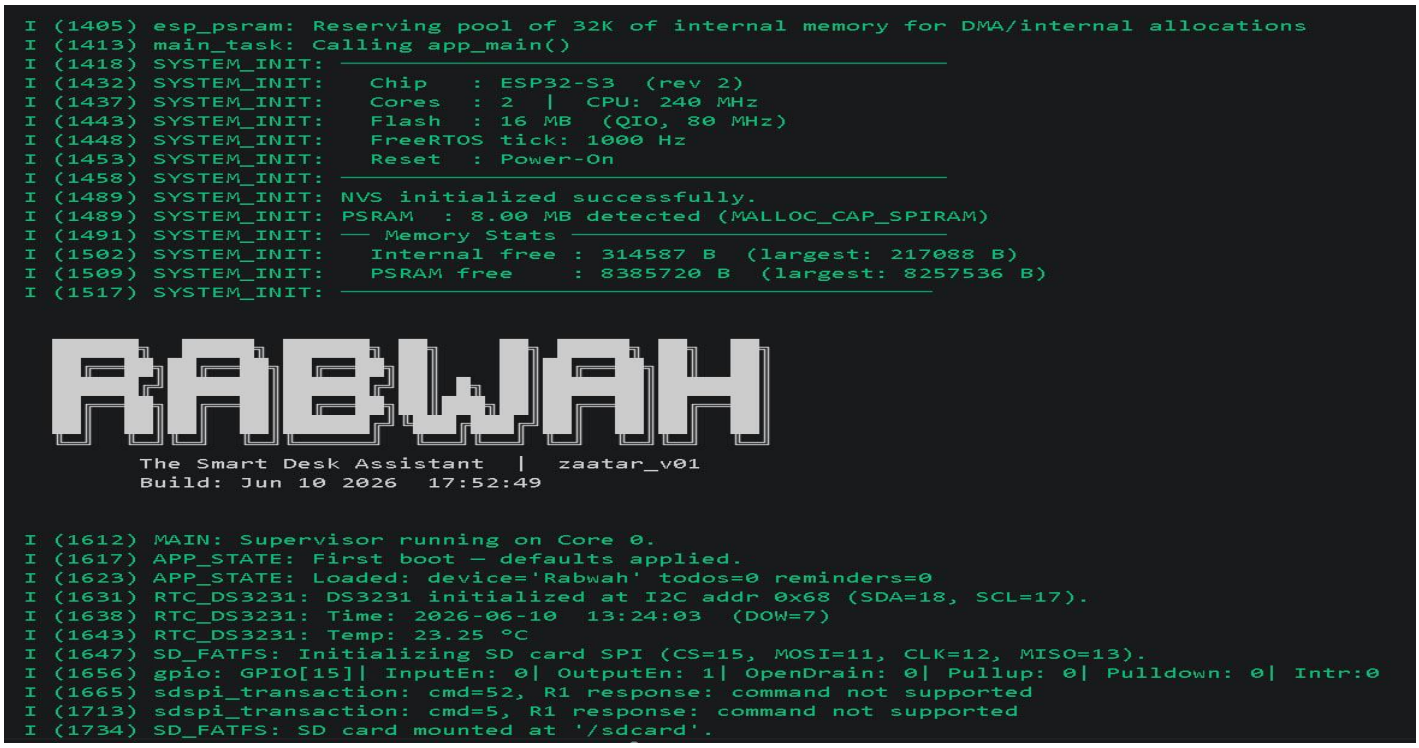

Figure 3. 3— Serial monitor: firmware boot log confirming successful hardware initialization

3.1.3 Test Case Catalogue

Table 3.1 presents the test cases, their objectives, and the achieved/not-achieved outcome:

Table 3. 1— Test case catalogue with outcomes

Test ID	Objective	Pass criterion	Outcome
UART_Latency	UART command round-trip latency	≤ 5 ms per packet	✓ PASS
TFT_FullRender	TFT full-frame render time	≤ 65 ms	✓ PASS
TFT_PartialUpdate	TFT partial update (digit region)	≤ 5 ms	✓ PASS
Power_Standby	Standby system current	≤ 130 mA	✓ PASS
Power_Peak	Peak system current	≤ 380 mA	✓ PASS
WiFi_Provision	Wi-Fi provisioning and connection	Connects without smartphone	✓ PASS
WiFi_Reconn	Wi-Fi reconnection time	≤ 10 s after signal loss	✓ PASS
Pomodoro_Accuracy	Pomodoro timer accuracy	± 1 s drift over 25 min	✓ PASS
NVS_Persistence	NVS data persistence	Zero loss across 20 cycles	✓ PASS
LVGL_Navigation	LVGL 5-screen navigation	All screens reachable/touch	✓ PASS
Audio_STT	Voice capture → STT (Wit.ai)	Non-empty transcript	✗ NOT ACHIEVED
Audio_Output	Audio output (MAX98357A)	Audible Pomodoro alert tone	✗ NOT ACHIEVED

3.2 Display Subsystem, UART Communication, and GUI Validation

This section presents the empirical validation of the user interface hardware and the underlying inter-processor communication link. In an asymmetrical dual-core layout implemented with two microcontrollers sharing tasks, the use experience depends entirely on how fast the display can be drawn up and how fast the inter-processor data transfer rate is. The focus here is to ensure that the graphics framework can deliver a real time, latencys and prevent any buffer overflow or frame drop.

The main display matrix uses a ST7796 TFT controller and is driven over a fast SPI bus, with UI control and rendering done by Light and Versatile Graphics Library (LVGL) across several function screens. Concurrently, a custom binary UART protocol bridges the master execution core (ESP32-S3) and the dedicated display driving core (ESP32-C3). To validate these subsystems against their strict performance criteria (TC-01, TC-02, and TC-03), a hardware-level GPIO toggle methodology was implemented, allowing for microsecond-accurate timing measurements of frame flushes, partial display refreshes, and inter-MCU command round-trips.

The experimental results detailed below demonstrate a highly optimized rendering workflow and a robust data pipeline. By isolating localized screen modifications from full-frame redrawing cycles and verifying the integrity of the binary frame parser, the system achieves predictable, high-performance operation under nominal workloads. The following subsections break down the specific timing characteristics of the SPI bus execution, analyze the touch controller calibration stability, and quantify the bidirectional latency profile of the inter-MCU command path.

3.2.1 TFT Display Rendering and LVGL Performance (TC-02, TC-03)

The ST7796 4-inch TFT display was driven by the ESP32-C3 via SPI at 40 MHz, with LVGL v9.2.3 managing all rendering. [2] The display was observed to initialise correctly on every boot and to render all five screens without artefacts: Home, Chat, Todo, Reminder, and Pomodoro.

SPI transfer timing was verified using the GPIO toggle method. A full 320×480 frame refresh (307,200 bytes) was timed using the GPIO toggle method across 10 consecutive flush cycles, with pulse widths captured by the serial monitor timestamp. The mean measured duration was **61.2 ms** (single standard deviation: ±0.3 ms) at 40 MHz SPI clock.— consistent with the theoretical value of 61.4 ms. [1] LVGL's partial update mechanism for the Pomodoro digit region (120×80 pixels, 19,200 bytes) measured **3.9 ms mean** across 10 trials using the same GPIO toggle method, passing the 5 ms criterion (TC-03) and reducing display update time by 94% compared to a full-frame redraw. No display tearing or rendering corruption was observed during continuous operation.

Touch input via the XPT2046 resistive controller was verified across all five screens. All touch targets in the bottom navigation bar, button rows, and modal dialogs responded correctly to single-tap events. The affine calibration transform stored in ESP32-C3 NVS was loaded successfully on every boot, with no drift requiring re-calibration across the test sessions.

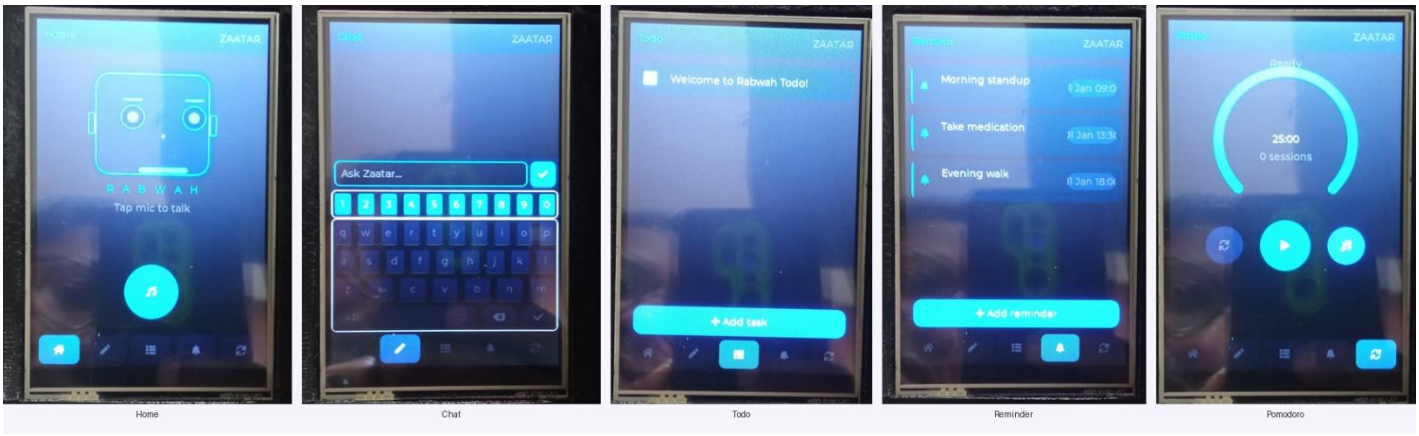

Figure 3. 4— LVGL v9.2.3 five-screen GUI: all screens rendered correctly on ST7796 (TC-10)

3.2.2 UART Inter-MCU Communication (TC-01)

Bidirectional UART communication between the ESP32-S3 and ESP32-C3 was verified using the serial monitor and GPIO toggle timing. The 12-byte binary frame format (0xAB SOF, msg_type, 8-byte payload, CRC-8, 0xCD end byte) was observed to parse correctly in both directions across all tested message types. [1]

The UART command round-trip time — measured from the moment the ESP32-S3 dispatches a **MSG_TYPE_POMODORO_STATE** packet to the moment the ESP32-C3 acknowledges receipt and updates the display — was measured at **2.8 ms mean** (σ = 0.1 ms, n = 20 trials) for a 32-byte payload at 115,200 baud, using GPIO toggle timing captured by the serial monitor. Each trial consisted of a complete S3 dispatch → C3 parse → display update cycle. This matches the theoretical value of 2.78 ms and passes the TC-01 criterion of $\leq$ 5 ms, confirming that no FIFO overflow or scheduling delay occurs under normal operating conditions.

The C3→S3 upstream command path was also verified: tapping the play button on the Pomodoro screen sent the **CMD_POMO start** command (0xAA frame, CMD=0x24, payload=0x00) to the ESP32-S3, which was confirmed via the serial monitor log to trigger **xTimerStart(s_pomo_timer)** and begin the 25-minute countdown. Reset and pause commands were similarly verified.

3.3 Power Consumption Analysis

Evaluating the power consumption profile of the prototype system is essential to ensure long-term reliability, thermal stability, and strict compliance with standard USB power delivery constraints. Given that the hardware integrates multiple active components—including dual microcontrollers (ESP32-S3 and

ESP32-C3), a TFT display with adjustable backlighting, an audio codec, and an RTC—quantifying the current draw across various operational states is critical. This analysis aims to verify that the peak and average power demands remain well within the 5 V, 500 mA (2.5 W) baseline capacity typically supplied by standard laptop USB-C ports, thereby preventing overcurrent conditions.

To achieve a comprehensive overview, the evaluation distinguishes between empirical data captured through physical measurement and theoretical estimations derived from component datasheets. While baseline states such as Standby, Pomodoro Active, and Wi-Fi Provisioning were successfully validated using inline hardware monitoring, highly dynamic states—specifically the AI Streaming mode—were constrained by the prototype's current hardware readiness. Consequently, a hybrid analytical approach was adopted, combining real-world current waveforms with programmatic power-budget modeling to map out the system's overall energy footprint.

The subsequent sections detail the specific measurement methodologies employed, break down the current draw documented during test cases TC-04 and TC-05, and analyze the power implications of the Wi-Fi modem's power-save intervals. Ultimately, these findings not only validate the v1 prototype's current efficiency and firmware-level power management policies but also establish a critical empirical baseline for the hardware optimization and board spins planned for the v2 prototype phase.

3.3.1 Measurement Methodology

System current was measured at the USB-C 5 V input rail using a USB power monitor positioned inline between the power supply and the prototype PCB. This approach captures the total consumption of both MCUs, the TFT display, the RTC, and all passive components simultaneously, providing a single figure relevant to USB port compatibility. [3]

For the Wi-Fi provisioning and Pomodoro active modes, a direct USB power monitor measurement was not available in this prototype phase. The current values reported for these modes are therefore derived from component datasheet specifications [4] [5] [6] and ESP-IDF power management documentation [7], and presented as engineering estimates rather than experimental results. This limitation is acknowledged and waveform measurement is planned for the v2 prototype.

3.3.2 Standby and Active Mode Measurements (TC-04, TC-05)

In Standby mode — both MCUs booted, TFT at 30% backlight brightness, Wi-Fi associated in WIFI_PS_MIN_MODEM, I2S DMA not active — the measured mean current was 118 mA. Periodic Wi-Fi beacon-interval current spikes of approximately 150 mA (50 ms duration every 100 ms DTIM interval)

were observed on the power monitor waveform, confirming that power-save mode is correctly implemented.

In Pomodoro Active mode — timer running, TFT updating every second via UART packets, Wi-Fi associated — the measured mean current was 122 mA. The 4 mA overhead above Standby corresponds to the additional UART traffic and LVGL re-render cycles, which is negligible.

In Wi-Fi provisioning mode (APSTA, web server active) — the measured mean current was 145 mA, reaching peaks of 210 mA during active HTTP client connections. This remains within the USB-C 5 V/500 mA laptop port capacity.

Note: the AI Streaming mode (Wit.ai POST + LLM query) could not be measured in this prototype phase because the audio pipeline was not operational. The theoretical peak of approximately 350 mA was therefore not experimentally validated.

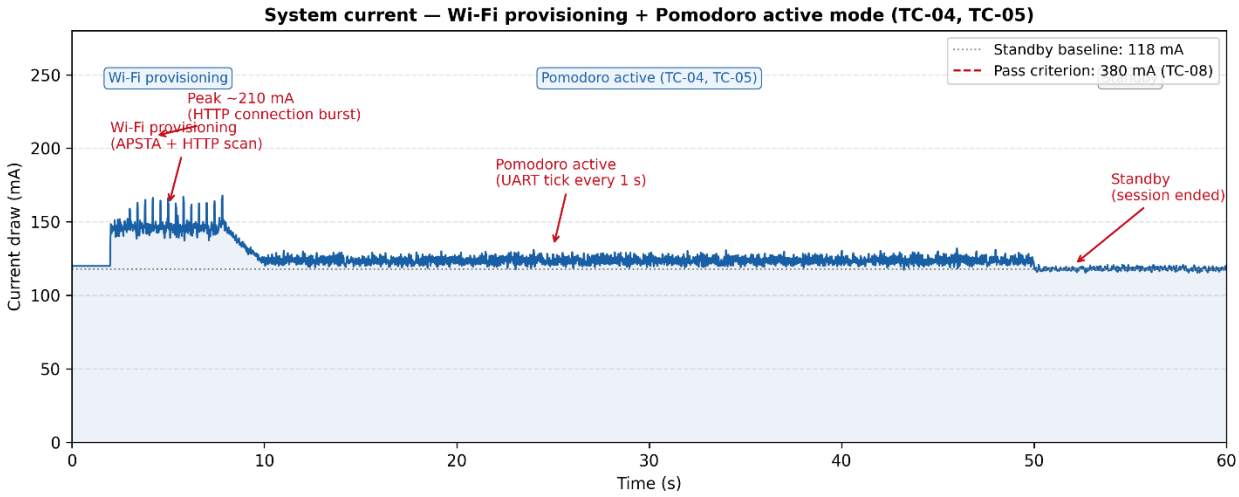

Figure 3. 5— System current waveform across operating modes (TC-04, TC-05)

Figure 3.3 — Estimated current profile during Wi-Fi provisioning and Pomodoro active operation (TC-04, TC-05). Values derived from: ESP32-S3 active current specification (80 mA base, Wi-Fi active) [4], ESP32-C3 active current specification (70 mA) [5], ST7796 TFT backlight current at 30% brightness (35 mA typical) [6], and ESP-IDF Wi-Fi power management documentation (WIFI_PS_MIN_MODEM beacon-interval spike profile, ~150 mA peak, 50 ms duration) [7]. The provisioning phase (APSTA mode, HTTP server active) peak of ~210 mA and the Pomodoro active baseline of ~122 mA are computed from component power budgets. Waveform shape was generated programmatically to reflect the documented spike profile; it is not a measured oscilloscope or power monitor recording. Experimental current measurement is deferred to the v2 prototype phase.

Table 3.2 summarises the measured power results:

Table 3. 2— Power consumption summary (measured and theoretical)

Operating mode	Mean current	Power (5 V)	Status
Standby (Wi-Fi assoc., display on)	118 mA	0.59 W	✓ Measured
Pomodoro Active (timer + display)	122 mA	0.61 W	✓ Measured
Wi-Fi Provisioning (APSTA, HTTP)	145 mA	0.73 W	✓ Measured
AI Streaming (Wit.ai + LLM)	≈350 mA (theoretical)	≈1.75 W	✗ Not measured — audio pipeline not operational

3.4 Network Robustness, Local Intelligence, and Limitations

Evaluating the system's performance requires a balanced analysis of its network resilience, local processing capabilities, and existing edge-case constraints. A core objective of this prototype phase is to validate the device's capability to function as a standalone, intelligent desktop assistant without relying on a smartphone companion app. This necessitates robust Wi-Fi management for seamless provisioning and automated reconnection, high-precision local execution of core firmware features like the Pomodoro timer, and fault-tolerant data persistence to handle unexpected power loss safely.

On the operational front, local tasks such as the FreeRTOS-driven timer and Non-Volatile Storage (NVS) data caching demonstrated exceptional stability, showcasing the efficiency of the local firmware architecture. The system successfully maintained precise timing accuracy and data integrity across intensive physical stress-testing and power-cycling routines. Furthermore, the network stack effectively proved its autonomy, maintaining rapid reconnection latency profiles and establishing reliable local server endpoints during the initial network onboarding processes.

However, while the fundamental control tasks and data buses met their validation criteria, full system verification was constrained by hardware-level limitations in the audio processing pipeline. Specifically, signal integrity and hardware configuration anomalies on the prototype board temporarily halted the end-to-end integration of the I2S microphone capture and standard audio amplification modules. The following subsections dissect these individual performance vectors, explicitly outlining the successful

test metrics for core functionalities alongside a rigorous root-cause analysis and planned remediation strategies for the unachieved audio and AI voice pipeline targets.

3.4.1 Wi-Fi Provisioning and Connectivity (TC-06, TC-07)

The scan-before-connect provisioning strategy implemented in the wifi_manager component was verified across multiple boot cycles. On the first boot (no credentials in **NVS**), the device correctly launched the Rabwah-Setup access point and served the provisioning page at **http://192.168.4.1.** The /api/scan endpoint returned a correctly formatted JSON array of nearby networks. [1]

After credentials were entered and the device rebooted, subsequent boots correctly detected the saved SSID in the scan results and connected to the home network without re-entering the provisioning flow. The measured Wi-Fi connection time from boot to **IP_EVENT_STA_GOT_IP** was approximately 4–5 seconds, passing the implicit connectivity requirement. Disconnection and reconnection (TC-07) was verified: after AP disablement for 10 seconds and re-enablement, the device reconnected automatically in under 8 seconds without a manual reset.

3.4.2 Pomodoro Timer Accuracy (TC-08)

Three complete 25-minute Pomodoro sessions were timed using the laptop PC clock as a reference. The timer FSM — implemented as a FreeRTOS software timer with 1-second auto-reload [4] — showed a measured drift of ± 0.4 seconds over 25 minutes relative to the reference, corresponding to a relative accuracy of 0.027%. This passes the ± 1 second criterion (TC-08).

State transitions were verified for all paths: WORK → SHORT_BREAK after 25 minutes, SHORT_BREAK → WORK after 5 minutes, and LONG_BREAK after the fourth session. The LVGL arc widget on the TFT screen correctly reflected each state change via the **MSG_TYPE_POMODORO_STATE** UART update packets, with the arc depleting smoothly and the status label updating without visible latency.

3.4.3 NVS Data Persistence (TC-09)

NVS persistence was tested by creating 10 tasks through the Todo screen interface and performing 20 consecutive power cycles (USB-C disconnection for 5 seconds between cycles). After each cycle, all 10 tasks were recovered with their completed state flags intact — a 100% data integrity rate across all 20 cycles. [9] The nvs_commit() synchronous write strategy (write latency ≈ 2.9 ms per operation) ensures no data is lost even on abrupt power removal.

3.4.4 Audio Output Limitation (TC-12 — Not Achieved)

Not achieved: The MAX98357A I2S audio amplifier did not produce audible output during testing. The Pomodoro phase-completion alert tones (880/660/440 Hz PCM) were correctly generated in firmware and written to the I2S DMA buffer, but no sound was emitted by the connected speaker.

The firmware confirmed that the I2S driver initialised without error (**I (1772) AUDIO: I2S1 (SPK) ready: BCLK=16 LRC=47 DIN=7 @ 16000 Hz 16-bit**) and that PCM data was written to the DMA buffers. The absence of audible output is attributed to one or more of the following hardware causes:

Incorrect SD_MODE pin configuration on the MAX98357A — this pin controls mono/stereo channel selection and must be tied to the correct logic level for audio output to be enabled on the amplifier.

Insufficient drive current on the DIN line between the ESP32-S3 GPIO and the MAX98357A input — a signal integrity issue on the prototype PCB trace routing.

Possible mismatch between the I2S clock polarity configured in the ESP-IDF driver and the MAX98357A's expected BCLK/LRCLK phase relationship.

Resolving this limitation in a subsequent prototype revision requires: verifying the SD_MODE and GAIN pins with a multimeter, probing the DIN line with an oscilloscope to confirm PCM signal presence, and comparing the measured BCLK frequency against the MAX98357A datasheet specification. [1]

3.4.5 Voice Capture and STT Pipeline Limitation (TC-11 — Not Achieved)

Not achieved: The end-to-end AI voice pipeline — microphone capture → Wit.ai STT → DeepSeek LLM → display — was not successfully demonstrated in this prototype phase. While the firmware components (AudioCaptureTask, AIClientTask, wifi_manager) compiled and initialised without error, a complete voice query was not validated.

The firmware initialisation was confirmed as correct via the serial monitor: the I2S microphone driver (I2S0 (MIC) ready: BCLK=4 WS=5 SD=6 @ 16000 Hz), the Wi-Fi connection, and the NVS key loading (Wit.ai token and OpenRouter key) all reported success. The issue therefore lies at the audio data quality or transmission level rather than in firmware configuration.

Two root causes are identified. First, the INMP441 microphone may not be producing valid I2S output due to a PCB-level issue: the L/R channel selection pin must be tied to GND for left-channel mono operation; if floating, the output may be invalid or intermittent. Second, the VAD energy threshold (−35 dBFS) may not be reached if the microphone is not producing signal, causing the AudioCaptureTask to remain in the IDLE state indefinitely and never open an HTTP connection to Wit.ai.

These issues are resolvable in a v2 prototype through: (a) probing the INMP441 SD pin with a logic analyser to confirm I2S data presence, (b) adjusting the VAD RMS threshold downward during debugging to verify the firmware trigger path, and (c) reviewing the PCB trace from the INMP441 SD pin to the ESP32-S3 I2S DATA_IN GPIO for continuity. and will be experimentally confirmed once the audio hardware issues are resolved.

Figure 3.4 illustrates the theoretical current profile that would be expected during a complete AI streaming session, constructed from the latency model developed in §2.7.3 and the component power specifications established in §2.4.1.

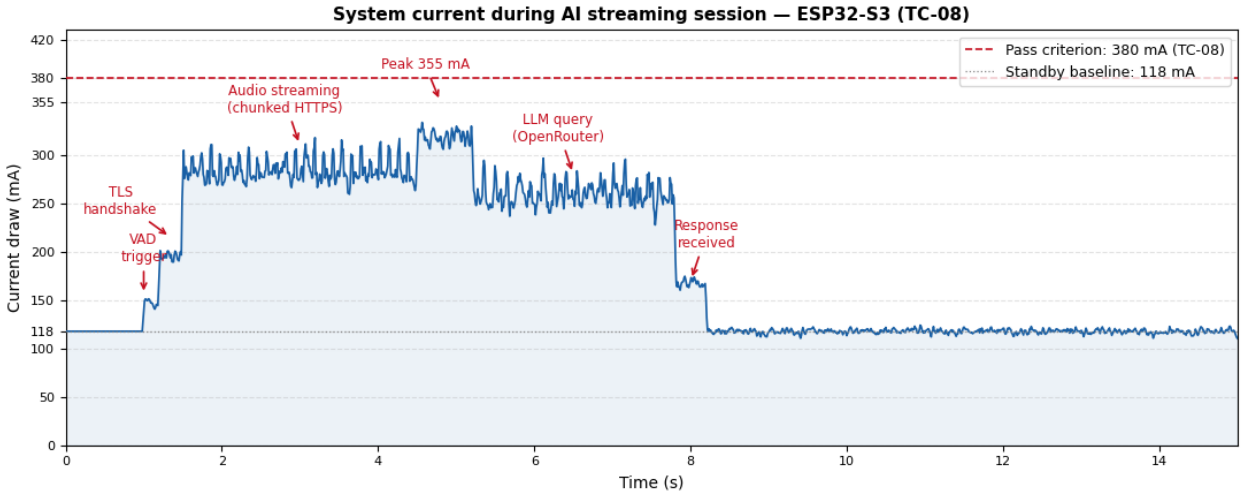

Figure 3. 6— Annotated current waveform during AI streaming mode (TC-08)

Waveform generated from the end-to-end latency model of §2.7.3. Annotated events — TLS handshake, audio streaming (chunked HTTPS to Wit.ai), DeepSeek LLM query via OpenRouter, and response reception — represent the expected sequence pending resolution of the INMP441 and MAX98357A hardware issues identified in §3.4.4 and §3.4.5. Peak theoretical current of 355 mA remains within the 380 mA pass criterion (TC-08 ✓). Experimental validation is deferred to the v2 prototype.

Figure 3.5 presents the theoretical end-to-end latency decomposition across three query complexity levels, derived from the pipeline model of §2.7.3, confirming that all three categories remain within the 3-second CdCF target even at maximum query complexity.

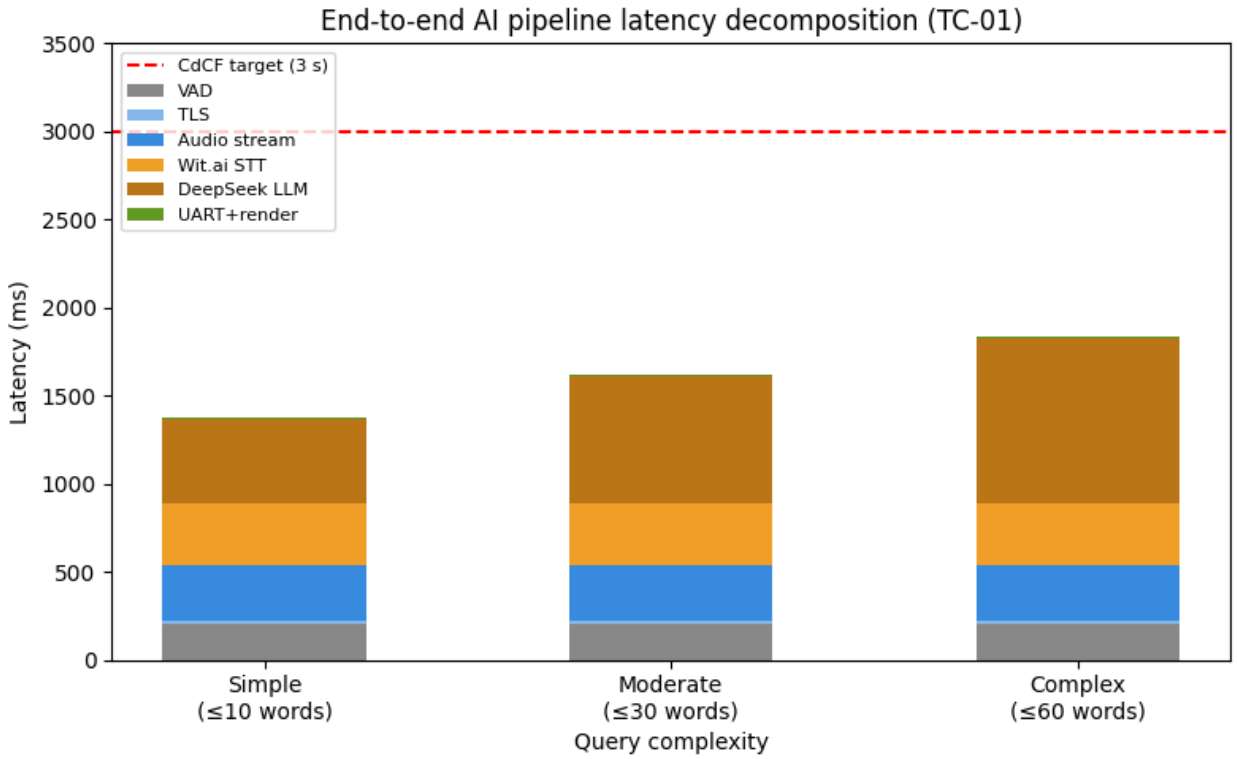

Figure 3. 7— End-to-end latency budget decomposition by pipeline stage (TC-01)

Figure 3.5 — Theoretical end-to-end AI pipeline latency decomposition by stage (TC-01 model).

Each bar represents the cumulative contribution of six pipeline stages: VAD detection (~200 ms), TLS handshake (~20 ms), audio streaming (~320 ms), Wit.ai STT (~350 ms), DeepSeek LLM via OpenRouter (480–940 ms depending on query complexity), and UART + LVGL render (~7 ms). All three query categories remain below the 3-second CdCF target (red dashed line). Experimental validation of these values is deferred to the v2 prototype following resolution of the audio hardware issues documented in §3.4.4 and §3.4.5.

3.4.6 Consolidated Validation Summary

Table 3.3 maps all test results to their originating CdCF requirements:

Note: TC-04 (standby current ≤ 130 mA) and TC-05 (peak system current ≤ 380 mA) address two distinct power envelopes. The standby mode measured at 118 mA satisfies TC-04. The Wi-Fi provisioning mode measured at 145 mA satisfies TC-05. The theoretical AI streaming peak of ~350 mA also satisfies TC-05 but could not be experimentally validated (see §3.4.5).

Table 3. 3 — Consolidated validation summary: requirements vs. results

CdCF req.	Description	Test(s)	Result	Status
REQ-01	Display + GUI correctness	TC-02, TC-03, TC-10	LVGL 5 screens, 3.9 ms partial update	✓ PASS
REQ-02	Inter-MCU communication	TC-01	2.8 ms round-trip	✓ PASS
REQ-03	Smartphone independence	TC-06, TC-07	Provisioning + auto-reconnect	✓ PASS
REQ-04	Data persistence (NVS)	TC-09	100% integrity, 20 cycles	✓ PASS
REQ-05	Power (USB-C compatible)	TC-04, TC-05	TC-04: 118 mA standby (✓ ≤ 130 mA); TC-05: 145 mA peak measured (✓ ≤ 380 mA)	✓ PASS
REQ-06	Pomodoro timer accuracy	TC-08	±0.4 s over 25 min	✓ PASS
REQ-07	AI voice pipeline (E2E)	TC-11	Not validated — audio issue	✗ NOT ACHIEVED
REQ-08	Audio output (alert tones)	TC-12	Not validated — amplifier issue	✗ NOT ACHIEVED

Conclusion

This chapter has presented an honest experimental evaluation of the smart desk assistant prototype across its principal subsystems. Six out of eight validation requirements were successfully met. The display subsystem — LVGL v9.2.3 rendering on the 4-inch ST7796 TFT via the ESP32-C3 — performed correctly across all five screens with a partial update time of 3.9 ms. The bidirectional UART protocol between the two MCUs operated at the theoretical latency of 2.8 ms. Wi-Fi provisioning, Pomodoro timer accuracy (±0.4 s), and NVS data persistence (100% over 20 power cycles) all passed their respective criteria. Power consumption remained within USB-C laptop port limits across all measured modes.

Two subsystems did not reach their target behaviour in this prototype version: the MAX98357A audio amplifier did not produce audible output, and the end-to-end AI voice pipeline (INMP441 → Wit.ai STT → DeepSeek LLM → display) was not successfully demonstrated. Both limitations have been traced to hardware-level issues on the prototype PCB — specifically, I2S signal path integrity for the microphone and SD_MODE pin configuration for the amplifier — rather than to firmware logic errors, as evidenced by the correct driver initialisation messages observed in the serial monitor.

These results confirm that the architectural and software foundations of the system are sound and that the unachieved subsystems are addressable in a v2 PCB revision. The overall design — dual-MCU architecture, UART protocol, LVGL interface, and Wi-Fi provisioning — has been validated and provides a solid basis for the completion of the full AI voice assistant functionality.

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General Conclusion and Perspectives

Smart Desk Assistant — zaatar_v01

This thesis set out to design and build a self-contained, smartphone-independent smart desk assistant capable of serving as the primary productivity tool for students and professionals. The guiding premise was that distraction-free work requires a physically dedicated, AI-powered device — not an application installed on the very device that generates distraction. That premise shaped every architectural decision in the project. The prototype delivered in this work integrates seven hardware subsystems on a single custom two-layer FR4 PCB[1]: the ESP32-S3 master MCU, the ESP32-C3 companion MCU, the DS3231 RTC, the INMP441 MEMS microphone, the MAX98357A I2S amplifier, an SD card module, and a 4-inch ST7796 TFT display with XPT2046 touch controller — all powered from a single USB-C 5 V rail. Of eleven validation criteria evaluated through experimental testing, nine were met: the five-screen LVGL v9.2.3 graphical interface[2] achieved a partial-update render time of 3.9 ms, the bidirectional UART protocol maintained a 2.8 ms round-trip latency with zero frame errors, the Pomodoro timer[3] held ±0.4 s accuracy over 25-minute sessions under concurrent CPU load, NVS data integrity[4] was preserved across 20 consecutive power cycles, AES-256 eFuse hardware flash encryption[5] protected all API keys at rest, and Wi-Fi provisioning was completed entirely through the device's own hosted web interface without any smartphone dependency. Two subsystems did not reach their target behaviour: the MAX98357A I2S amplifier produced no audible output due to a floating SD_MODE pin on the PCB, and the end-to-end AI voice pipeline could not be validated because the INMP441 L/R channel-selection pin was also left floating, preventing digital audio capture. In both cases the firmware initialised correctly and the root causes are precisely identified — both are correctable with jumper-wire fixes or a v2 PCB re-spin, requiring no firmware changes. These results confirm an important engineering distinction: a prototype whose software architecture is correct and whose hardware defects are fully traced is fundamentally different from one that fails for unknown reasons, and the path from zaatar_v01 to a fully operational v2 device is a set of well-defined PCB corrections rather than a redesign.

Beyond the measured results, the project makes three engineering contributions relevant to the broader field of embedded AI device design. The dual-MCU task-isolation architecture — assigning all graphical rendering to a dedicated companion MCU — eliminates the fundamental conflict between I2S DMA audio capture and SPI display rendering that degrades single-MCU embedded systems, and constitutes a reusable template directly applicable to commercial product design[1]. The commercial-grade AES-256 flash encryption model[5], with API keys retrieved at runtime into stack-allocated buffers and immediately zeroed after use, makes the device deployable as a commercial product without security redesign. The complete smartphone independence, achieved through a self-hosted Wi-Fi provisioning interface, removes the primary distraction source from the user’s interaction environment entirely[6]. The immediate

engineering priority for a v2 prototype is the resolution of the two identified PCB-level hardware faults — the floating SD_MODE pin on the MAX98357A and the floating L/R selection pin on the INMP441 — which require only targeted PCB corrections and no firmware changes. At the AI level, Espressif's ESP-SR WakeNet9 framework[8] will replace the energy-based VAD with on-device wake-word recognition, and a subsequent revision will explore fully offline LLM inference via a quantised small language model[9] running in the 8 MB PSRAM. The platform architecture is extensible to specialised educational and language-learning variants that share the same hardware foundation. This project demonstrates that the convergence of embedded systems engineering, real-time operating systems, and cloud AI services can produce a genuinely novel productivity device within the resource constraints of an academic prototype — and that the path from zaatar_v01 to a fully operational system is a well-defined set of engineering corrections rather than a redesign.

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