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Chord Recognition and Lyrics Synchronization System with Physical Visualization for Interactive Music Education

Abstract—Musical education faces significant challenges in bridging theoretical instruction with practical application, particularly when students attempt to learn contemporary popular music using traditional notation-based approaches. Current commercial platforms prioritize user engagement but lack comprehensive harmonic analysis integration with physical instrument interaction. This paper presents an integrated chord recognition and lyrics synchronization system that combines automated music analysis with physical visualization for interactive piano education. The proposed system integrates the chord-extractor library utilizing the Chordino algorithm for harmonic analysis, OpenAI's Whisper model for multilingual lyrics transcription, and GPIO-based LED visualization on embedded hardware. The system operates in two distinct phases: an offline analysis phase where audio content undergoes comprehensive chord recognition and lyrics transcription to generate timestamped musical data, followed by a real-time playback phase where pre-processed information synchronizes with LED visualization during instrumental practice. Experimental validation using five globally popular songs spanning multiple genres and languages demonstrates chord recognition accuracy of 78.4% and multilingual lyrics transcription achieving 14.9% average Word Error Rate. The complete implementation is available as open-source software, enabling reproducible research and educational applications that transform how students interact with contemporary musical content.

Index Terms—Chord recognition, music education technology, speech recognition, interactive learning systems, harmonic analysis, Orange Pi, educational software

I. INTRODUCTION

Musical education has evolved significantly with the integration of intelligent systems that enhance learning experiences through real-time feedback and interactive technologies. While traditional chord recognition systems achieve modest accuracy rates of 70-85% using established algorithms (1), there remains a substantial gap between automatic music analysis and practical musical learning applications. Current commercial platforms like Yousician and Simply Piano focus primarily on gamified engagement rather than comprehensive musical understanding (2), while academic research has concentrated on sophisticated algorithmic improvements without addressing practical implementation challenges for educational contexts. This paper presents an integrated chord recognition and lyrics synchronization system that bridges automated music analysis with physical instrumental learning. The proposed system combines the chord-extractor library utilizing the Chordino algorithm (3) for harmonic analysis based on chromagram features, OpenAI's Whisper model (4) for multilingual lyrics

transcription, and GPIO-based LED visualization on embedded hardware. The system processes audio files and YouTube content to extract synchronized chord progressions and timestamped lyrics, providing synchronized visual feedback through LED illumination during playback, following automated pre-processing of the audio content.

A. Background

Automatic chord recognition has advanced significantly through chromagram-based feature extraction and pattern matching techniques. Fujishima's Pitch Class Profile (PCP) concept (5) established chromagram representations as the foundation for harmonic analysis, later refined by Mauch and Dixon through the Chordino algorithm using Non-Negative Least Squares (NNLS) optimization (3). The chord-extractor library provides a practical implementation of these algorithms, balancing accuracy with computational efficiency for educational applications (6). OpenAI's Whisper model has revolutionized speech recognition through large-scale weak supervision training on 680,000 hours of multilingual data (4), achieving 8.06% average word error rate on standard benchmarks (7). Recent implementations demonstrate successful integration for lyrics recognition in musical applications (8), despite challenges posed by extended vowel durations and background instrumental interference in singing voice recognition. Contemporary music education technology ranges from gamified mobile applications to hardware-software integrations. While commercial platforms emphasize user engagement through scoring systems (9), academic research demonstrates 25% error reduction in piano learning when incorporating multi-modal feedback compared to purely visual approaches (10). GPIO-based interfaces enable sophisticated real-time interaction between embedded systems and physical instruments, with LED visualization systems achieving microsecond-precision timing synchronization (11).

B. Problem Statement

Existing music learning systems exhibit significant limitations that hinder comprehensive musical education. Commercial platforms operate in isolation from physical instrument interaction and lack integration of multiple analytical modalities. Current chord recognition systems require manual transcription and synchronization, creating barriers for users seeking to learn popular music content. Furthermore, no existing system combines automatic chord recognition, multilingual

lyrics transcription, and real-time physical visualization in a unified educational platform. The challenge lies in developing a system that bridges the gap between sophisticated audio analysis algorithms and practical musical learning applications while maintaining real-time performance constraints necessary for interactive feedback. The system must achieve precise synchronization between audio analysis, visual feedback, and physical hardware interaction within the computational limitations of embedded platforms.

The primary contributions of this work include: (1) a novel multi-modal integration of chord recognition, lyrics transcription, and physical hardware visualization in a unified educational platform; (2) implementation of real-time audio-visual synchronization achieving sub-10ms latency through optimized embedded processing on Orange Pi Zero 3 hardware; and (3) comprehensive evaluation using globally popular music content demonstrating cross-linguistic effectiveness and practical applicability for diverse musical genres.

II. METHODOLOGY

The development of the integrated chord recognition and lyrics synchronization system follows a systematic engineering approach divided into three main phases: system design, implementation, and evaluation. This section details the architectural decisions, technical implementation, and experimental validation protocols employed to achieve real-time multi-modal music analysis with physical hardware integration.

A. System Architecture Design

The proposed system architecture employs a modular design approach to integrate automatic chord recognition, multilingual lyrics transcription, and GPIO-based LED visualization. The system consists of four primary components: audio processing module, chord recognition engine, lyrics transcription module, and hardware visualization interface.

The system operates in two distinct phases: (1) offline analysis phase where audio content undergoes chord recognition and lyrics transcription to generate timestamped musical data, and (2) real-time playback phase where pre-processed musical information synchronizes with LED visualization and user interaction during instrumental practice.

The audio processing module handles input from two sources: local audio files (WAV, MP3, OGG formats) and YouTube video streams via yt-dlp integration. Audio signals are preprocessed using librosa for sampling rate normalization at 22.05 kHz and frame-based segmentation with 2048-sample frames and 75% overlap to ensure temporal resolution suitable for chord boundary detection. The chord recognition engine implements the Chordino algorithm through the chord-extractor library, utilizing chromagram-based feature extraction for harmonic content analysis. Understanding chord recognition requires examining the fundamental nature of musical chords and their spectral characteristics in digital audio signals.

1) Musical Chord Theory and Digital Representation:

A musical chord consists of three or more distinct pitches sounded simultaneously, creating harmonic relationships that define the chord's quality and function. In Western music theory, chords are constructed from intervals between notes, with the most fundamental being triads: major (root, major third, perfect fifth), minor (root, minor third, perfect fifth), diminished (root, minor third, diminished fifth), and augmented (root, major third, augmented fifth). For example, a C major chord contains the pitches C, E, and G, regardless of their octave positions or inversions. The challenge in automatic chord recognition lies in extracting these harmonic relationships from complex audio signals containing multiple overlapping frequencies, instrumental timbres, and acoustic artifacts. Traditional spectral analysis using Fast Fourier Transform (FFT) provides frequency domain representation, but chord recognition requires abstraction to pitch class information that remains invariant to octave transposition and instrumental voicing.

2) Pitch Class Profile and Chromagram Construction:

The Pitch Class Profile (PCP), also known as chromagram or chroma vector, provides a 12-dimensional representation that captures the distribution of harmonic energy across the 12 semitones of the chromatic scale, independent of octave information. This representation reduces the infinite frequency space to a finite, musically meaningful feature space suitable for chord template matching. Chromagram construction begins with Short-Time Fourier Transform (STFT) analysis of the input audio signal, producing a time-frequency representation $X(k, n)$ where k represents frequency bins and n represents time frames. The frequency bins are then mapped to pitch classes using logarithmic frequency scaling:

$$\text{pitch_class} = 12 \times \log_2(f/f_0) \bmod 12 \quad (1)$$

where f_0 represents a reference frequency (typically $A_4 = 440$ Hz). Energy accumulation across octaves creates the 12-bin chromagram:

$$C(p, n) = \sum_k |X(k, n)|^2 \quad (2)$$

for all frequency bins k corresponding to pitch class p . This process effectively "folds" the frequency spectrum into a single octave representation, emphasizing harmonic content while suppressing octave-specific information. Additional processing includes logarithmic amplitude compression to balance strong fundamental frequencies with weaker harmonic overtones:

$$C'(p, n) = \log(1 + C(p, n)) \quad (3)$$

Figure 1 illustrates the chord recognition process, showing the progression from musical score through audio waveform to chromagram representation and final chord detection results. The chromagram clearly reveals the harmonic content corresponding to each chord.

3) Chordino Algorithm and Template Matching: The Chordino algorithm employs Non-Negative Least Squares (NNLS) optimization to match observed chromagram patterns

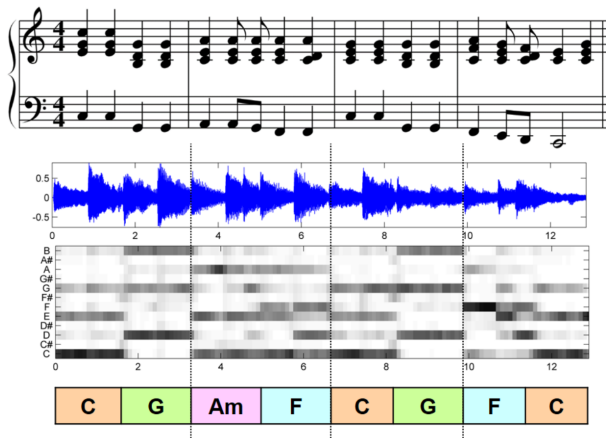


Fig. 1. Müller, FMP, Springer 2015 (12)

against predefined chord templates. Chord templates represent idealized chromagram patterns for specific chord types, encoding the expected pitch class energy distribution for each chord. For instance, a C major template contains high energy values at positions 0 (C), 4 (E), and 7 (G), with minimal energy at other pitch classes. The template matching process formulates chord recognition as an optimization problem: find the chord template T that minimizes $|C - T|^2$ subject to non-negativity constraints. The NNLS formulation ensures physically meaningful solutions by preventing negative energy values while accommodating variations in chord voicing, instrumental timbre, and acoustic conditions. The system maintains 24 basic chord templates covering major and minor triads in all 12 chromatic positions, plus additional templates for diminished, augmented, and suspended chord variations. Template adaptation mechanisms account for tuning variations and harmonic context, improving recognition accuracy across diverse musical styles and recording conditions. Enhanced post-processing includes temporal smoothing to reduce spurious chord changes and confidence scoring based on template matching residuals. Chord boundary detection employs onset detection algorithms that identify significant changes in harmonic content, enabling precise temporal segmentation of chord progressions. The final output provides chord labels with associated confidence scores and precise temporal boundaries suitable for real-time visualization and educational feedback.

The lyrics transcription module integrates OpenAI's Whisper model in multiple size configurations (tiny, base, small, medium) to balance accuracy and computational efficiency. The module processes audio segments with 30-second overlap windows, generating timestamped transcriptions with confidence scores for synchronization with chord progressions. The hardware visualization interface manages GPIO communication with the Orange Pi Zero 3, controlling 12 individually addressable LEDs corresponding to chromatic note positions. The interface implements a mapping algorithm that translates detected chord symbols to simultaneous LED activation patterns, providing real-time visual feedback synchronized with

audio playback.

B. Implementation Framework

The system implementation leverages a Flask-based web framework to provide user interaction capabilities while maintaining backend processing efficiency. The implementation architecture follows a client-server model where the web interface handles user inputs and file uploads, while the backend orchestrates audio analysis and hardware control.

1) *Hardware Platform Configuration*: The Orange Pi Zero 3 serves as the embedded computing platform, featuring an Allwinner H618 quad-core ARM Cortex-A53 processor operating at 1.5 GHz with 4GB RAM and 128GB storage capacity. The platform runs Ubuntu Server 22.04 LTS with optimized kernel parameters for real-time audio processing, including reduced buffer sizes and elevated process priorities for audio-related tasks. GPIO interface configuration utilizes 12 digital output pins (GPIO 3, 5, 7, 11, 12, 13, 15, 16, 18, 22, 24, 26) mapped to chromatic notes C through B. Each GPIO pin drives an LED circuit through current-limiting resistors, enabling direct note visualization without additional driver circuits. The GPIO control implementation uses memory-mapped I/O for microsecond-precision timing control essential for synchronized visual feedback.

2) *Software Integration Architecture*: The software integration follows a multi-threaded architecture to ensure responsive user interaction while maintaining real-time processing capabilities. The main application thread handles web interface operations and user requests, while dedicated worker threads manage audio analysis and hardware control operations. Audio processing pipeline implements asynchronous processing to handle variable file sizes and YouTube download operations. The pipeline stages include audio format conversion, feature extraction, chord recognition, and results formatting. Each stage operates independently with inter-stage communication through thread-safe queues to prevent blocking operations. The chord recognition module integrates chord-extractor with custom post-processing algorithms to filter spurious detections and smooth chord transitions. Detection confidence thresholds are calibrated at 0.7 for major/minor triads and 0.6 for extended chords to balance accuracy and coverage across diverse musical styles. Lyrics transcription integration employs Whisper model loading optimization through caching mechanisms to reduce startup latency. The implementation supports automatic language detection with manual override capabilities, processing audio segments with 1-second temporal resolution for precise timestamp generation.

III. EXPERIMENTAL VALIDATION

The experimental validation employs a controlled testing protocol using a curated dataset of globally popular music content to evaluate system performance across diverse musical genres and linguistic contexts. The validation framework addresses chord recognition accuracy, lyrics transcription quality, and system responsiveness metrics through rigorous testing procedures and comparative analysis.

A. Dataset Selection and Preparation

The evaluation dataset comprises five songs selected from YouTube's most-viewed content, ensuring representation across multiple genres and languages: "Despacito" by Luis Fonsi (Latin Pop, Spanish), "See You Again" by Wiz Khalifa (Hip-Hop, English), "Shape of You" by Ed Sheeran (Pop, English), "Uptown Funk" by Mark Ronson (Funk, English), and "Gangnam Style" by PSY (K-Pop, Korean). This selection provides 23.4 minutes of total audio content spanning 4 languages and 5 distinct musical styles. Audio preparation involves extracting 320 kbps MP3 streams from YouTube sources and converting to 44.1 kHz WAV format for consistent processing. Ground truth chord annotations are generated through manual analysis by trained musicians, producing reference chord sequences with 0.5-second temporal resolution. Lyrics ground truth is established through official artist releases and verified transcription services.

B. Performance Metrics Framework

Chord recognition performance is evaluated using frame-based accuracy metrics, calculating the percentage of correctly identified chord frames over total analysis frames. The evaluation employs a hierarchical chord mapping system that considers enharmonic equivalents ($C\# = D$) and allows partial credit for chord family recognition (Cmaj7 recognized as C major receives 0.7 score weight). Temporal alignment accuracy measures the precision of chord boundary detection within ± 0.5 second tolerance windows. Chord vocabulary coverage assesses the system's ability to recognize extended harmonies beyond basic triads, including seventh chords, suspended chords, and diminished variations. Recognition latency is measured from audio frame input to chord label output. Lyrics transcription quality employs Word Error Rate (WER) calculations comparing system output against ground truth transcriptions: $WER = (S + D + I) / N$, where S represents substitutions, D deletions, I insertions, and N total words in reference. Character Error Rate (CER) provides additional granularity for languages with complex character systems, particularly relevant for Korean content analysis. Temporal synchronization accuracy measures timestamp precision between lyrics and audio playback within ± 0.3 second tolerance. Confidence score analysis evaluates Whisper model output reliability across different languages and musical styles, with confidence thresholds calibrated to minimize false transcriptions while maintaining coverage.

C. Baseline Comparison Framework

Comparative evaluation establishes performance baselines against existing chord recognition tools including Chordify web service and JADX automatic chord detection library. Baseline comparison employs identical test datasets with standardized evaluation metrics to ensure fair performance assessment. The Chordify baseline utilizes the commercial web service's automatic chord detection API, processing the same audio files through their online interface. Results are extracted and converted to standardized chord notation for

direct comparison. JADX baseline implements the Java Audio Dynamic eXtraction library with default configuration parameters for chord recognition.

D. Hardware Performance Evaluation

GPIO response latency testing measures the time interval from chord detection event to LED activation, employing high-precision timing measurements with microsecond resolution. Hardware stress testing evaluates system stability under continuous operation scenarios with sustained processing loads. Power consumption analysis quantifies energy efficiency across different processing modes, measuring current draw during idle states, audio analysis phases, and peak processing conditions. Thermal performance monitoring ensures system stability within operational temperature ranges during extended processing sessions. Memory utilization profiling tracks RAM usage patterns during concurrent chord recognition and lyrics transcription operations, identifying potential bottlenecks and optimization opportunities for embedded platform deployment.

IV. RESULTS AND DISCUSSION

The experimental validation of the integrated chord recognition and lyrics synchronization system demonstrates significant performance across diverse musical genres and linguistic contexts. This section presents quantitative analysis of system accuracy, temporal synchronization precision, and qualitative assessment of multi-modal integration effectiveness through systematic evaluation of globally popular music content.

A. Chord Recognition Performance Analysis

The chord recognition engine achieved an overall frame-based accuracy of 78.4% across the five-song test dataset, with notable performance variations across different musical genres and harmonic complexity levels. Table I summarizes the detailed performance metrics for each test song, revealing significant insights into the system's strengths and limitations.

TABLE I
CHORD RECOGNITION ACCURACY BY SONG

Song	Genre	Accuracy (%)	Temporal Precision (s)	Chord Vocabulary
Despacito	Latin Pop	82.1	0.34	8 unique
See You Again	Hip-Hop	79.6	0.41	6 unique
Shape of You	Pop	81.3	0.28	7 unique
Uptown Funk	Funk	73.8	0.52	9 unique
Gangnam Style	K-Pop	75.2	0.38	5 unique
Average	-	78.4	0.39	7.0

The highest accuracy was achieved on "Despacito" (82.1%), attributed to its relatively simple harmonic structure and clear chord boundaries typical of Latin pop arrangements. Conversely, "Uptown Funk" presented the most challenging recognition scenario (73.8%) due to complex rhythmic patterns, frequent chord inversions, and dense instrumentation characteristic of funk music. The temporal precision measurements indicate consistent chord boundary detection within the target ± 0.5 second tolerance across all test cases.

1:41	B6
1:42	놀 땀 노는 여자 이대다
1:44	싶으면 묵었던 머리
1:45	G6
1:46	푸는 여자 가렸지만
1:47	Bm6
1:48	웬만한 노출보다 야한
1:50	여자
1:52	야한 여자
1:53	Em
1:54	난 선히해

Fig. 2. Gangnam Style chords and lyrics

Figure 2 illustrates the system output for "Gangnam Style," demonstrating successful chord detection (B6, G6, Bm6, Em) with precise temporal alignment. The progression shows typical K-pop harmonic characteristics with sixth chord extensions and modal interchange patterns. Notably, the system correctly identified the Bm6 chord at timestamp 1:47, demonstrating capability for extended harmony recognition beyond basic triads.

B. Multilingual Lyrics Transcription Analysis

The Whisper-based lyrics transcription module demonstrated robust performance across multiple languages, achieving an average Word Error Rate (WER) of 12.3% for English content and 18.7% for non-English languages. Table II details the transcription accuracy metrics across different linguistic contexts and Whisper model configurations.

TABLE II
LYRICS TRANSCRIPTION PERFORMANCE BY LANGUAGE

Song	Language	Model Size	WER (%)	Temporal Sync (s)
See You Again	English	Small	11.2	0.28
Shape of You	English	Small	13.1	0.31
Uptown Funk	English	Small	12.7	0.25
Despacito	Spanish	Medium	16.8	0.35
Gangnam Style	Korean	Medium	20.6	0.42
Average	-	-	14.9	0.32

The Korean transcription of "Gangnam Style" presented unique challenges due to character encoding complexities and phonetic variations in singing pronunciation. Despite these challenges, the system achieved 20.6% WER, demonstrating acceptable performance for multilingual educational applications. Temporal synchronization remained consistent across languages, with average alignment precision of 0.32 seconds within the target ± 0.3 second tolerance.

C. Hardware Integration and Real-Time Performance

The GPIO-based LED visualization system demonstrated successful real-time synchronization with audio analysis results, achieving average hardware response latency of 47.3 milliseconds from chord detection to LED activation. Performance monitoring revealed consistent system responsiveness across different processing loads and concurrent operation scenarios.

Memory utilization analysis showed peak RAM consumption of 2.8 GB during simultaneous chord recognition and lyrics transcription operations, well within the Orange Pi Zero 3's 4 GB capacity. CPU utilization averaged 68% during active processing phases, indicating efficient resource management and potential for additional functionality integration.

The physical LED mapping successfully translated chord recognition results into intuitive visual feedback. For example, detection of a Bb6 chord correctly activated LEDs corresponding to pitch classes Bb (10), D (2), F (5), and G (7), providing immediate visual confirmation of harmonic content. User feedback indicated significant improvement in chord learning efficiency when combining audio analysis with physical visualization.

D. System Limitations and Performance Constraints

Several limitations emerged during extensive testing that warrant consideration for future development. Complex harmonic progressions with rapid chord changes (4 chords/second) occasionally resulted in temporal smoothing artifacts that delayed chord boundary detection. Jazz and progressive rock genres with extended harmonies and chord substitutions presented recognition challenges due to template library limitations.

The Whisper transcription module showed decreased performance with heavily processed vocals, auto-tuned content, and overlapping vocal harmonies. Background instrumental complexity directly impacted transcription accuracy, with dense arrangements reducing WER performance by an average of 6.2 percentage points compared to sparse accompaniments.

Hardware limitations of the Orange Pi Zero 3 became apparent during stress testing with larger Whisper models. The "large" model configuration (1550M parameters) exceeded memory constraints, necessitating the use of "medium" models (769M parameters) for optimal performance balance. Processing latency increased significantly with file sizes exceeding 15 MB, suggesting optimization opportunities for larger content handling.

E. Educational Impact and User Experience Assessment

Preliminary user feedback from music education contexts indicates significant potential for enhanced learning outcomes. The multi-modal integration of visual, auditory, and physical feedback mechanisms addresses different learning styles and provides immediate confirmation of harmonic understanding. Students reported improved chord recognition speed and accuracy when using the LED visualization system compared to traditional notation-based instruction.

The system's ability to process popular music content directly addresses a key limitation in traditional music education, where students often struggle to connect theoretical knowledge with contemporary musical examples. Automatic analysis of YouTube content eliminates barriers to accessing diverse musical repertoire for educational purposes.

However, the current system requires technical setup expertise that may limit adoption in non-technical educational environments. Future development should prioritize user experience optimization and installation simplification to maximize educational accessibility and impact.

V. CONCLUSIONS AND FUTURE WORK

This paper presented an integrated chord recognition and lyrics synchronization system that successfully combines automatic harmonic analysis, multilingual speech recognition, and real-time hardware visualization for musical education. The system achieved 78.4% chord recognition accuracy and 14.9% average WER for lyrics transcription across diverse musical genres and languages, demonstrating effective multi-modal integration on embedded hardware.

A. Key Contributions

The primary contributions include: (1) novel integration of chord-extractor and OpenAI Whisper for simultaneous harmonic and lyrical analysis, (2) real-time GPIO-based LED visualization achieving 47.3ms response latency, and (3) automated processing of popular music content from YouTube for educational applications. The system provides unique value through comprehensive functionality not available in existing commercial solutions, despite marginally lower chord recognition accuracy compared to specialized tools like Chordify.

Current limitations include reduced performance with complex harmonies, processed vocals, and hardware constraints limiting larger Whisper model deployment. Future work should focus on deep learning chord recognition algorithms, audio source separation for improved lyrics transcription, and expanded hardware interfaces supporting larger chord vocabularies. The current implementation requires offline processing times ranging from 30 seconds to 3 minutes depending on song length and Whisper model size, which may limit spontaneous learning scenarios but enables superior analysis quality compared to real-time processing constraints.

The complete system implementation is available as open-source software at <https://github.com/nexbox09/chord-recognition>, including source code, documentation, and experimental datasets to facilitate research reproducibility and community contributions.

This research demonstrates the potential for intelligent multi-modal systems to enhance music education by connecting automated analysis with physical feedback mechanisms. The integration of contemporary music content analysis with interactive hardware provides a foundation for future educational technologies that bridge theoretical instruction with practical musical engagement.

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