ISBN: 979-8-3315-4220-7
IEEE Catalog Number: CFP24Y38-ART

CONFERENCE PROCEEDINGS

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE)

Empowering Innovations : Navigating The Future Of Semiconductor Industry

24 - 25 October 2024
Udayana University

Organized By :

Forum Pendidikan Tinggi Tenik Elektro Indonesia

UNIVERSITAS UDAYANA

Bali, Indonesia

IEEE INDONESIA SECTION

Forum Pendidikan Tinggi Teknik Elektro Indonesia

IEEE Industrial Electronics Society

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE) | 979-8-3315-4220-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/FORTEI-ICEE64706.2024.10824590

COPYRIGHT PAGE

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE)

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE) | 979-8-3315-4220-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/FORTEI-ICEE64706.2024.10824258

WELCOME MESSAGE

General Chair of FORTEI-ICEE 2024

It is my pleasure to extend a warm welcome to all participants of 2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE), taking place in Bali, Indonesia from October 24th through October 25th, 2024. The purpose of the conference is to provide a platform for the exchange of findings, ideas, innovations, and visions related to the advancement of the future of semiconductor technologies. The FORTEI-ICEE 2024 is presented in a hybrid format, and is organized by Forum Pendidikan Tinggi Teknik Elektro Indonesia (FORTEI) and the Department of Electrical Engineering Udayana University.

The FORTEI-ICEE 2024 accepted submissions from multiple fields, including Electronics, Power and Energy Systems, Control Systems Engineering, Telecommunications & Signal Processing. Each submission underwent a peer review process before being accepted for presentation. The conference received 109 submissions, with only 55 being chosen for presentation. In addition to the paper presentations, the program features plenary keynote speeches, gala dinner and social events.

I would like to thank Professor Tuo-Hung Hou of Taiwan Semiconductor Research Institute, Taiwan, for sharing his latest perspectives and research in the field of Semiconductor Technologies. I also would like to thank Professor Trio Adiono of Indonesia Chip Design Collaborative Center, Indonesia and Dr. Ali Murtopo Simbolon, the Coordinating Ministry for Economic Affairs, Deputy for Commerce and Industry Coordination, Indonesia for their insight of future development and policy in the semiconductor industry.

I would like to express my gratitude to the IEEE Indonesia Section, the IEEE Industrial Electronics Society, and the IEEE Udayana University Student Branch, for their valuable support.

In addition, I would like to extend my appreciation to the Technical Program Committee and the Organizing Committee for their diligent efforts in coordinating the conference. Last but not least, gratitude is extended to all the presenters and authors who have selected FORTEI-ICEE 2024 as their platform for disseminating their research. Their participation has been instrumental in making this conference a reality.

I wish all conference attendees a productive and gratifying experience.

Best regards,

Dr. Gede Sukadarmika
General Chair of FORTEI-ICEE 2024

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE) | 979-8-3315-4220-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/FORTEI-ICEE64706.2024.10824511

Chair of Forum Pendidikan Tinggi Teknik Elektro Indonesia (FORTEI)

Starting from concerns about climate change on earth, currently all parties are trying to carry out more environmentally friendly activities to reduce greenhouse gas emissions. One of them is the use of renewable energy which is more environmentally friendly. Indonesia, as one of the countries in the world that has large renewable energy potential, has also taken important steps in reducing the effects of greenhouse gases with an energy transition plan based on the NZE target in 2060. The use of renewable energy for the electricity sector cannot be separated from power electronics converter technology and supporting components. The need for semiconductors for the energy sector will increase rapidly. This prompted the Indonesian government to prepare a road map towards a new era in the semiconductor sector. FORTEI as a higher education forum for electrical engineering in Indonesia has an important role in developing science and preparing human resources in the field Electrical Engineering, of semiconductors. Therefore, the biennial International Conference on Electrical Engineering (FORTEI-ICEE) raised the theme "Empowering Innovations: Navigating the Future of Semiconductor Industry". This conference is aimed at publishing and promoting the latest results of research in Electrical Engineering fields, especially on semiconductor technology. In this conference, researchers, academics, and practitioners exchange ideas in developing and improving knowledge and technology on semiconductors to help the Indonesian government in paving the road to a new era of semiconductors in Indonesia.

Finally, success of this conference is achieved by hard work of many parties, especially University of Udayana as the organizer in collaboration with Directorate of Academic & Publication of FORTEI. We also thank to keynote speakers, authors, participants, and sponsors who had full support in the success of FORTEI-ICEE 2024. We wish you all can enjoy the conference and also the beauty of Bali, Island of Gods. We hope to meet you again in the next conference, FORTEI-ICEE 2026.

Best regards,

Dedet Candra Riawan, Ph.D.
Chair of Forum Pendidikan Tinggi Teknik Elektro Indonesia (FORTEI)

Chair of IEEE Indonesia Section

Dear distinguished guests, colleagues, researchers, professionals, ladies, and gentlemen,
A prosperous, warm, and spirited greetings to all of you.

On behalf of the IEEE Indonesia Section, I would like to extend our warmest welcome to all keynote speakers, presenters, and participants of FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE 2024). The conference is held on 24^{th} -25^{th} October 2024 in University of Udayana, Jimbaran, Bali, Indonesia in hybrid mode by Forum Pendidikan Tinggi Teknik Elektro Indonesia (FORTEI), with the IEEE Indonesia Section and Industrial Electronics Society as co-sponsor.

In 2024, the IEEE Indonesia Section co-sponsors many international conferences held in Indonesia, including this conference. But co-sponsoring conferences is not the only activity we do. The IEEE Indonesia Section has carried out a large variety of activities since its formation in February 1988. The IEEE and the IEEE Indonesia Section share the same mission, namely, Advancing Technology for Humanity, but for us it is within the scope of Indonesia. However, at the same time we are also contributing to the IEEE mission internationally.

The IEEE Indonesia Section presently have 22 Technical Society Chapters and Joint Chapters covering the fields of interest of 27 IEEE Societies, widely ranging from power and energy, to communications, to oceanic engineering, to education, and to social implications of technology. These Chapters support various scientific and academic activities in Indonesia, including technical co-sponsorship of international conferences.

The IEEE Indonesia Section technically co-sponsors more than 70 international conferences annually. As the co-sponsor of these conferences, we strive to assist them to maintain the quality of the papers at the highest level and within the scientific scope of the IEEE. In terms of international publication, as of July 2024 there are more than 36,000 scientific papers in total with at least one author coming from Indonesia published in the IEEE Xplore, which consist of those published in IEEE conferences and others in IEEE journals. However, out of those 36,000, there are only around 1,000 papers that have been published in IEEE journals with at least one Indonesian author. Accordingly, we would like to encourage Indonesian researchers to publish their research works in IEEE journals, which have been widely recognized as high impact journals.

To conclude this remark, we highly appreciate the commitment shown by the organizer of FORTEI-ICEE 2024 to keep the quality of accepted papers at the highest level, focusing only on papers within the scope of the IEEE. We hope that such a strong commitment be sustained through the coming years.

Finally, we wish all participants an enjoyable and valuable experience during this conference by sharing your best knowledge in the research area of your interest. Please make FORTEI-ICEE 2024 a memorable event.

Thank you and have a good day.

Prof. Ir. Gamantyo Hendrantoro, M.Eng, PhD., SMIEEE.
Chair of IEEE Indonesia Section

Chair of IEEE IES Indonesia Section Chapter

Ladies and gentlemen, esteemed colleagues, and distinguished guests,

In the 3rd International Conference on Electrical Engineering, organized by the Forum Pendidikan Tinggi Teknik Elektro Indonesia (FORTEI), we gather to explore the transformative potential of technology in shaping the future landscape of the semiconductor industry. This conference provides us with a unique platform to discuss the latest developments, share knowledge, and collaboratively address the pressing challenges we face as we move towards an increasingly interconnected world.

As many of you are aware, semiconductors serve as the backbone for a plethora of innovations, from the smartphones that connect us to the vast networks of information, to the smart devices that monitor our health and optimize our energy consumption. The continuous evolution of semiconductor materials and fabrication techniques opens new frontiers for high-performance computing, energy-efficient solutions, and innovative electronic devices. The integration of artificial intelligence and machine learning with semiconductor technologies is paving the way for smarter systems, enabling us to automate processes, enhance data processing capabilities, and create unprecedented efficiencies across sectors like healthcare, manufacturing, and transportation. The advancements in this field not only drive economic growth but also foster breakthroughs in various applications such as automation, telecommunications, and biomedical engineering. Moreover, this era compels us to consider not just technological innovation, but the ethical implications and responsibilities that come with these advancements. As we develop new technologies, we must also ensure that they contribute to societal well-being and sustainability.

In closing, I would like to express my sincere gratitude for your participation and dedication. I am confident that the connections we establish and the knowledge we share during this conference will resonate far beyond these walls and contribute meaningfully to our communities and industries. By harnessing cutting-edge technologies and fostering collaboration among academia, industry leaders, and policymakers including the invaluable support of the IEEE Industrial Electronics Society, we can prepare ourselves for the future and develop a skilled workforce that meets the demands of this new era, and together we can craft strategies that ensure the semiconductor industry thrives in Indonesia.

Thank you and let us move forward with purpose and passion.

Prof. Dr. Ir. Mauridhi Hery Purnomo, M.Eng.
Chair of IEEE Industrial Electronics Society (IES) Indonesia Section Chapter

COMMITTEE

General Chair:
Gede Sukadarmika

Co-Chair:
Dian Retno Sawitri
Wayan Gede Ariastina

Technical Programs Chair:
Ngurah Indra ER
Devan Junesco Vresdian
Brainvendra Widi Dionova
I Nyoman Satya Kumara

Publication Chair:
Prasetiyono Hari Mukti
I Made Arsa Suyadnya
Duman Care Khrisne

Secretary:
Ni Made Ary Esta Dewi Wirastuti

Treasurer:
I Nyoman Setiawan
Devy Kuswidiastuti

TPC Members:
Norkhairani Abdul Rawi (Malaysia)
Azinoor Azida Abu Bakar (Malaysia)
Iwan Adhicandra (Indonesia)
Andi Adriansyah (Indonesia)
Nur Afiyat (Indonesia)
Mohammad Afroni (Indonesia)
Mohd Ashraf Ahmad (Malaysia)
Ali Othman Al Janaby (Iraq)
Omar Ibrahim Al saif (Iraq)
Jawad K. Ali (Iraq)
Mohammad Alibakhshikenari (Spain)
Farrikh Alzami (Indonesia)
Cucun Very Angkoso (Indonesia)
Zaenal Arifin (Indonesia)
Farrukh Arslan (USA)
Rustam Asnawi (Indonesia)
Muhammad Attamimi (Indonesia)
Aniruddha Bhattacharjya (India)
Puneeth Bhurat (India)
Sergey B. Biryuchinskiy (USA)
Ankur Bist (India)

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE) | 979-8-3315-4220-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/FORTEI-ICEE64706.2024.10824515

Novie Theresia Br. Pasaribu (Indonesia)
Angelo Bruno (Italy)
Rodrigo Campos Bortoletto (Brazil)
Alessandro Carrega (Italy)
Pablo Corral (Spain)
Puput Dani Prasetyo Adi (Indonesia)
Arsyad Ramadhan Darlis (Indonesia)
Narottam K. Das (Australia)
Sorin Ioan Deaconu (Romania)
Jayanta Kumar Debnath (USA)
George Dekoulis (Cyprus)
Ika Novita Dewi (Indonesia)
Yoga Divayana (Indonesia)
Nishant Doshi (India)
Machmud Effendy (Indonesia)
Mochammad Facta (Indonesia)
Omar Farooq (India)
Helmy Fitriawan (Indonesia)
Dhomas Hatta Fudholi (Indonesia)
Indra Gamayanto (Indonesia)
Siamack Ghadimi (Sweden)
Alireza Ghasempour (USA)
A Ginting (Indonesia)
Nyoman Gunantara (Indonesia)
Brij B. Gupta (Taiwan)
Fakhriy Hario (Indonesia)
Hanny Haryanto (Indonesia)
Norazlan Hashim (Malaysia)
Sri Heranurweni (Indonesia)
Duy C Huynh (Vietnam)
Nur Iksan (Indonesia)
Astria Nur Irfansyah (Indonesia)
Ramkumar Jaganathan (India)
UC Jha (India)
Mohd Muzafa Jumidali (Malaysia)
Apri Junaidi (Malaysia)
S Kannadhasan (India)
Chutisant Kerdvibulvech (Thailand)
Muhammad Khosyi'in (Indonesia)
Dragana Krstić (Serbia)
Samir Ladaci (Algeria)
Magfirawaty Magfirawaty (Indonesia)
Ida Bagus Gede Manuaba (Indonesia)
Rina Mardiati (Indonesia)
Ronny Mardiyanto (Indonesia)
Ernita Dewi Meutia (Indonesia)
Totok Mujiono (Indonesia)
Kusprasapta Mutijarsa (Indonesia)
Aris Nasuha (Indonesia)
I Putu Elba Duta Nugraha (Indonesia)

Yurid Nugraha (Indonesia)
Aryo Nugroho (Indonesia)
Levy Olivia Nur (Indonesia)
Nurussa'adah Nurussa'adah (Indonesia)
Rosaura Palma-Orozco (Mexico)
Sarwo Pranoto (Indonesia)
Sri Arttini Dwi Prasetyowati (Indonesia)
Tri K Priyambodo (Indonesia)
Gigih Priyandoko (Indonesia)
Muhammad Puriza (Indonesia)
Fajar Purnama (Indonesia)
Djoko Purwanto (Indonesia)
Nining Purwasih (Indonesia)
Ali Rafiei (Canada)
Helmy Rahadian (Indonesia)
Harikumar Rajaguru (India)
Priya Ranjan (India)
Dedet Riawan (Indonesia)
Arwindra Rizqiawan (Indonesia)
Ikhsan Romli (Indonesia)
Komang Oka Saputra (Indonesia)
Nyoman Putra Sastra (Indonesia)
Siti Sendari (Indonesia)
Novianto Sendi (China)
De Rosal Ignatius Moses Setiadi (Indonesia)
Iwan Setiawan (Indonesia)
Widyadi Setiawan (Indonesia)
Iwan Setyawan (Indonesia)
Dean Sharafi (Australia)
Aditi Sharma (India)
Bambang Sujanarko (Indonesia)
I. N. Sukajaya (Indonesia)
Hung-Min Sun (Taiwan)
Catur Supriyanto (Indonesia)
Titiek Suryani (Indonesia)
Heri Suryoatmojo (Indonesia)
Cucut Susanto (Indonesia)
Ming-Fong Tsai (Taiwan)
Ardian Ulvan (Indonesia)
Herlina Wahab (Indonesia)
Wahyudi Wahyudi (Indonesia)
Dimas Aditya Putra Wardhana (Indonesia)
Theophilus Wellem (Indonesia)
Eliana Werbin (Argentina)
Rony Seto Wibowo (Indonesia)
I Made Oka Widyantara (Indonesia)
Wijono Wijono (Indonesia)
Tri Ngudi Wiyatno (Indonesia)
Phang Yook Ngor (Malaysia)

Rindra Yusianto (Indonesia)
Ahmad Turmudi Zy (Indonesia)

TABLE OF CONTENTS

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE) | 979-8-3315-4220-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/FORTEI-ICEE64706.2024.10824459

Performance of DCT-DWT Feature Extraction in Recognizing Guitar Chords

Linggo Sumarno
Electrical Engineering Study Program
Sanata Dharma University
Yogyakarta, Indonesia
lingsum@usd.ac.id

2024 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE) | 979-8-3315-4220-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/FORTEI-ICEE64706.2024.10824451

Abstract— **This work deals with optimization problems in the field of audio signals with particular emphasis on recognizing guitar chords. As an extension to the previous works done in this field, the primary goal was to minimize the feature extraction length without loss of recognition performance. In this case, this work used two such well known methods in audio signal processing as the Discrete Cosine Transform (DCT) and the Discrete Wavelet Transform (DWT). This method is based on the iterative analysis of three main system attributes: the frame blocking length; the choice of wavelet functions; and the DWT coefficient selection offset. After careful tuning of these parameters, this work was able to optimize the feature extraction length to only three, which however represents a modest improvement on the previous works in this field. The system developed in this research obtained recognition accuracy of up to 91.43% when the optimized feature extraction length was employed. The significance of this study extends to the non-conventional applications of guitar chord recognition. Shortening the feature extraction length is expected to improve more usages in the different applications of the music technology.**

Keywords—DCT, DWT, feature extraction, guitar chord recognition

I. Introduction

Feature extraction is one of the important steps in the analysis of data. It helps in reducing the bulk of data into a few critical components. This not only reduces the volume of data but also optimizes the performance of later data processing. In the context of chord recognition, feature extractions methods can be divided into two groups: chroma-based features and non chroma-based features.

Chroma-based feature extraction methods aim to capture the harmonic contents in the musical signals. The Pitch Class Profile (PCP) is a classic example [1], it has a feature extraction length of 12. This feature extraction describes the energy distribution over the fundamental frequencies of a chord. Some subsequent improvements of the original PCP have been proposed [2-4]. All of these improvements also have feature extraction length of 12.

On the other hand, there are other approaches, such as non chroma-based feature extraction methods such as those of Mel Frequency Cepstral Coefficients (MFCC) [5-6] and Discrete Sine Transform (DST)-Wavelet [7]. At a fundamental level, these two MFCC and the DST-Wavelet are aimed at capturing the spectral shape of a chord. The more recent developments in MFCC [6] and DST-Wavelet [7] for the purpose of chord recognition have been able to perform a fairly effective recognition of chords with a feature extraction length of only four. By applying the above-mentioned feature extraction, the chord recognition system was able to do so with a recognition accuracy of up to 92.14 % and 92.86 % respectively.

Nevertheless, there is still room for further optimization. Reducing the length of feature extraction could improve the efficiency of data processing operations, which would be beneficial for applications like Field Programmable Gate Array (FPGA)-implemented chord recognition [8-9]. FPGA systems offer an advantage in developing application-specific integrated circuits (ASICs) for electronic devices, which can be further improved for both performance and power efficiency.

This work investigates the feasibility of further reducing the feature extraction length by incorporating the use of DCT-DWT feature extraction method for chord recognition. More specifically, this work investigates the effect of varying three parameters: frame blocking length, wavelet functions and DWT coefficient selection offset on achieving feature extraction length to be less than four while retaining the recognition accuracy.

II. Methodology

A. Developing Chord Recognition System

The chord recognition system developed for this work is illustrated in Fig. 1. The figure presents a detailed block diagram of the system. As a note, the implementation of this system utilized Python software. A thorough explanation of each block depicted in Fig. 1 is provided below.

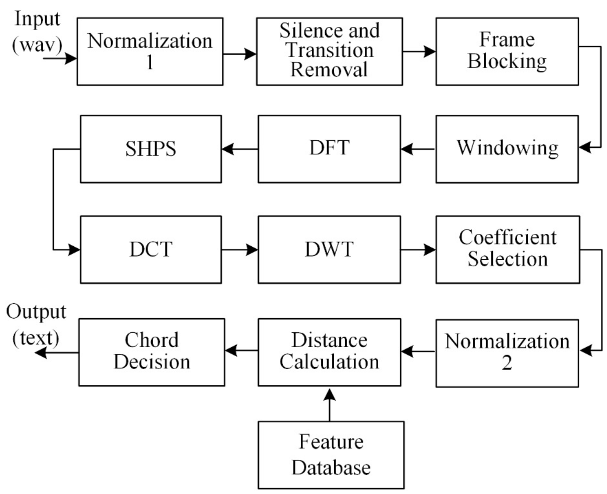

Fig. 1. The system developed for chord recognition.

1) Input: The chord recognition system uses isolated guitar chord signal recordings in WAV format as the input. It consists of seven guitar chords. They are C, D, E, F, G, A, and B. The sampling rate for the recordings was five kHz. The duration for each recording was two seconds. The number of channels for the recordings was one channel. The guitar for the recordings was Yamaha CPX-500-II. The recordings were taken in a quiet environment. More information about the recordings can be obtained from the publicly available dataset on GitHub: https://github.com/lingsum/Chord-DST-DWT. As a note this dataset is considered as primary data.

2) Normalization 1: Normalization 1 standardizes the input signal data by scaling its maximum value to a fixed range of either 1 or -1. This scaling is crucial as the maximum amplitude of recorded chord signals can fluctuate due to variations in recording conditions and musical equipment

3) Silence and transition removal: Silence and transition removal eliminates non-informative segments from the signal data sequence. This step performs in sequence as follows.

1. Silence removal: By visually inspecting the signal, a threshold of |0.5| is applied to the left side of the sequence. Signal data with absolute values below this threshold are discarded when scanning from left to right.
2. Transition removal: The initial 200 milliseconds of the signal, identified through visual inspection, is removed to account for transient effects.

4) Frame blocking: Frame blocking involves segmenting a short sequence of signal data [10]. This segmentation is typically performed on the left side of the signal data. The length of this short sequence, known as the frame blocking length, significantly impacts the signal's resolution after applying the DFT step. Both too low and too high signal resolutions can detrimentally affect the feature extraction's discrimination capability, ultimately lowering recognition accuracy. Therefore, this work evaluated frame blocking length of 128, 256, 512, 1024, and 2048. As a note there was no overlap in this frame blocking.

5) Windowing: Windowing minimizes the effects of the left and right edges of a signal data sequence. If these edges are not reduced, spectral leakage may occur in the signal data after the Discrete Fourier Transform (DFT) step. This leakage introduces extraneous frequencies that do not correspond to the actual frequencies present in the chord. To mitigate spectral leakage, windowing is employed. This work used the Hamming window, a commonly applied windowing function in signal processing [11].

6) DFT: The Discrete Fourier Transform (DFT) maps a finite sequence of the signal data into a finite sequence of complex values in the frequency domain. This work utilizes the magnitude of these complex values. Due to the symmetry of the magnitude sequence, only the left half of the data sequence could be considered.

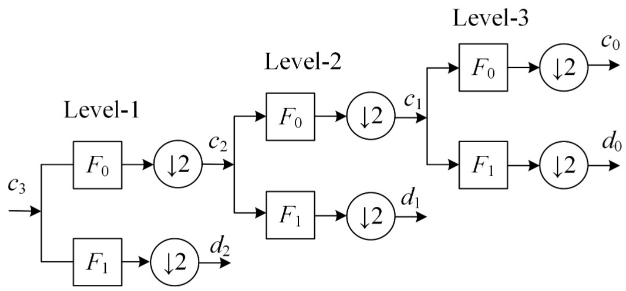

Fig. 2. Example of DWT with three-level decomposition.

7) SHPS: The Simplified Harmonic Product Spectrum (SHPS) improves the visibility of peaks at the fundamental frequency and its harmonics. This method, as introduced by Sumarno [12], is a variation of the Harmonic Product Spectrum (HPS) originally developed by Noll [13].

8) DCT: The Discrete Cosine Transform (DCT) concentrates the signal's energy into a small number of coefficients. As a result, most of the relevant information about the signal is captured in the lower-frequency components. This characteristic makes the DCT especially valuable for feature extraction tasks.

9) DWT: The Discrete Wavelet Transform (DWT) decomposes signals into components representing different frequency bands and resolutions. Fig. 2 illustrates an example of this DWT. Low-pass (LPF) and high-pass (HPF) filters, derived from the chosen wavelet filter, are applied as shown, represented by F_0 and F_1, respectively. This work evaluated Haar, Daubechies (2-6), and biorthogonal (1.3, 1.5, 2.2, 2.4, 2.6, 2.8, 3.1, 3.3, 3.5, 3.7) wavelet filters. To preserve signal length, periodization was applied in filtering mode. The ↓2 symbol in Fig. 2 denotes a downsampling factor of 2.

In Fig. 2 and Fig. 3, c_3 is the input of DWT, while c_0, d_0, d_1, and d_2 are the resulting DWT coefficients at different scales and frequencies. Additionally, Fig. 3 illustrates the decomposition steps of the DWT shown in Fig. 2, for an 8-point DWT input.

10) Coefficient selection: Coefficient selection involves choosing a set of DWT coefficients that will be used to

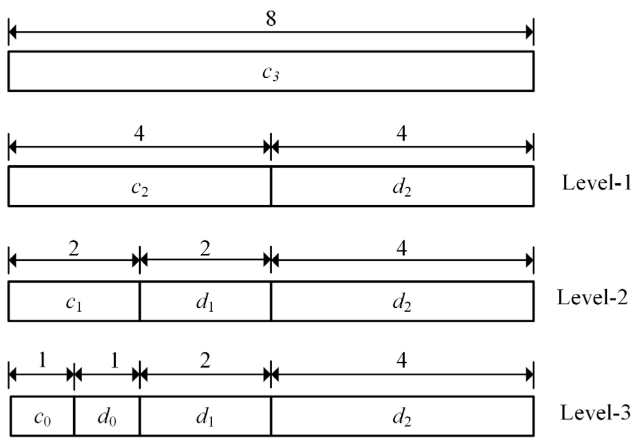

Fig. 3. Decomposition steps from DWT in Fig. 2, for an 8-point DWT

TABLE I. TESTING RESULTS USING A DWT COEFFICIENT SELECTION OFFSET OF 2 AND A HAAR WAVELET FILTER. RESULTS SHOWN: RECOGNITION ACCURACY (%)

Frame blocking length	**Feature extraction length**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
128	20.71	45.71	63.57	63.57	71.43	68.57	74.29	76.43
256	16.43	52.14	57.86	76.43	77.14	81.43	83.57	85.71
512	27.14	61.43	71.43	72.86	81.43	88.57	81.43	86.43
1024	28.57	80.00	**91.43**	92.86	91.43	94.29	94.29	94.29
2048	28.57	72.86	61.43	69.29	94.29	91.43	97.14	97.14

TABLE II. TESTING RESULTS USING A FRAME BLOCKING LENGTH OF 1024 AND A HAAR WAVELET FILTER. RESULTS SHOWN: RECOGNITION ACCURACY (%)

DWT coefficient selection offset	**Feature extraction length**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	14.29	58.57	74.29	87.14	92.86	92.86	92.86	95.71
1	22.86	35.71	87.14	92.86	92.86	92.86	95.71	95.71
2	28.57	80.00	**91.43**	92.86	91.43	94.29	94.29	94.29
3	28.57	59.29	85.71	90.00	93.57	92.86	92.86	92.86
4	28.57	75.71	88.57	92.86	92.86	92.86	94.29	92.86

represent the feature extraction of the input signal. Coefficient selection is carried out in the following manner.

1. Let the result of the previous DWT step be $W = \{w_0, w_1, \dots, w_{N-1}\}$ where N is the length of W.
2. Determine the number of coefficients to be selected, n, where $n \leq N$.
3. Determine the DWT coefficient selection offset, m, where $m + n \leq N$.
4. The result of the coefficient selection is $C = \{w_m, w_{m+1}, \dots, w_{m+n-1}\}$

This work evaluated the number of coefficients to be selected (feature extraction length) as 1, 2, ..., and 8, as well as the DWT coefficient selection offsets of 0, 1, ..., and 4.

11) Normalization 2: Normalization 2 standardizes the output from the Coefficient Selection step by scaling its maximum value to a fixed range of either 1 or -1. This scaling improves the performance of the classification algorithms [14]. It is important to note that the data resulting from Normalization 2 is referred to as the feature extraction from the input signal.

12) Distance Calculation, Feature Database, and Chord Decision: Distance calculation and feature database refer to a classification approach that employs template matching techniques [15-17]. The feature database includes a set of features for the chords utilized in this work. In this work, distance calculations employed the cosine distance function, derived from cosine similarity. This measure is commonly used to compute similarity values [18-19]. The distance calculation yields a number of seven distance values. These values represent the comparison between the feature extraction of the input signal data and a number of seven feature extraction references in the feature database.

Chord decision involves identifying the chord corresponding to the input signal. Among the seven distance values calculated, the one with the smallest distance is selected. The chord associated with this minimum distance is then identified as the output chord.

B. *Developing Training and Testing*

Training was conducted by developing the feature database. Firstly, features were extracted from 10 training samples for each chord using the output from the Normalization 2 step. Secondly, the average of these features was then computed, and the resulting averages served as the feature extraction references. Finally, the feature database includes seven feature extraction references, one for each chord. Testing was conducted by using 140 testing samples where it consisted of 20 testing samples for each chord.

III. TESTING RESULTS AND DISCUSSIONS

A. *Testing Results*

TABLE I, II, and III present testing results of this work. They were obtained by simultaneously evaluating three different parameters: frame blocking length, wavelet filter, and DWT coefficient selection offset. Detailed descriptions of these parameter variations can be found in the Methodology section above.

B. *Discussions*

TABLE I indicates that both too short and too long frame blocking lengths can negatively impact recognition accuracy. A frame blocking length that is too short results in insufficient detail in the signal data derived from the DFT step, leading to low signal resolution. Conversely, extensively long frame blocking length introduces excessive detail, resulting in high signal resolution. Both insufficient and excessive detail can impair the feature extraction process, ultimately diminishing recognition accuracy.

TABLE III. TESTING RESULTS USING A FRAME BLOCKING LENGTH OF 1024, AND A DWT COEFFICIENT SELECTION OFFSET OF 2. RESULTS SHOWN: RECOGNITION ACCURACY (%)

Wavelet filter	Feature extraction length							
	1	2	3	4	5	6	7	8
Haar	28.57	80.00	**91.43**	92.86	91.43	94.29	94.29	94.29
Daubechies 2	24.29	42.14	65.00	78.57	92.86	92.86	90.71	92.86
Daubechies 3	14.29	57.86	62.86	80.00	85.00	85.00	89.29	86.43
Daubechies 4	14.29	57.86	81.43	70.71	84.29	84.29	78.57	87.14
Daubechies 5	14.29	49.29	60.71	84.29	85.71	85.71	83.57	78.57
Daubechies 6	14.29	49.29	55.00	75.00	78.57	80.00	89.29	75.00
Biorthogonal 1.3	28.57	50.71	79.29	87.86	88.57	90.00	90.00	82.86
Biorthogonal 1.5	14.29	60.00	56.43	75.71	82.14	71.43	75.71	76.43
Biorthogonal 2.2	14.29	52.86	67.14	75.71	84.29	86.43	88.57	88.57
Biorthogonal 2.4	14.29	48.57	49.29	72.86	77.86	80.71	78.57	82.86
Biorthogonal 2.6	14.29	47.86	65.71	78.57	85.00	84.29	77.86	82.14
Biorthogonal 2.8	14.29	47.86	60.71	78.57	80.71	85.71	79.29	77.86
Biorthogonal 3.1	28.57	71.43	81.43	88.57	90.00	90.00	90.00	88.57
Biorthogonal 3.3	28.57	70.00	75.71	81.43	84.29	82.86	85.71	84.29
Biorthogonal 3.5	28.57	72.86	79.29	75.71	82.14	87.14	80.00	81.43
Biorthogonal 3.7	14.29	55.71	67.14	78.57	81.43	78.57	72.86	75.00

TABLE II indicates that both very small and very large DWT coefficient selection offset can reduce recognition accuracy. If the offset is too small, the feature extraction data offset is too large, the feature extraction data may have too many details that are not essential for distinguishing between different patterns. Both scenarios can impair the discrimination ability of feature extraction, leading to decreased recognition accuracy.

TABLE III indicates that selecting an appropriate wavelet filter enhances recognition accuracy. This is because the effectiveness of a wavelet filter depends on its ability to effectively separate low and high-frequency components using its LPF and HPF in a multi-resolution context. Proper separation improves feature extraction discrimination, leading to optimal recognition accuracy.

TABLE I, II, and III indicate that, generally, increasing the feature extraction length (from 1 to 8) tends to improve recognition accuracy. This indicates that up to feature extraction length 8, the feature extraction data still captures fundamental features. Utilizing these features allows for capturing the fundamental information from the input data. This information relates to the most relevant and discriminative characteristics, which helps in class separation [20]. In this work, increasing the number of fundamental features (from 1 to 8) enhances the feature extraction's discriminative capability, thereby improving recognition accuracy.

TABLE IV. PERFORMANCE COMPARISON OF FEATURE EXTRACTION METHODS

Feature Extraction Methods	Feature Extraction Length	Recognition Accuracy (%)	Chord Test Set Size
Improved PCP [2]	12	95.83	192
CRP Enhanced PCP [3]	12	99.96	4608
MFCC [5]	6	91.43	140
MFCC with Kaiser windowing [6]	4	92.14	140
DST-Wavelet [7]	4	92.86	140
DCT-DWT (this work)	**3**	**91.43**	140

Note: The displayed table presents the shortest feature extraction length to exceed 90% recognition accuracy.

C. *Performance Comparison*

TABLE IV presents a performance comparison between the proposed feature extraction method and other previous feature extraction methods. As shown in Table 4, when considering recognition accuracy above 90%, the proposed method proves to be the most efficient. The proposed method enables the recognition system to achieve a recognition accuracy of up to 91.43% using a feature extraction length of three. In comparison, the previous feature extraction methods needed to use a feature extraction length of more than three to achieve a recognition accuracy of above 90%. As a note, the results from TABLE IV, namely those in [5-7] and this work, were obtained from the same dataset.

IV. CONCLUSION AND FUTURE WORK

This work proposes a novel combination of DCT-DWT for a feature extraction method in guitar chord recognition. The method achieves a recognition accuracy of up to 91.43% using a feature extraction length of only three. This level of performance is attained with a frame blocking length of 1024, a Haar wavelet filter, and a DWT coefficient selection offset of 2.

For future work, it is recommended to explore other feature extraction methods that may offer not only higher recognition accuracy but also a feature extraction length of less than three. This ongoing exploration will contribute to optimizing the accuracy and efficiency of guitar chord recognition systems.

ACKNOWLEDGMENT

This work received support from the Institute for Research and Community Services at Sanata Dharma University, Yogyakarta.

REFERENCES

[1] T. Fujishima, "Realtime chord recognition of musical sound: a system using Common Lisp Music", Proceeding of the International Computer Music Conference (ICMC), Beijing, 1999, pp. 464–467.

[2] K. Ma, "Automatic Chord Recognition", Department of Computer Sciences, University of Wisconsin-Madison, http://pages.cs.wisc.edu/~kma/projects.html, (May 2016). (accessed Jul. 22, 2024).

[3] P. Rajparkur, B. Girardeau, and T. Migimatsu, "A Supervised Approach to Musical Chord Recognition", Stanford Undergraduate Research Journal, Vol. 15, 2015, pp. 36-40.

[4] E. Demirel, B. Bozkurt, and X. Serra, "Automatic chord-scale recognition using harmonic pitch class profiles" , Proc. Sound Music Comput. Conf. , 2019, pp. 72–79.

[5] L. Sumarno, "Chord Recognition using FFT Based Segment Averaging and Subsampling Feature Extraction," Proceeding of 8th International Conference on Information and Communication Technology (ICoICT 2020), 2020, pp. 465–469.

[6] L. Sumarno, "Guitar chord recognition using MFCC based feature extraction with Kaiser windowing", Proceeding of Transdisciplinary Symposium on Engineering and Technology (TSET 2022), Published 2024.

[7] L. Sumarno, "The performance of DST-Wavelet feature extraction for guitar chord recognition", Proceeding of The 1st International Conference on Applied Sciences and Smart Technologies (InCASST 2023), Published 2024.

[8] K. Vaca, M. M. Jefferies, and X. Yang, "An Open Audio Processing Platform with Zync FPGA", Proceeding of 22nd IEEE Int. Symp. Meas. Control Robot. Robot. Benefit Humanit. ISMCR 2019, 2019, pp. D1-2-1–D1-2-6.

[9] K. Vaca, A. Gajjar, and X. Yang, "Real-Time Automatic Music Transcription (AMT) with Zync FPGA", Proceeding of IEEE Comput. Soc. Annu. Symp. VLSI, ISVLSI, Vol. 2019-July (2019), 2019, pp. 378–384.

[10] O.K. Hamid, "Frame Blocking and Windowing Speech Signal", J. Information, Commun. Intell. Syst., Vol. 4, No. 5, 2018, pp. 87–94.

[11] H. Rakshit, and M. A. Ullah, "A comparative work on window functions for designing efficient FIR filter", Proceeding of 2014 9th Int. Forum Strateg. Technol. (IFOST 2014), July 2014, 2014, pp. 91–96.

[12] L. Sumarno, "Chord recognition using segment averaging feature extraction with simplified harmonic product spectrum and logarithmic scaling", Int. J. Electr. Eng. Informatics, Vol. 10, No. 4, 2018, pp. 753–764.

[13] A.M. Noll, "Pitch Determination of Human Speech by the Harmonic Product Spectrum, the Harmonic Sum Spectrum and a Maximum Likelihood Estimate", Proceeding of the Symposium on Computer Processing in Communications, Vol. 19, Polytechnic Press, Brooklyn, New York, 1970, pp. 779-797.

[14] M. Voelsen, D.L. Torres, R.Q. Feitosa, F. Rottensteiner, and C. Heipke, "Investigations on feature similarity and the impact of training data for land cover classification", ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci., Vol. 5, No. 3, 2021, pp. 181–189.

[15] I. Izonin, R. Tkachenko, N. Shakhovska, B. Ilchyshyn, and K.K. Singh, "A Two-Step Data Normalization Approach for Improving Classification Accuracy in the Medical Diagnosis Domain", Mathematics, Vol. 10, No. 11, 2022

[16] A.K. Jain, R.P.W. Duin, and J. Mao, "Statistical pattern recognition: A review", IEEE Trans. Pattern Anal. Mach. Intell. Vol. 22, No. 1, 2000, pp. 4–37.

[17] A. Massari, R.W. Clayton, and M. Kohler, Damage detection by template matching of scattered waves, Bull. Seismol. Soc. Am. Vol. 108, No. 5, 2018, pp. 2556–2564.

[18] H.U. Zhi-Qiang, Z. Jia-Qi, W. Xin, L.I.U. Zi-Wei, and L.I.U. Yong, "Improved algorithm of DTW in speech recognition", in Proceeding of IOP Conf. Ser. Mater. Sci. Eng., Vol. 563, No. 5, 2019.

[19] S. Sohangir, and D. Wang, "Improved sqrt-cosine similarity measurement", J. Big Data, Vol 4, No 1, 2017.

[20] H.R. Shahdoosti, and F. Mirzapour, "Spectral–spatial feature extraction using orthogonal linear discriminant analysis for classification of hyperspectral data", Eur. J. Remote Sens., Vol. 50, No. 1, 2017.