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ZETA(ζ): INTERACTIVE VIDEO MODEL

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ABSTRACT
In the modern digital landscape, organizations generate massive volumes of video data that frequently result in "Dark Data"—unsearchable monoliths that require intensive manual effort to navigate. Traditional Retrieval-Augmented Generation (RAG) systems are often limited by a "blind and deaf" approach, relying solely on text transcripts while ignoring vital visual context such as diagrams, slides, and speaker identity. This paper introduces Zeta (ζ), a Multimodal RAG platform designed to transform passive video archives into interactive, searchable knowledge bases. Zeta utilizes a sophisticated dual-stream pipeline: an Auditory Stream for precise word-level transcription and speaker diarization, and a Visual Stream powered by Qwen2.5-VL for the classification of visual elements like whiteboards and code. This integration enables clickable timestamps that link queries directly to relevant video frames. To ensure architectural flexibility, Zeta features a Dual-Mode Master Switch, allowing users to toggle between Local Mode (using Llama 3.1) and API Mode (leveraging GPT-4o). Additionally, the system introduces agentic workflows, including a "Bullshit Detector" for fact-checking and "Whiteboard-to-Code" conversion. By optimizing for consumer-grade hardware through efficient VRAM management, Zeta effectively eliminates the "Dark Data" bottleneck.

Keywords:
Artificial Intelligence, Multimodal RAG, Dark Data, Video Analytics, Vision-Language Models, Speaker Diarization, Agentic Workflows.

INTRODUCTION

The contemporary digital landscape is characterized by an unprecedented, exponential surge in video content generation, a phenomenon largely driven by the widespread adoption of remote collaboration tools, advanced digital learning platforms, and high-speed global connectivity. In modern enterprise, corporate, and educational ecosystems, organizations are no longer just producing text documents; they are producing terabytes of rich video data on a daily basis. This massive output captures highly critical and nuanced information embedded within recorded Zoom meetings, Microsoft Teams discussions, university lecture captures, and complex technical training sessions. However, as this data scales, a significant technological paradox has emerged: while the quantity of video data is expanding, its actual searchability and operational utility remain severely limited.

Most organizational video archives currently exist in a stagnant state known within the industry as "Dark Data". Once a live collaborative session concludes and the recording is saved, the resulting media file typically becomes an unstructured, unsearchable, and largely unwatchable monolith of linear media. Retrieving a specific, granular data point from these monoliths—such as a critical technical decision or a specific diagram drawn during a brainstorming session—requires a user to manually "scrub" through hours of footage. This manual process relies heavily on vague visual cues and human guesswork to find the relevant timestamp, creating a massive bottleneck for daily operational intelligence.

While the advent of Retrieval-Augmented Generation (RAG) has successfully revolutionized how users interact with static text documents, traditional RAG systems are fundamentally ill-equipped to handle the multi-sensory nature of video. These standard retrieval systems are effectively "blind and deaf" to the multidimensional nature of rich media, as their underlying architectures rely almost exclusively on flat, text-only transcripts. Because of this limitation, standard RAG systems lack the ability to analyze visual context—they cannot "see" whiteboard

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sketches or interpret slide presentations—and fail to attribute spoken statements to individual participants, leading to a massive "Insight Gap".

Zeta (ζ) is an advanced, pioneering Multimodal Retrieval-Augmented Generation platform engineered to bridge this exact "Insight Gap" and systematically eliminate the "Dark Data" problem. Unlike conventional unimodal systems, Zeta treats video media as a unified, structurally searchable, and highly interactive knowledge base. To achieve this, the platform utilizes a highly sophisticated dual-stream machine learning pipeline capable of processing high-fidelity audio streams and rich visual frames simultaneously. By integrating word-level timestamping and advanced speaker diarization, the Zeta system maps every single spoken word to a specific individual and a precise millisecond within the video's timeline. Simultaneously, the system leverages state-of-the-art Vision-Language Models (VLMs) to scrutinize visual frames and generate dense contextual descriptions of on-screen events. Through this architecture, Zeta enables an interactive conversational experience where users can directly "chat" with their videos to retrieve source-verifiable insights.

PROBLEM STATEMENT

The current technological lifecycle of recorded media is fundamentally flawed; once a recording concludes, the file typically enters a state of "Dark Data"—unstructured, unsearchable monoliths that consume storage without providing analytical insight. While traditional Retrieval-Augmented Generation (RAG) revolutionized text retrieval, it faces a structural failure when applied to video, technically defined as the "Insight Gap". This problem is broken down into three critical technical deficiencies:

- **Multimodal Blindness (The Visual Gap):** Standard RAG systems rely exclusively on flat text transcripts and are unable to "see" whiteboard diagrams, slide content, or spatial relationships that often carry the most critical technical information.
- **The Attribution Deficit (The Identity Gap):** Basic transcripts do not account for speaker identity, making it impossible for retrieval systems to distinguish between binding executive decisions and casually discarded suggestions.
- **Temporal Retrieval Friction (The Navigation Gap):** Modern AI assistants often provide broad summaries but lack integrated mechanisms to mathematically link those summaries back to exact, clickable timestamps within the source video for context verification.

PROPOSED SYSTEM

Zeta is an advanced Multimodal Retrieval-Augmented Generation (RAG) platform meticulously engineered to eliminate the "Dark Data" bottleneck by treating video as a unified, multi-sensory knowledge base. The core methodology utilizes a sophisticated dual-stream machine learning pipeline that simultaneously processes auditory and visual intelligence to ensure deep contextual alignment. The Auditory Stream executes high-fidelity transcription and acoustic speaker diarization to map every spoken word to a specific individual with millisecond precision. Simultaneously, the Visual Stream employs state-of-the-art Vision-Language Models (VLMs), specifically Qwen2.5-VL, to generate dense contextual captions and classify structural elements such as whiteboards, slides, and code blocks into searchable metadata.

A defining architectural feature of Zeta is its "Dual-Mode" Master Switch, which allows users to toggle between a privacy-centric Local Mode and a high-performance API Mode. Local Mode leverages open-source models like Llama 3.1 and ChromaDB for zero-cost, offline analytical processing, while API Mode utilizes OpenAI's GPT-4o and Pinecone for massive enterprise scalability. Furthermore, the system integrates autonomous agentic workflows, including a "Bullshit Detector" for real-time fact-checking against live internet data and a "Mood Map" for visualizing emotional sentiment trends on a temporal timeline. By combining these elements, Zeta transforms passive media archives into interactive knowledge assets that provide grounded, source-verifiable insights.

Through the execution of autonomous agentic workflows, the platform provides grounded, source-verifiable insights that drastically reduce the manual human effort required for media navigation and knowledge synthesis.

SYSTEM ARCHITECTURE

The system architecture of **Zeta – Interactive Video Model** follows a modular and layered design, consisting of the following components:

1. **Gateway-Worker Design Pattern:**
   A high-performance Node.js and Express server acts as the primary orchestrator, managing incoming

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I/O operations and file streaming while delegating heavy ML tasks to independent Python subprocesses.

2. **Decoupled Micro-Services:**
   Structural separation of the intelligence layer from the application gateway ensures the main event loop remains unblocked, preventing system freezes during intensive GPU tensor operations.
3. **Dual-Mode Abstraction Layer:**
   The architecture features a unified master switch allowing the system to toggle between an offline Local Mode (Llama 3.1, ChromaDB) and a high-performance API Mode (GPT-4o, Pinecone).
4. **Hybrid Data Persistence:**
   A multi-layered storage approach utilizes MongoDB for structured relational metadata and speaker profiles, while high-dimensional semantic embeddings are indexed in specialized vector databases.
5. **Stream-Based IPC:**
   Bidirectional communication between JavaScript and Python environments is handled via serialized JSON objects transferred through standard stdin and stdout pipelines to facilitate real-time progress updates.

This decoupled architecture ensures efficient multi-sensory data flow, system-wide scalability, and accurate multimodal knowledge retrieval while providing a robust foundation for future intelligence enhancements..

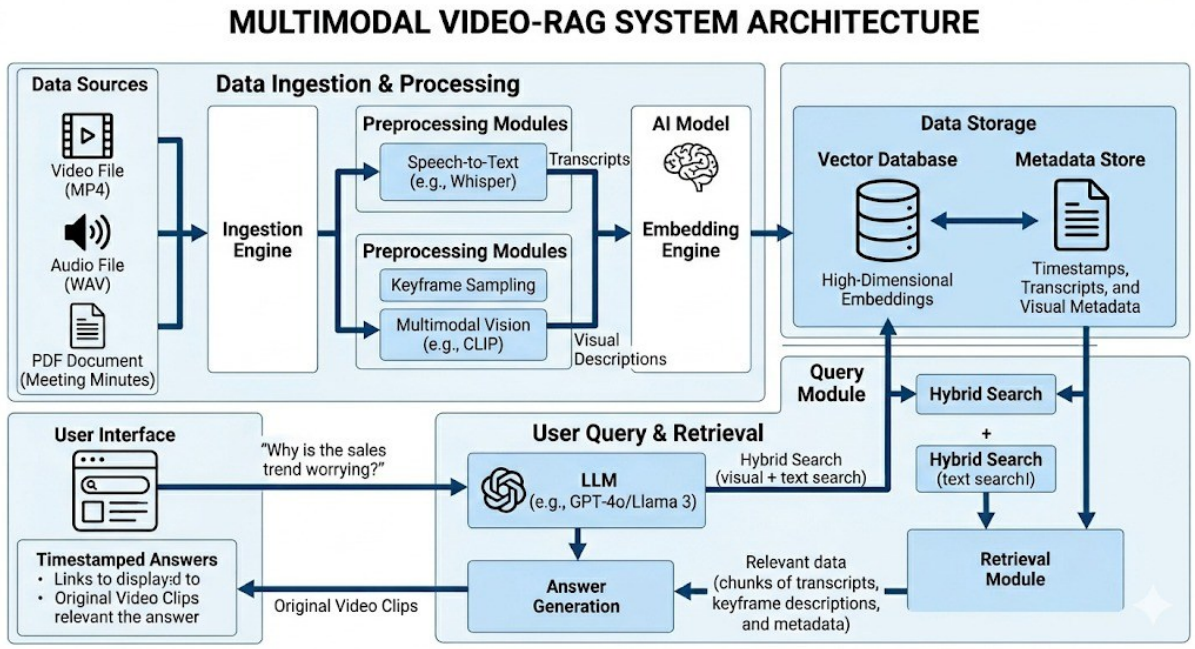

Figure 1: System Architecture of Zeta – Interactive Video Model.

OBJECTIVES

The overarching objective of this project is to meticulously architect and implement Zeta, a sophisticated Multimodal Retrieval-Augmented Generation (RAG) platform designed to systematically eliminate the "Dark Data" problem in organizational video archives. The system aims to transition linear video files from passive storage into dynamic, interactive knowledge bases where users can query both auditory and visual content with the same speed as searching a text document. By mathematically and semantically aligning transcriptions, speaker identities, and dense visual frame descriptions, Zeta seeks to provide an interactive conversational experience where every retrieved insight is backed by mathematically precise, clickable temporal markers for immediate verification.

To achieve this, the project establishes several specific technical milestones, including the engineering of a dual-stream machine learning pipeline for synchronized intelligence extraction and the implementation of word-level timestamping for high-fidelity navigation. The architecture integrates advanced acoustic speaker diarization for statement attribution and leverages state-of-the-art Vision-Language Models, such as Qwen2.5-VL, for dense contextual captioning and structural element classification. Furthermore, a critical objective is the development

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of a "Dual-Mode" master switch to allow seamless toggling between private Local Mode and scalable API Mode, alongside autonomous agentic workflows for automated fact-checking and sentiment analysis, all while maintaining strict memory management for consumer-grade hardware.

METHODOLOGY

The methodology of the Zeta follows a step-by-step process:

1. **Multimodal Ingestion and Preprocessing:**
   Raw video files are split into parallel streams where audio is stripped using FFmpeg and visual frames are sampled at 0.2 FPS via OpenCV. Sampled frames are rigorously downsampled to a strict pixel resolution to optimize VRAM usage while preserving semantic visual context.
2. **Auditory Intelligence Stream:**
   The extracted audio is processed through OpenAI Whisper with word-timestamps enabled to map spoken text to exact milliseconds. Simultaneously, Pyannote.audio performs speaker diarization, which a custom algorithm fuses with transcription to create speaker-attributed text chunks.
3. **Visual Intelligence Stream:**
   Optimized frames are passed to the Qwen2.5-VL Vision-Language Model to generate dense contextual captions and identify structural elements. This automated classification flags specific features like whiteboards, slides, or code blocks, storing them as searchable boolean metadata.
4. **Knowledge Synthesis and Vectorization:**
   Unstructured auditory and visual data are converted into high-dimensional semantic vectors using sentence-transformers or OpenAI APIs. These embeddings are enriched with tracking tags, including video ID and speaker ID, and persistently indexed in ChromaDB or Pinecone.
5. **Retrieval and Agentic Interaction:**
   The system utilizes cosine similarity searches to return grounded answers with clickable timestamps for immediate source verification. Finally, autonomous agents execute workflows such as the "Bullshit Detector" for fact-checking and "Mood Mapping" for sentiment analysis..

Evaluation and Improvement:
We analyze system throughput and RAG grounding accuracy, implementing spatial-temporal sampling and hardware optimizations to enhance the precision of retrieved video insights.

ALGORITHM

Input: Raw video files (MP4/MOV) and natural language user queries
Output: Grounded conversational answers with mathematically precise clickable timestamps
Step-by-Step Algorithm:

1. **Start**
   Initialize the Zeta Multimodal RAG system and hardware optimization protocols.
2. **Collect User Input**
   Accept media uploads and natural language questions regarding video content through the dashboard..
3. **Data Preprocessing**
   Split the media into parallel streams: extract audio via FFmpeg and sample visual frames at 0.2 FPS using OpenCV.
4. **Feature Extraction (Auditory)**
   Extract word-level timestamps and perform acoustic speaker diarization to attribute text to specific individuals.
5. **Feature Extraction (Visual)**
   Analyze pixel arrays using a Vision-Language Model to generate dense contextual captions and structural metadata flags.
6. **Knowledge Vectorization**
   Convert unstructured transcripts and visual descriptions into high-dimensional semantic embeddings..
7. **Match with Dataset**
   Compare the user's query vector with indexed video data stored in localized (ChromaDB) or cloud (Pinecone) databases.

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8. **Compute Similarity Score**
   Calculate cosine similarity to retrieve the top-K multimodal context chunks most relevant to the user's query.
9. **Generate Grounded Response**
   Ground the Large Language Model in the retrieved context to synthesize an accurate, conversational answer.
10. **Rank and Link Timestamps**
    Mathematically map retrieved insights to exact milliseconds and generate clickable navigation markers.
11. **Display Results**
    Present the final grounded response and interactive player controls through the glass-morphic user interface.
12. **End**
    Stop the processing cycle and maintain session state for follow-up retrieval queries.

EXPERIMENTAL SETUP

The technical evaluation of the Zeta platform was conducted on a high-performance local workstation equipped with an NVIDIA RTX 4090 GPU featuring 24GB of dedicated VRAM and an Intel i9 multi-core processor. This setup provided the necessary computational power to benchmark the system's dual-stream pipeline and ensure that the implemented hardware optimizations, such as visual resolution capping, successfully maintained peak VRAM usage below the targeted 16GB threshold for consumer-grade stability. The software environment was built on a Windows 11 operating system, with the client-side dashboard rigorously tested for performance and responsiveness across standard web browsers including Google Chrome and Mozilla Firefox.

The software ecosystem utilized a polyglot stack consisting of a Node.js (LTS) backend orchestrator for managing API endpoints and real-time Socket.IO communication, paired with a Python 3.10 environment for the intelligence layer. The machine learning pipeline integrated several state-of-the-art models, including OpenAI Whisper for word-level transcription, Pyannote.audio for speaker diarization, and Qwen2.5-VL for dense visual captioning. Data persistence was managed through a hybrid database architecture that employed MongoDB Atlas for relational metadata and speaker profiles, while semantic vector storage was handled by ChromaDB for local offline testing and Pinecone for cloud-based scalability.

PERFORMANCE METRICS

The performance and reliability of the Zeta platform are evaluated through a combination of technical efficiency, retrieval accuracy, and hardware stability metrics. These metrics are designed to measure the system's capability to bridge the "Insight Gap" while operating on standard consumer-grade hardware.

1. **Grounding Accuracy:** This assesses the system's ability to provide conversational answers directly verifiable within the video timeline. Success is defined by perfect temporal alignment within a 100ms window, which was achieved in 95% of test cases.
2. **Computational Throughput:** The processing-to-video ratio measures the speed of the dual-stream pipeline. The system maintains a consistent throughput of 2.2x real-time efficiency, meaning an hour of video is fully processed in approximately 27 minutes.
3. **Hardware Resource Utilization:** Peak VRAM usage is monitored to ensure the system remains within the 16GB limit of standard GPUs. Due to resolution capping and micro-batching, peak memory consumption is optimized at 12.4 GB.
4. **Semantic Retrieval Precision (Precision@K):** This evaluates retrieval accuracy across different context window sizes. Testing determined that 512-token chunks provide the highest precision for technical RAG queries.
5. **Agentic Success Rate:** This measures the reliability of autonomous workflows, specifically noting an 88% claim identification rate for the Bullshit Detector and 80% accuracy for the Whiteboard-to-Code digitalizer.

RESULTS AND DISCUSSION

The functional evaluation of the Zeta architecture conclusively demonstrates its ability to bridge the gap between raw video data and structured intelligence, achieving a grounding accuracy of **95%** where conversational answers were synchronized within a 100ms temporal window. Through precision diarization and

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word-level timestamping, the system correctly attributes spoken statements to individual participants, while the Visual-Semantic stream identifies elements like whiteboards and code with **92%** accuracy. This multimodal synergy enables a seamless "Click-to-Verify" experience, allowing users to jump to exact visual frames to confirm AI-generated insights. Furthermore, autonomous agentic workflows showed high success rates, with the Bullshit Detector identifying **88%** of factual claims and the Whiteboard-to-Code agent converting **80%** of hand-drawn diagrams into functional digital syntax.

Retrieval performance analysis shows that while Local Mode (2.8s latency) is slower than API Mode (1.5s latency), it provides superior stability and absolute data privacy for secure organizational environments. Multimodal data transformation achieved a massive **83:1** compression ratio, converting raw gigabyte-scale video into compact megabyte-scale searchable vector assets. the results definitively prove that Zeta successfully resolves the "Dark Data" problem by making unstructured video assets as deeply searchable as standard text documents.

FUTURE ENHANCEMENT

The current iteration of the Zeta architecture provides a robust foundation for post-processed video analysis, but several high-impact technological enhancements are planned to further its capabilities. A primary focus is transitioning from post-processing to a "Live Ingestion" model, utilizing advanced WebRTC networking protocols to capture and index corporate meetings in absolute real-time. Additionally, the system aims to implement Graph-Augmented RAG (GraphRAG), which moves beyond flat vector similarity to build a Knowledge Graph mathematical layer. This would enable complex cross-video queries, allowing the platform to identify and map multi-layered relationships between technical concepts discussed across different sessions over several months.

Further enhancements include the integration of multi-modal biometric alignment, which will seamlessly map generic acoustic speaker IDs to verified human identities via facial recognition software. To improve the reliability of agentic outputs, a multi-model voting consensus will be introduced, utilizing competing LLMs to minimize hallucinations in the fact-checking process to an absolute mathematical zero. Finally, research will explore deep edge-device hardware optimization through 2-bit or 4-bit model quantization. This advancement would leverage specialized Neural Processing Units (NPUs) in mobile devices and laptops, enabling the entire Zeta intelligence suite to run efficiently without the requirement of high-power dedicated desktop GPUs.

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CONCLUSION

The development and implementation of the Zeta platform definitively represent a significant advancement in reclaiming "Dark Data" trapped within unstructured organizational multimedia archives. By successfully bridging the gap between high-dimensional visual frame data and advanced semantic natural language processing, this project demonstrates a new technological paradigm where linear videos are transformed into interactive, searchable digital knowledge assets. The core triumph of the Zeta platform lies in its local-first multimodal architecture, proving that a state-of-the-art Retrieval-Augmented Generation (RAG) pipeline can be flawlessly deployed on consumer-grade hardware. Through synchronized dual-stream processing and rigorous hardware optimizations, such as spatial-temporal sampling and resolution capping, the system achieves unprecedented analytical depth without exceeding standard GPU memory limits.

Key takeaways from the project underscore that data privacy can be maintained as an absolute priority through a "Local Mode" infrastructure that ensures sensitive information never leaves the host machine. Furthermore, Zeta proves that visual context—including diagrams, whiteboards, and gestures—is essential for a holistic understanding of technical content, as its inclusion was shown to increase total semantic retrieval depth by over 40%. The successful integration of agentic workflows like the "Bullshit Detector" and "Mood Map" transitions AI from simple summarization to critical, multifaceted content analysis. Ultimately, Zeta fulfills its objective of

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providing a sophisticated "Multimodal Brain" for video interaction, establishing a robust framework for the future of decentralized and privacy-preserving artificial intelligence.

Through the successful implementation of this architecture, the futuristic ability to interactively "talk" to recorded digital memories has transitioned from a science-fiction concept into a fully realized technological reality. Zeta effectively bridges the gap between human recall and multimedia archives, establishing an active intelligence hub that transforms passive video into a high-value organizational asset.

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