IN THIS JOURNAL

Great Britain Journals Press

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London Journal of Research in Computer Science & Technology

Volume 25 | Issue 1 | Compilation 1.0

Print ISSN 2514-863X
Online ISSN 2514-8648
DOI 10.17472/LJRCST

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COMPILED IN UNITED KINGDOM

ENGLISH

Great Britain Journals Press

London Journal of Research in Computer Science and Technology

Volume 25 | Issue 1 | Compilation 1.0

PUBLISHER

Great Britain Journals Press
1210th, Waterside Dr, Opposite Arlington Building, Theale, Reading
Phone:+444 0118 965 4033 Pin: RG7-4TY United Kingdom

SUBSCRIPTION

Frequency: Quarterly

Print subscription
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Classification of Acoustic Data with Transformer Model

Denitsa Panova-Vatcheva

Shumen University Bishop Konstantin Preslavski

ABSTRACT

Bees are essential to global ecosystems, particularly for pollinating crops, yet in recent years their populations have faced significant decline. One critical aspect of bee colony health is the ability to detect negative in-hive events such as a queen leaving the hive. Traditionally, beekeepers rely on manual inspections to assess hive conditions, a labor-intensive and time-consuming process. However, recent advances in machine learning offer new approaches to automating this task. Since 2016, there have been attempts to classify bee sounds using machine learning, employing the power of different machine learning methods, including deep learning architectures.

In this research, we explore the use of acoustic labeled data for in-hive event classification, focusing specifically on detecting when a queen leaves the hive. We utilize 12-hour recordings from different locations, with the data preprocessed and transformed to be suitable for input into a transformer based neural network. Our goal is to demonstrate that transformer models yield superior results in this task compared to previous approaches.

Keywords: NA

Classification: LCC Code: QA76.9.A25

Language: English

Great Britain Journals Press

LJP Copyright ID: 975811
Print ISSN: 2514-863X
Online ISSN: 2514-8648

London Journal of Research in Computer Science & Technology

Volume 25 | Issue 1 | Compilation 1.0

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Classification of Acoustic Data with Transformer Model

Denitsa Panova-Vatcheva

ABSTRACT

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In this research, we explore the use of acoustic labeled data for in-hive event classification, focusing specifically on detecting when a queen leaves the hive. We utilize 12-hour recordings from different locations, with the data preprocessed and transformed to be suitable for input into a transformer based neural network. Our goal is to demonstrate that transformer models yield superior results in this task compared to previous approaches. The study is organized into several key sections: we first highlight the ecological importance of bees, followed by a literature review on the state of bee sound classification research. We then delve into the data preparation process, model design, and present our findings. Our results underscore the potential of transformer models in automating hive monitoring, offering a scalable solution for beekeepers to protect and preserve bee populations.

Author: Department of Mathematics and Informatics, Shumen University "Bishop Konstantin Preslavski".

I. THE IMPORTANCE OF BEES

Bees play an essential role in global agriculture, serving as primary pollinators for a wide variety of crops. [1] Without bee pollination, the agricultural sector would suffer significant setbacks, leading to decreased crop quantity and reduced quality. In fact, numerous studies dating back to the 1990s have emphasized the critical impact of bees on crop health, particularly in crops like strawberries, where successful pollination directly correlates with higher quality and yield. [2] [3] [4] The deepening decline in bee populations threatens the ecological and economic stability of every country, underscoring the vital need to protect and sustain bee pollination services.

In recent years, there has been a noticeable and alarming decline in bee populations, which is attributable to a variety of factors. [5] These factors can be classified into two main categories: external, or outside-the-hive events, and internal, or in-hive events. External factors include the widespread use of pesticides and the aggressive spread of African killer bees, both of which pose a significant threat to local bee populations. [6] [7] In-hive events, such as swarming and the departure of the queen bee, also present challenges. Swarming can be triggered by various conditions, such as the emergence of a new queen, and can lead to the collapse of the hive if not properly managed. Such occurrences are particularly devastating for beekeepers as the entire colony may be lost. [8]

To address these challenges, this paper focuses on leveraging data-driven techniques to aid in precision beekeeping. By developing an algorithm capable of identifying harmful in-hive events, beekeepers can proactively monitor the state of their colonies and prevent destructive outcomes, such as swarming or queen loss. Recent research shows that bees communicate not only through physical movements, such as the famous "waggle dance," but also through subtle vibrations and acoustic signals. [9] [8] Different in-hive events are associated with specific sound frequencies, many of which fall outside the range of human hearing. Therefore, sound-based monitoring systems, particularly those that can detect these lower-frequency vibrations, hold great potential for beekeepers.

In this paper, we focus specifically on using labeled acoustic data to identify and prevent harmful in-hive events. By accurately recognizing sound patterns associated with swarming or the hive entering a queenless state, we aim to assist beekeepers in maintaining healthy colonies. This proactive approach to hive management not only supports the agricultural sector by ensuring consistent pollination but also contributes to broader ecological stability by helping sustain bee populations. Without a data-driven approach, manual inspections disturb the bees, potentially leading to negative consequences for their health and behavior, especially by inexperienced beekeepers.

II. RELATED WORK

The classification of bee sounds using machine learning (ML) has garnered significant attention, particularly in recent years, with most of the research occurring after 2022. This section reviews relevant studies focused on the use of acoustic data for classifying in-hive events, highlighting key methodologies and results that inform our current research.

One of the earlier works in this domain was conducted by Zgank in 2017, who explored the classification of bee sounds, particularly in the context of swarming. [10] Zgank utilized data from the Open-Source Beehives Project and applied feature engineering techniques such as Mel-Frequency Cepstral Coefficients (MFCC) and Linear Predictive Coding (LPC). The study employed Gaussian Mixture Models (GMM) and Hidden Markov Models (HMM) for classification. The best model is HMM with a 15- state using MFCC features achieving a notable F1 score of 90% for the binary prediction of a swarming event.

In 2018, Cejrowski attempted to model active bee days and identify patterns associated with the removal of the queen from the hive. [11] However, the study did not achieve satisfactory results in classifying these events using the clustering algorithm t-SNE (t-distributed stochastic neighbor embedding), which was explored as a potential classification tool.

Howard's 2013 research focused on predicting the queenless state of a hive using sound data. [12] The study transformed acoustic data into spectrograms and applied Fast Fourier Transformation (FFT) and S-transformation before utilizing a Self-Organizing Map (SOM) neural network for classification. Although the predictive results were not particularly strong, the study successfully visualized the two hive states using the neural network's output.

More recently, Rustum (2023) revisited the classification of queenless states using a combination of feature engineering methods and classification models. [13] The study found that a hybrid approach combining MFCC features with K-Nearest Neighbors (KNN) or Random Forest (RF) algorithms yielded the best results, with accuracy rates of 83% and 82%, respectively. Another study in the same year further explored the classification of queenless states using MFCC for feature engineering and logistic regression with Lasso for feature selection, achieving a 95% accuracy in distinguishing bee sounds associated with the queenless state. [14]

Beyond hive conditions, researchers have also explored the classification of bee species based on their flying sounds. In 2021, Ribeiro applied support vector machines (SVM) combined with MFCC to distinguish between different types of bees and other insects, achieving an accuracy of 73.39%. [15] This research aimed to correlate the types of bees pollinating tomato plants with the quality of the resulting fruit.

In 2023, Di conducted a comparative study on feature engineering methods for bee sound

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recognition.[16] The study compared two feature engineering approaches - a convolutional neural network (CNN) hidden layer and MFCC. Four different machine learning algorithms (RF, SVM, KNN, Decision Trees) were tested across three datasets. The CNN layer consistently outperformed MFCC, with the best model—KNN with CNN feature engineering—achieving a 94.79% accuracy rate.

Another study in 2023 by Ruvinga focused on the classification of queenless states using MFCC features as inputs to a Long Short-Term Memory (LSTM) classifier and spectrograms as inputs to CNNs. The CNN-based approach achieved a remarkable accuracy of 99%. [17]

In addition to these approaches, a novel study in 2023 applied Log Mel-Spectrograms and CNN EfficientNet V2 with Pre-trained Audio Neural Networks (PANNs) to recognize different bee species. This study introduced a data augmentation step and achieved an F1 score of 58.04%. [18]

Lastly, in 2021, Benetos annotated an acoustic dataset with labels indicating the presence or absence of bee sounds and tested SVM and CNN algorithms to predict hive events like swarming. [19] The results, however, were not satisfactory.

In conclusion, the literature indicates that researchers have explored both classical machine learning approaches, such as Random Forest and Support Vector Machines, as well as more advanced neural network models, particularly CNNs, for the classification of bee sounds. These efforts lay a solid groundwork for our research, which focuses on further refining sound classification methods for detecting in-hive events and enhancing accuracy using a specific type of neural network—a transformer—an approach not previously explored in other studies.

III. DESING OF THE EXPERIMENT

The design of the experiment follows a systematic approach to classify bee sounds into three categories: ‘active day,’ ‘queenless,’ and ‘queen present.’ The process begins by utilizing an already labeled dataset, which is then cleaned to remove silence and ensure all recordings are of uniform length. This step is crucial for standardizing the data, making it suitable for further analysis and modeling.

To enhance the dataset and introduce greater diversity, data augmentation techniques are applied. This step artificially increases the number of data points, providing a richer and more varied training set that helps improve model performance and reduce the risk of overfitting.

Given that the overarching goal of this experiment is to train a transformer model, the subsequent step involves partitioning the dataset into distinct training and testing subsets. This partitioned data must then be meticulously converted into a data dictionary format, which is the required input structure for compatibility with HuggingFace's transformer models. This transformation ensures that the data is optimized for efficient processing, allowing the model to effectively learn and generalize from the training data while being rigorously evaluated on the test set.

The final phase of the experiment involves training a model to classify the bee sounds. Neural networks, particularly CNNs, have been identified as the most promising models in previous research. To the best of the authors' knowledge, transformer models have not yet been explored for this specific task. In this experiment, we employ the HuBERT model, which incorporates CNN layers, and fine-tune a pretrained version of the model using the augmented and original datasets, leveraging its prior knowledge to improve classification accuracy.

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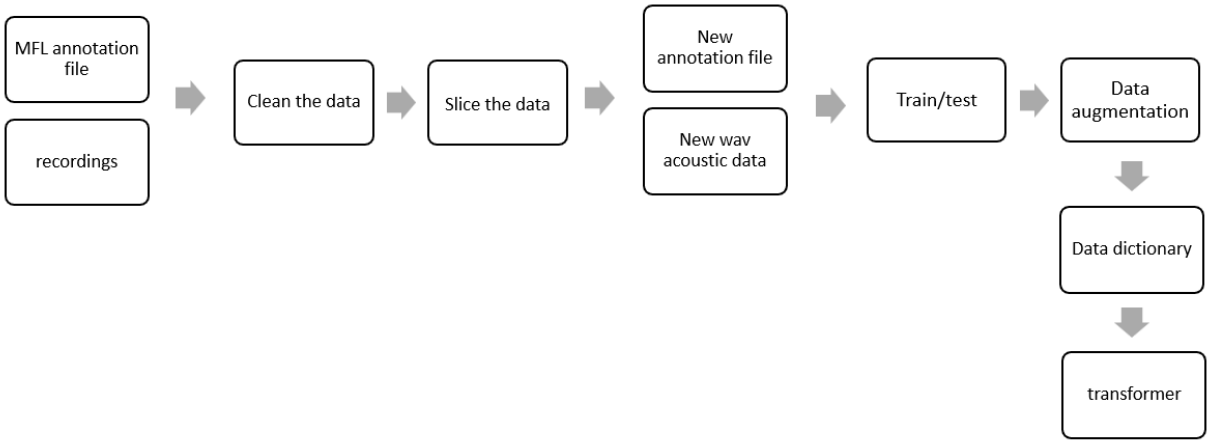

Figure 1: Design of the Experiment

IV. DATA

4.1 Raw Data

The raw data used in this study originates from the research titled "To bee or not to bee: Investigating machine learning approaches for beehive sound recognition." [19] This dataset consists of 78 annotated audio files in three formats: WAV, MP3, and LAB. However, for the purposes of this paper, we focus exclusively on the WAV and MP3 files, as the LAB format is tied to specific software that may not be readily accessible to the broader machine learning community. The annotations within these files capture various states of the beehive, including active beehive days, queenless states, and states with a present queen, with a total duration of 12 hours of recordings. Figure 2 provides a visual representation of how the files are labeled.

```
CF001 - Missing Queen - Day -
0       11.25   bee
11.26   11.52   nobee
11.53   15.4    bee
.
CF003 - Active - Day - (214)
0       7.3     bee
7.31    7.87    nobee
7.88    10.37   bee
10.38   10.63   nobee
10.64   15.64   bee
15.65   17.32   nobee
17.33   20.93   bee
20.94   28.96   nobee
28.97   33.01   bee
33.02   36.43   nobee
36.44   37.65   bee
37.66   44.42   nobee
44.43   49.98   bee
49.99   58.07   nobee
```

Figure 2: Snippet of the MFL File with Annotations

Each audio file is meticulously segmented into portions where bee sounds are either audible or not. These segments are documented in text files with an MFL extension, which contain start and end timestamps corresponding to "Bee" or "NoBee" labels. The acoustic data was gathered through two projects, "Open Source Beehive" (OSBH) and "NU-Hive," conducted across diverse geographical locations including North America, Australia, and Europe. This global data collection approach ensures that the results of the classification efforts are not biased by local

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environmental sounds or the behaviors of specific bee species, thereby enhancing the generalizability of the findings.

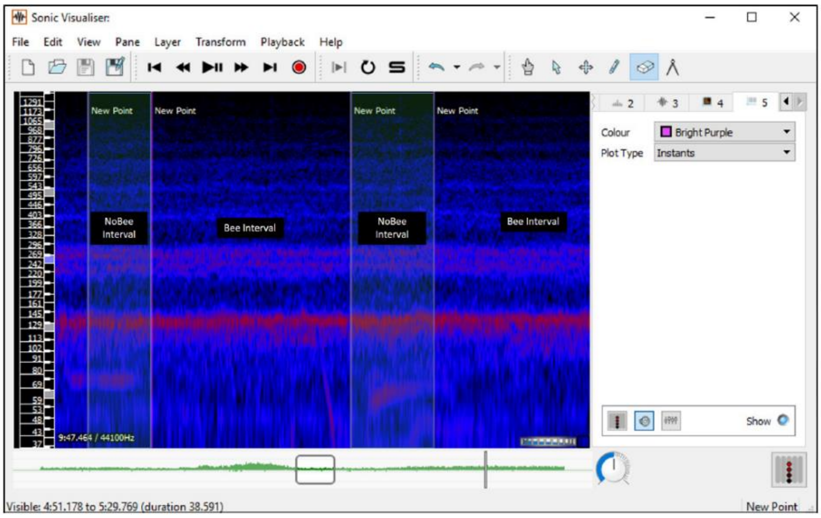

Figure 3: Bee and NoBee Labeling Process [20]

4.2 Data Cleaning

The data cleaning process is crucial in preparing the raw dataset for the modeling phase. Initially, the annotated dataset contains 2,420 rows of labeled data, where each row represents a segment of audio labeled as either "active day," "missing queen," or "queen present," corresponding to the filenames. The first step in the cleaning process involvestransforming the MFL text file into a standard Pandas DataFrame, making it easier to manipulate and analyze. (Table 1)

Table 1: Structured Annotation Data from the MFL File

Start	End	Label	File Name
0	11,25	bee	CF001 - Missing Queen - Day -
11,26	11,52	nobee	CF001 - Missing Queen - Day -
11,53	15,4	bee	CF001 - Missing Queen - Day -
0	7,3	bee	CF003 - Active - Day - (214)
7,31	7,87	nobee	CF003 - Active - Day - (214)
7,88	10,37	bee	CF003 - Active - Day - (214)

To ensure the dataset is relevant for modeling, we first remove all rows where no bee sounds are present (i.e., rows labeled as "nobee"). Following this, we eliminate any rows where the duration of the audio segment is less than 5 seconds, as shorter durations may not provide sufficient information for reliable classification. This filtering process reduced the dataset to 679 rows.

However, these remaining rows vary in duration, which pose a challenge for the machine learning algorithms, as they typically require uniform input lengths. To address this, the 679 rows are further split into 5-second intervals, and each interval is saved as a separate WAV file. A new annotation file is then created, mapping each 5-second interval to its corresponding label. (Table 2)

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Table 2: Snippet of the Updated Annotation Data

Index	Index_original_file	Start	End	Label	Start_sliced	End_sliced
0	1	0	11,25	bee	0	5000
1	1	0	11,25	bee	5000	10000
2	6	0	7,3	bee	0	5000
3	18	44,43	49,98	bee	44430	49430

This process not only cleans the dataset but also standardizes the audio segments, making them more suitable for input into machine learning algorithms. As a result, the structure of the dataset shifted from a collection of multi-length segments to a larger, more uniform set of 5-second audio files, ready for effective modeling. Table 3 presents a concise summary of the cleaned dataset, highlighting data quantity after preprocessing. Notably, these specific cleaning and processing steps are not documented in the original article "To bee or not to bee: Investigating machine learning approaches for beehive sound recognition", representing an enhancement in our approach.

Table 3: Cleaned Data Summary

Actions	Sum Duration	Count Rows
active day	7327,38	395
missing queen	13895,06	1178
queen	8379,4	480

4.3 Data Augmentation

Before transforming the audio data into a format which is suitable for training Transfomer model, it is advantageous to perform data augmentation, a step that is often overlooked but can significantly enhance model performance. As mentioned in one of the papers in the related work, the authors observed an increase in model accuracy after incorporating data augmentation, highlighting its importance.

The primary objective of data augmentation is to artificially expand the dataset by generating new examples from the existing labeled data. This process is especially crucial when dealing with limited datasets, as it provides the machine learning algorithm, particularly neural networks, with more input data. Additionally, data augmentation introduces variability into the dataset, which helps prevent the model from overfitting to the original training data and enhances its generalization capabilities. [21] [22]

For acoustic data, the Python library `audiomentations` is commonly used for this purpose. [23] In this study, four different augmentation techniques were applied randomly, each with a 50% probability of being applied to any given audio sample from the train data set:

1. *Add Gaussian Noise:* This method introduces Gaussian noise to the audio signal, with a maximum amplitude of 0.015 and a minimum of 0.01, simulating the effect of random background noise.
2. *Tanh Distortion:* The tanh function is applied to the audio signal to slightly distort and smoothen the recording, mimicking the natural variations that might occur during real-world recordings.

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3. *Gain Transition:* This technique randomly increases or decreases the sound volume in logarithmic intervals, simulating natural changes in volume, such as a bee moving closer to or farther from the microphone.
4. *Air Absorption:* This filter simulates environmental effects like moisture and air absorption, which can subtly alter the audio signal, making the dataset more representative of real-world conditions.

$$att = \exp\left(-distance * absorption\ coefficent\right)$$

In the above equation, distance is the distance to the recording microphone and the absorbing coefficient is the ability of the microphone to record.

By incorporating these augmentation techniques, the dataset becomes richer and more diverse, providing the model with a broader range of examples to learn from, ultimately leading to better performance and robustness in real-world applications. In this experiment, the data size for the training data has been doubled using the above-mentioned data augmentation techniques.

4.4 Data Dictionary

The HuggingFace Transformer model necessitates a specific data format known as a data dictionary for effective training. This format is based on Apache Arrow, a memory-efficient data structure designed for high-performance analytics. [24]

While Python provides an existing implementation to transform data from a Pandas DataFrame to a data dictionary, this conversion process is computationally intensive and time-consuming. To optimize performance and prevent hardware failures given the current experimental setup, parallelization of the transformation process (specifically, row-by-row transformation) is required. The structure of the data dictionary is as follows:

```
{"dataset": "cornell-movie-review-data/rotten_tomatoes",
 "config": "default",
 "split": "train",
 "features": [{"feature_idx": 0,
   "name": "text",
   "type": {"dtype": "string",
   "id": null,
   "_type": "Value"}},
  {"feature_idx": 1,
   "name": "label",
   "type": {"num_classes": 2,
    "names": ["neg", "pos"],
    "id": null,
    "_type": "ClassLabel"}}],
  ...
 }
```

Figure 4: First row from the data dictionary Totten Tomatoes. [25]

The data dictionary specifies the dataset source and the data split, indicating whether the subset is used for training or testing. Within the features section, each column of the dataset is individually detailed, including information about its format and data type. For this exercise, the dataset was divided into training and testing subsets, with 80% allocated to training and 20% to testing, using stratified sampling based on the labels to maintain proportional representation across the splits. The transformation into the data dictionary format is performed after the data augmentation stage, ensuring that the cleaned, split, and augmented data is properly structured for use with the Hugging Face Transformer models. The graph below illustrates the final state of the data, showcasing how the cleaned, split, augmented, and transformed dataset appears. This concludes the data preparation section of this paper.

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```
>>> data
DatasetDict({
    train: Dataset({
        features: ['audio', 'train_index', 'file_index', 'label', '__index_level_0__'],
        num_rows: 5648
    })
    test: Dataset({
        features: ['audio', 'train_index', 'file_index', 'label', '__index_level_0__'],
        num_rows: 961
    })
})
>>>
```

Figure 5: Data Dictionary

V. TRANSFORMER

In this section, following an overview of the data and the transformation processes required to prepare it for input into the HuggingFace transformer model, we provide a concise explanation of the transformer's design, with a particular emphasis on the feature engineering components. Additionally, we discuss the advantages of utilizing a pre-trained model, the rationale behind this approach, and the specific model chosen for the task.

5.1 Overall Architecture

In this paper, we leverage a transformer model, originally developed for sequence-to-sequence tasks like text translation, to classify bee sounds. It has demonstrated remarkable success in the domain of text-related tasks. [26] Transformers offer a significant advantage by combining the strengths of Recurrent Neural Networks (RNNs) and Convolutional Neural Networks (CNNs), enabling them to model sequential data effectively while being computationally efficient due to their parallel execution capability. A key innovation in transformer models is the Attention mechanism, which allows the model to capture relationships between both closely related and distant elements in the sequence. [26] This is particularly useful for understanding complex patterns not only in text but also in audio data, where distant dependencies might be as critical as immediate ones. The Attention component enables the model to weigh the importance of different parts of the audio sequence, allowing it to focus on key segments that are more relevant for the classification task, such as specific bee sounds that indicate different hive states Another critical component of transformers is positional encoding, which preserves the order of inputs—such as the sequence of words in text or phonemes in audio—across the entire network. This ensures that the model not only understands the content but also the context provided by the sequence or the acoustic file.

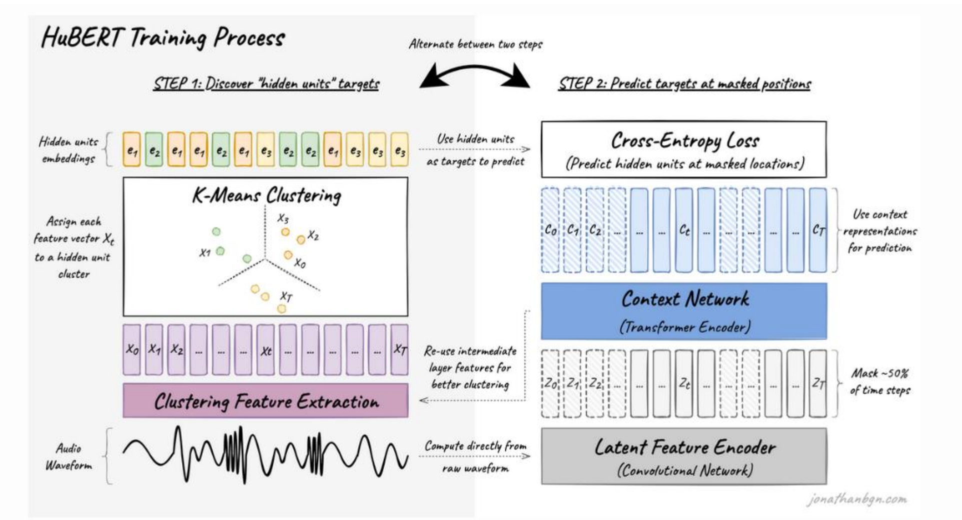

Figure 6: HuBERT Architecture [27]

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In 2020, the transformer model was modified for the first time to accept acoustic data as input, rather than textual data, demonstrating outstanding performance in this domain of machine learning. [28] The specific transformer model used in our research is HuBERT (Hidden Units Bidirectional Encoder Representations from Transformers), a variant designed to process audio data. HuBERT is based on the BERT model, which utilizes only the encoder part of the original transformer architecture. [27] Figure 6 presents a visual representation of the architecture of the HUBERT model.

The architecture of HuBERT comprises several key components, some of which align with the standard transformer structure previously described. The HuBERT-specific elements are detailed briefly below:

- Convolutional Network – Following the extraction of Mel-Frequency Cepstral Coefficients (MFCC) features from the input data—detailed extensively in the subsequent section—these features are processed through a CNN layer. The purpose of this step is to capture local patterns, such as sound frequencies, as well as the hierarchical structure inherent in the data. The resulting output consists of transformed vectors - latent features.
- Transformer encoder – Those latent features are then passed to transformer encoder. Unlike other transformer models that process input in a sequential manner, the encoder in HuBERT is bidirectional, meaning it can attend to information from both past and future contexts simultaneously. This bidirectionality is crucial for capturing the complex temporal dependencies present in audio data, allowing the model to understand the full context of the sound sequence.
- K-means clustering – the unsupervised approach is used to group different audio segments together as latent labels, capturing sound patterns in the data. The model is then trained to predict the cluster assignments, which helps in learning robust representations of the audio data even before the labeled data is introduced.

5.2 Feature Engineering

In the transformation of audio data for machine learning applications, Mel-spectrograms and Mel Frequency Cepstral Coefficients (MFCC) are two of the most widely employed feature engineering techniques. HuBERT uses MFCC as the feature engineering method. Both techniques are grounded in the Fourier Transform, a mathematical method that converts time-domain signals into their frequency-domain representations. [29] This transformation is crucial for analyzing the spectral content of audio, which is essential for tasks like sound classification.

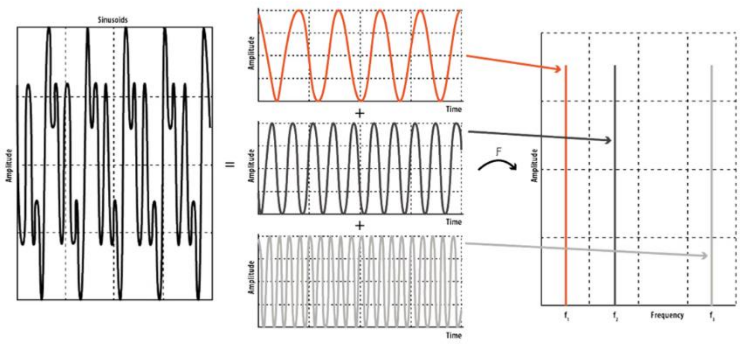

Figure 7: FFT Transformation

When audio is digitized, it is typically sampled at a rate of 44,100 samples per second, capturing the amplitude of the sound wave at discrete time intervals. The Fast Fourier Transform (FFT) is then applied to this sampled data, decomposing the complex audio signal into its constituent

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sinusoidal components—specifically, sine and cosine waves. [21] This decomposition allows us to analyze the frequency components of the signal. (*Figure 7*) However, one of the underlying assumptions of FFT is that the signal is stationary and repetitive, which is rarely true for natural sounds.

To address this limitation, the audio signal is first segmented into overlapping time windows, often using a window function like the Hamming or Hann window to minimize spectral leakage. FFT is then applied to each windowed segment individually. This process, known as Short-Time Fourier Transform (STFT), allows the analysis of how the frequency content of the signal evolves over time. To better align the frequency representation with human auditory perception, the resulting frequency values are then mapped onto the Mel scale, a perceptual scale of pitches judged by listeners to be equal in distance from one another. This transformation yields the Mel-spectrogram, where frequencies are represented on a logarithmic scale, reflecting the human ear's reduced sensitivity to lower frequencies. [30] The equation below demonstrates the calculation of the Mel-spectrogram:

$m = 2595 log_{10}\left(1 + \frac{f}{700}\right)$, *log is the natural logarithm with base 10 and f is the frequence frequence in Hz.*

Mel-Frequency Cepstral Coefficients (MFCC) take this process a step further. After obtaining the Mel-spectrogram, the log-magnitude of each Mel-frequency band is computed. These values are then subjected to a Discrete Cosine Transform (DCT), which decorrelates the Mel-spectrogram's frequency components and compacts the most significant information into a small number of coefficients. The first few coefficients typically capture the bulk of the relevant information, making MFCCs an efficient and effective representation of the audio signal for machine learning tasks.

Both Mel-spectrograms and MFCCs are essential for transforming raw audio data into structured features that can be readily processed by machine learning models. By capturing both the temporal and spectral characteristics of the sound, these techniques enable the development of robust algorithms for audio classification and other related applications.

5.3 Pretrained Models

In this paper, we utilize a pretrained HuBERT model from the Hugging Face platform, specifically the `hubert-base-ls960` model, which has been trained on a diverse dataset of animal sounds, including those of cats and dogs. [31] Hugging Face is a leading platform for research collaborations on transformer models. It provides a robust ecosystem for implementing these state-of-the-art pre-trained models, making it an ideal choice for this experiment. [32] Utilizing pre-trained model has a lot of advantages. It is environmentally friendly, as it reduces the computational resources required for training a model from scratch. [31] It also saves time and requires less data, making it particularly suitable for tasks with limited datasets. The pretrained HuBERT model comes with a well-learned understanding of general audio patterns, which can be fine-tuned for specific tasks like bee sound classification. This approach not only accelerates the training process but also enhances the model's ability to generalize from the provided data.

VI. RESULTS

The results of our experiment demonstrate a significant breakthrough in the field of acoustic classification of bee sounds, achieving an unprecedented accuracy of 99.7%. This marks the highest accuracy reported in the literature for this type of problem, indicating the robustness and effectiveness of our approach. The model's exceptional performance underscores the advantages of leveraging the HuBERT architecture, particularly when fine-tuned with augmented and diverse datasets. The code for the experiment is wrapped into a Python library and shared in GitHub repository. [33]

After training, which took approximately seven hours on a system equipped with a 13th Gen Intel (R) Core (TM) i7-13700H processor (20 CPUs, ~2.4 GHz) and 32GB of RAM, the model is

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well-suited for deployment in real-world applications. For practical implementation, the trained model can be integrated with platforms like Weights & Biases, which facilitates hosting and managing the model for live predictions. In a real-world scenario, a Raspberry Pi or similar device with the appropriate microphones and sensors attached can be installed within a beehive to record the acoustic environment continuously. [34] This data can then be transmitted to the cloud, where the model processes it and provides real-time insights into the hive's state.

This integration of advanced machine learning techniques with accessible hardware and cloud platforms represents a promising direction for precision beekeeping, enabling beekeepers to monitor and respond to hive conditions with unprecedented accuracy and timeliness.

VII. CONCLUSION

This study explores the application of transformer models to classify bee acoustic data, focusing on detecting significant hive events such as the departure of the queen. By employing the HuBERT model, which is adapted from text-based transformer architectures, we achieved an accuracy of 99.7% in identifying hive conditions. This represents a substantial improvement over previous methods and illustrates the potential of advanced machine learning techniques in ecological monitoring.

The integration of HuBERT with labeled acoustic data and data augmentation strategies has demonstrated exceptional performance, paving the way for more efficient hive monitoring. This approach not only streamlines the process for beekeepers but also enhances the ability to respond promptly to critical hive events. Future research could expand on these findings by applying the model to various bee species and environments, potentially leading to even greater advancements in precision beekeeping and ecological management.

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Classification: LCC Code: QA76.9.D343

Language: English

Great Britain Journals Press

LJP Copyright ID: 975812
Print ISSN: 2514-863X
Online ISSN: 2514-8648

London Journal of Research in Computer Science & Technology

Volume 25 | Issue 1 | Compilation 1.0

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ABSTRACT

The dataset of competitors' performance in some recent years is the input of winner-domain algorithm selecting good student as member of a subject team participating in Vietnam national prize. The data of learning performance features may be retrieved from the competitors' learning outcomes. Meanwhile, the collection of non-learning performance feature data of competitors meets challenges relating to the individual right and interviewees' cooperation for answering questionnaire. This research analyzed competitors' skills and lifestyle into very simple questions with very easy answer mode, without the deep relation to their individual lifestyle. The reply-matrix and reply-cube are formed to map simple answers of questionnaire reply into quantitative values. This approach may be flexibly applied to easily form the datasets of competitors' performance for various subjects in different years and at different levels of competitions.

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I. INTRODUCTION

Beginning new school year, the leaders of high schools set up teams of subjects (subject teams), each of which is assigned to a teacher who acts as the team coach. The coach of a subject team sets up the team by choosing good students of the school as teamers (member of team) and deeply trains them before participating in national competitions.

Traditionally, the subject coach tests the good students of 11th and 12th grades to select the best students for his/her team. In some recent years, each teamer winning a national prize (winner) not only obtains the worth awards by the ministry, the province, the school but also is welcomed to enter big universities with high grant. Accordingly, the selection of teamers for subject teams becomes a big pressure towards subject coaches.

So far, the coaches of teams remain the traditional approach to find out teamers. Their feelings and students' learning outcomes indicate students for them to select. This selection is generating some negative problems. The winner-domain approach to objectively selecting teamers participating in National Prizes is developed according to the Vietnamese proverb "A man is known by the company he keeps" [1]. In other words, the winners of the same prize are similar in performance, including learning and non-learning performance.

The input of winner-domain algorithm is the dataset of competitors' performance features [1]. The learning performance features can be retrieved from the database of learning outcomes. Meanwhile, the non-learning performance data of competitors is a great challenge to coaches applying winner-domain algorithm for selecting teamers. The problem to reveal is how to adequately collect competitors' data of non-learning performance without offending their private life.

Moreover, the characteristics of some subject prize is different from another subject, from another time, and from another location. This research proposes a smart approach to setting up various datasets for selecting teamers participating in different prizes, without offending private life as well as not taking much time of interviewees. The idea to solve the challenges is to form the reply-matrix to transform the very simple answers of interviewees into numbers to set up smart dataset.

The article is structured as follows. The 2nd section reviews the performance features, especially non-learning performance including skills and lifestyle. The 3rd section proposes the approaches reply-matrix and reply-cube to collecting and processing competitors' data of non-leaning performance. The 4th section results in the dataset as a multivariable data table of competitors' non-learning performance. Finally, the conclusion in the 5th section summarizes the result of the research.

II. PERFORMANCE FEATURES

In the face of exam problem in the context of national excellent student competition, competitor is under intense pressure to solve challenging exam questions within limited time. In reality, some competitors of better learning performance may still fail due to factors beyond knowledge alone. It is considered that the competitors who win prizes not only have better learning performance but also possess good non-learning performance. In addition to academic knowledge, the skills, attitude and behavior are also the factors necessary for competitors' success [2-4].

For doing exam problems, competitors not only mobilize their own knowledge, but also automatically utilize skills necessary to cognize, thoroughly understand the challenges of the problem to defeat their obstacles as well as overcome unusual impacts from outside. The skills of passion, self-teaching, self-confidence, cognition, critical thinking, creative thinking, time management and the lifestyle affects competitors' behavior while doing exams. This research studies the non-learning factors impacting competitor's result.

2.1 Skills

The students' skills are not only native and heritable [5] but also affected by education, familial and social environment [1]. While doing exam problems, competitors face a number of pressure not only from the challenges of the problems, but also from the family, school, and social relations. Accordingly, they need possess necessary skills to overcome challenges of exam problems, potential facts, and their mentality.

Passion [6]. Winners of a competition are students who have had strong desire to take part in competition and win prize. Everyday, they can ignore other works to take all time for solving difficult problems of competition subject.

Self-Teaching [7, 8]. Winners of a competition are students proactive in learning to develop knowledge. Competitors are always passionate about academic issues of the subject, they self-motivate their learning, self-finding documents, self-discover new topics and approaches to solve new difficult problems.

Self- Confidence Skill [9]. The self-confidence skill enables competitors to deal with the challenge of exam problem. A competitor of high self-confidence may result in haughtiness and easily fail at competition. A competitor need own self-confidence skill without haughtiness.

Cognitive Skill [5, 10-15]. The cognitive skill enables competitors to acquire and process data from real world by the senses. The cognitive skill refers to the progress transforming information into knowledge to store in long-term memory, to the activities of storing and retrieving knowledge in the memory. Students of higher cognitive skills are more likely to achieve better results in learning. Competitors need possess good cognitive skill to well understand exam problems and recognize their challenges.

Critical Thinking Skill [15-20]. The critical thinking skill enables competitors to well understand a matter by reasoning, analyzing,

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evaluating, and commenting in the light of some perspective or theory relating to usual or unusual questions, situations and problems. A well critical thinker owns the skill receiving all various views on some matter to find out the answer most suitable for his decision. Competitors apply critical thinking skill to well understand exam problems and right recognize their challenges.

Creative Thinking Skill [16, 21-24]. The creative thinking skill enables competitors to generate new ideas for better making something or better processing an existent matter with a different and nontraditional approach. In most cases, the skills of creative thinking and critical thinking together with the activities of identifying, evaluating, analyzing and synthesizing, reasoning generate or develop new ideas to solve complex problems. In the face of hard exam problem, competitors concurrently mobilize critical and creative skills to generate the best solution.

Time Management Skill [25]. The time management skill refers to competitors' utilization of time while doing exam problems. The time management skill assists competitors in designing the reasonable plan to best solve the whole exam problem within the limited time frame.

2.2 Lifestyle

At high schools, competitors have been deeply trained at least one year before competition. Personal customs and family life strongly impact on the competitors' preparation for the mentality facing exam problems in competition context. Accordingly, the competitor's lifestyle is also considered as important factors affecting competition result.

Daily Time Usage [25]. Competitors are necessary to balance the amount of time spent on learning and relax with a reasonable timetable. Before competition, competitors have spent daily time in increasing academic knowledge, strengthening skills facing the possibilities of exam problems, and keeping reasonable relax time, concurrently. A competitor who has not the capacity for reasonable utilization of daily time is difficult to win prize.

Family Life [25]. The family life has strongly affected competitors' increase in knowledge, skills to prepare for participating in examination. The good learning tradition and kind interest of family morally encourage competitors in winning prize. The family of high income has the great capacity for assisting competitors in deeply training and participating in prizes.

Love. In reality, some event on competitor' love may affect his/her exam result. A competitor unlucky in love is very difficult to win prize at competition.

III. COLLECTION AND PROCESSING OF PERFORMANCE DATA

The competitor's performance is mathematically represented as a multivariable vector in multidimensional performance space, including learning feature variables and non-learning feature variables. The dataset applied for the winner-domain algorithm is a set of performance vectors of competitors belonging to the same subject of a prize. This article proposes an approach to form the non-learning performance dataset of competitors, including winners and non-winners of Vietnam national prizes on a subject for some recent years.

3.1 Questionnaires

Each year, the national excellent student competition in Vietnam is organized with various subjects such as information, mathematic, physic, chemistry, language, history, geography, and so on. The competitors are asked about knowledge and skills suitable for each yearly subject. The winner-domain approach may be applied for prizes of various subjects, each application for a subject of a prize in a year need a suitable dataset. The datasets applying for competitions of different subjects in different years at different levels are different.

In reality, it is impossible to collect the data of competitors' performance features by testing. With the respect of interviewees' personal life, this research has collected data by questionnaire with very simple questions and the request for very easy feedback. The non-learning performance

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features are analyzed into several simple questions not deeply referring to personal life of interviewees, each of which is studied as a performance factor and represented as a performance variable. The questionnaire is sent to some competitors of national prizes in two recent years.

The questions are flexibly edited based on editor's cognition about the relation between performance factors and life activities, the position of prize (province or nation) as the importance of the prize, the year and the subject of the competition. Each questionnaire can be edited with a number of suitable questions. Each question of questionnaire is composed of several responses with the symbols of a, b, c, d, e, f, g, h, i which interviewees can easily understand and fast answer by signing a simple tic symbol (X) to the convenient response.

3.2 Reply-Matrix

This research proposes the reply-matrix approach to processing the interviewees' replies of questionnaires. Reply-matrix is designed as a data table (Table 1), of which each line is in proportion to a question, each column is in proportion to responses of questions. This approach transforms each questionnaire reply into a reply-matrix as the table 1. Each questionnaire reply is mapped into a reply-matrix, where each response with the answer of X is assigned the number 1 to the corresponding position on the reply-matrix. The responses without answer are assigned the number 0 to the corresponding positions on the reply-matrix.

Table 1: Reply-matrix of the interviewee m | m=1,2,..,M

Questions	Responses of the interviewee m								
1	a_1^m	b_1^m	c_1^m	d_1^m	e_1^m	f_1^m	g_1^m	h_1^m	i_1^m
...	...	...	...	...	...	...	...	...	...
s	a_s^m	b_s^m	c_s^m	d_s^m	e_s^m	f_s^m	g_s^m	h_s^m	i_s^m
...	...	...	...	...	...	...	...	...	...
S	a_S^m	b_S^m	c_S^m	d_S^m	e_S^m	f_S^m	g_S^m	h_S^m	i_S^m

3.3 Reply-Cube

The model of reply-cube is formed to process all questionnaire replies. All reply-matrices of M interviewees are joined as a cube (Figure 1). Each line is in proportion to a performance variable $F_s|s{=}1,..,S$ and each column is in proportion to a value $f_{s.\beta} \in [0,10] \subset R|\beta{=}1,2,..\}$ of performance variables.

$$F_s = \{f_{s.\beta} \in [0,10] \subset R|\beta{=}1,2,..\} | s{=}1,..,S \quad (1)$$

The values $\{f_{s.\beta}|\beta{=}1,2,..\}$ of the performance variable $F_s|s{=}1,..,S$ is calculated as follows.

$$f_{s.1} = \frac{\delta}{M}\sum_1^M a_s^m \mid a_s^m \in \{0,1\} \mid m = 1,2,..,M; s = 1..,S \quad (2)$$

$$f_{s.2} = \frac{\delta}{M}\sum_1^M b_s^m \mid b_s^m \in \{0,1\} \mid m = 1,2,..,M; s = 1..,S$$

$$f_{s.3} = \frac{\delta}{M}\sum_1^M c_s^m \mid c_s^m \in \{0,1\} \mid m = 1,2,..,M; s = 1,..,S$$

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$$\mathrm{f}_{s.4} = \frac{\delta}{M}\sum_{1}^{M} d_s^m \mid d_s^m \in \{0,1\} \mid m = 1,2,..,M; s = 1,..,S$$

$$\mathrm{f}_{s.5} = \frac{\delta}{M}\sum_{1}^{M} e_s^m \mid e_s^m \in \{0,1\} \mid m = 1,2,..,M; s = 1,..,S$$

$$\mathrm{f}_{s.6} = \frac{\delta}{M}\sum_{1}^{M} f_s^m \mid f_s^m \in \{0,1\} \mid m = 1,2,..,M, s = 1,..,S$$

$$\mathrm{f}_{s.7} = \frac{\delta}{M}\sum_{1}^{M} g_s^m \mid g_s^m \in \{0,1\} \mid m = 1,2,..,M; s = 1,..,S$$

$$\mathrm{f}_{s.8} = \frac{\delta}{M}\sum_{1}^{M} h_s^m \mid h_s^m \in \{0,1\} \mid m = 1,2,..,M, s = 1,..,S$$

$$\mathrm{f}_{s.9} = \frac{\delta}{M}\sum_{1}^{M} i_s^m \mid i_s^m \in \{0,1\} \mid m = 1,2,..,M, s = 1,..,S$$

The number δ is customized to standardize the values of $\mathrm{f}_{s.\beta} \mid \mathrm{f}_{s.\beta} \in [0,10] \subset \mathbb{R} \} \beta=1,2,..|s=1,..,S$.

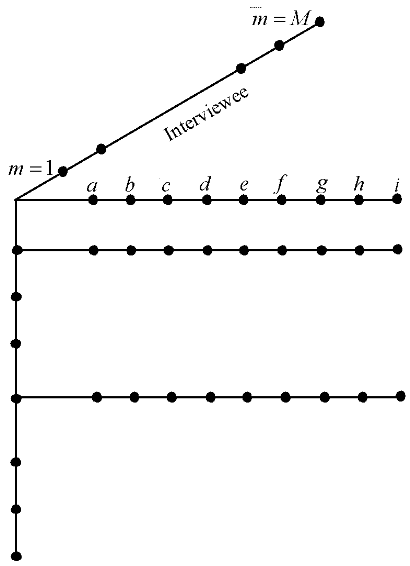

Fig. 1: Reply-cube to define the performance variables and determine the performance vectors of interviewees.

IV. SMART DATASET OF NON-LEARNING FEATURES

4.1 Performance Vector

The non-learning performance of an interviewee or a student $m \mid m = 1,..,M$ is represented as a vector $\vec{\mathrm{F}} = (\mathrm{f}_1 ,..,\mathrm{f}_S^m)|m = 1,2,..,M$ which is determined as follows.

$$\mathrm{f}_s^m = a_s^m.\mathrm{f}_{s.1} + b_s^m.\mathrm{f}_{s.2} + c_s^m.\mathrm{f}_{s.3} + d_s^m.\mathrm{f}_{s.4} + e_s^m.\mathrm{f}_{s.5} + f_s^m.\mathrm{f}_{s.6} + g_s^m.\mathrm{f}_{s.7} + h_s^m.\mathrm{f}_{s.8} + i_s^m.\mathrm{f}_{s.9}$$

$$\text{for } s = 1,..,S \mid m = 1,..,M \qquad (3)$$

4.2 Smart Dataset

The dataset is formed as a data table of interviewees' performance vectors

$$\vec{F}^{m} = (f_1^m, .., f_S^m) | m = 1, 2, .., M \quad (4)$$

Table 2: The dataset of interviewees' performance variables

Interviewee	Performance variables s						
m = 1	f_1^1	...	...	f_s^1	...	...	f_S^1
...		...	...	...	...	...	...
m	f_1^m	...	...	f_s^m	...	...	f_S^m
...	...	...	...	...	...	...	...
m = M	f_1^M	...	...	f_s^M	...	...	f_S^M

V. CONCLUSION

The approaches of reply-matrix and reply-cube enable to set up the non-learning dataset of competitors for winner-domain algorithm selecting teamers participating in excellent student prize for each subject, each year and each level. These approaches collect the data on non-learning performance features of competitors by questionnaires with simple questions and responses easy to answer.

Winners of a prize own performance features suitable for the subject, the year and the level of the competition. The mapping of questions of questionnaire to performance variables customizes the dataset for applying winner-domain approach to various competitions. The reply-matrix and reply-cube are flexible approaches to smartly form the input dataset of winner-domain algorithm.

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Advancement in Autonomous Navigation in Space through Artificial Intelligence: A Systematic Review

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ABSTRACT

Since the first trip to Mars, rovers have been used to conduct scientific experiments. The use of rovers continues to date due to Mars being uninhabitable for humans at its current state and time. Despite the invention of Mars rovers, many limitations have been challenging space exploration, even with improvements in the Curiosity and Perseverance rovers. This study aimed to investigate the advancement in autonomous navigation in space through artificial intelligence. The study used qualitative, desktop, and systematic review research designs. The study's objectives were to determine the types of autonomous navigation technologies in space and examine the role of artificial intelligence in autonomous navigation technologies. Data was collected from secondary sources, which were purely open-access online journals. A total of 61 journals were searched as the target population. The study then conducted judgmental sampling. The Preferred Reporting Items for Systematic Reviews and meta-analysis guidelines guided the sampling process, yielding a sample of 9 out of 61 journals.

Keywords: advancement, autonomous navigation, space, artificial intelligence, mars, rovers.

Classification: LCC Code: TL795.7

Language: English

Great Britain Journals Press

LJP Copyright ID: 975814
Print ISSN: 2514-863X
Online ISSN: 2514-8648

London Journal of Research in Computer Science & Technology

Volume 25 | Issue 1 | Compilation 1.0

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Advancement in Autonomous Navigation in Space through Artificial Intelligence: A Systematic Review

Aida Ildirimzade[α] & Prof. Pietro Lio[σ]

ABSTRACT

Since the first trip to Mars, rovers have been used to conduct scientific experiments. The use of rovers continues to date due to Mars being uninhabitable for humans at its current state and time. Despite the invention of Mars rovers, many limitations have been challenging space exploration, even with improvements in the Curiosity and Perseverance rovers. This study aimed to investigate the advancement in autonomous navigation in space through artificial intelligence. The study used qualitative, desktop, and systematic review research designs. The study's objectives were to determine the types of autonomous navigation technologies in space and examine the role of artificial intelligence in autonomous navigation technologies. Data was collected from secondary sources, which were purely open-access online journals. A total of 61 journals were searched as the target population. The study then conducted judgmental sampling. The Preferred Reporting Items for Systematic Reviews and meta-analysis guidelines guided the sampling process, yielding a sample of 9 out of 61 journals.

The study used an extraction form to collect data. The study found that star tracker navigation reduces positioning errors and environmental disturbances from sand and dust storms. It was also established that LOS navigation and star trackers ensured highly accurate navigation in challenging conditions for path-planning accuracy. Selecting the Next Coordinate, Obtaining Coordinates of Target Points, Generating Additional Coordinates, and optimising planned paths reduce travel time and energy consumption. On-orbit servicing robotics can extend rover missions up to 10 years. It was also found that 3D OctoMaps improves rovers' navigation accuracy. In addition, the study revealed that unsupervised homography networks, state recursive models, and inertial measurement models reduce localisation errors. Simultaneous Localization and Mapping can improve navigation accuracy and reduce mission delays. The use of RL navigation systems reduces mission delays. It was also found that Convolutional Neural network algorithms advance autonomous navigation accuracy in terms of terrain classification. The study also established that the Nvidia Jetson Nano AI controller and Rapidly-exploring Random Tree (RRT) in MATLAB reduce travel time and energy consumption. Finally, it was found that artificial neural networks advance the accuracy of terrain classification and lower navigation errors.

Keywords: advancement, autonomous navigation, space, artificial intelligence, mars, rovers.

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I. INTRODUCTION

1.1 *Background*

Artificial Intelligence (AI) advancements form the basis for advancing AI-driven autonomous space exploration technologies. Examples of successful inventions currently dominating different sectors include self-driving vehicles (i.e., the Tesla Model Y), manufacturing robots (i.e., the Cartesian robots), warehouse operating robots (i.e., Proteus in Amazon), building and construction robots (i.e., Vulcan and Phoenix by ICON), humanoids (i.e., Optimus by Tesla, and Atlas from Boston

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Dynamics) (Hansson et al., 2021; Tennant et al., 2024; Garikapati & Shetiya, 2024). Given that these technologies are already successful in their application, putting them into space exploration can boost the science of space exploration. The scope of application of advanced autonomous navigation in space through artificial intelligence is broad.

Space exploration has been in existence since 1957 (Siddiqi, 2010). After the launch of Sputnik, several other innovations have been made in the history of space exploration. The year 1998 marked the start of advancement in autonomous navigation in space with the help of artificial intelligence. This was related to the launch of the Deep Space 1 probe. Each year, scientists have been developing more advanced technologies to explore space. Humanity has been fascinated with planetary explorations besides flights into space and space satellites. The introduction of autonomous rovers led to a big leap courtesy of Artificial Intelligence, as seen with the launch of NASA's Sojourner rover that operated on Mars as a pathfinder in 1997. The rover utilised basic AI algorithms to navigate and avoid obstacles on the planet's surface. After the successful operations of the Sojourner rover, scientists have advanced other rovers that have increasingly achieved their intended roles. Examples of autonomous rovers sent to Mars after the Sojourner include the Opportunity (2004), the Curiosity (2012), and Perseverance (2020) (Zhou et al., 2024). Despite the advancement of autonomous innovations driven by AI being used on Earth, space exploration has limited application. Comparing the list of AI-driven autonomous innovations on Earth and in space (such as on the moon and Mars), space exploration is still ranked as the least advanced sector in such applications. There are various reasons why the space exploration sector is still lagging in applying advanced AI-driven autonomous innovations. One of the significant reasons is monopoly. Governments have dominated space exploration for years, leaving out the private sector. This slowed the competition to innovate advanced AI-driven machines (Pagallo et al., 2023).

AI is being adopted to solve long-duration missions and increase reliance on plans to operate autonomously in space. AI algorithms characterise spacecraft's autonomous navigation. According to the study, this increases efficiency in navigating complex space environments, which demand keenness, increased attention to avoid obstacles, and optimisation of trajectories. The use of machine learning and sensor data was the key highlight of the study in realising real-time informed decision-making in autonomous navigation, thereby achieving efficiency and reducing ground control dependency (Russo & Lax, 2022).

For example, since the launch of the SpaceX company in 2002, aggressive space exploration technological advancements have been made in such a short period. The company is set to make a better and appropriately modified rover to succeed the Perseverance rover launched to Mars in 2021 by NASA. These speculations are the subject of debate regarding the advancement required to establish a long-lasting impact on AI-driven autonomous space exploration technology. To date, NASA has continuously made rovers with the same characteristics, including appearance and functionality, with the significant differences being size and software updates (Rausser et al., 2023).

This study sought to establish advancements in autonomous navigation in space through artificial intelligence by systematically reviewing past journals. The researcher will conduct a comparative analysis of issues surrounding this advancement. The findings formed knowledge that sought to inform the scientific community of the possible opportunities in AI-driven autonomous machines that, if implemented, can transform space exploration in the future.

1.2 Objectives

1.2.1 General Objective

To analyse advancements in autonomous navigation in space through artificial intelligence.

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1.2.2 Specific Objectives

1. To determine types of autonomous navigation technologies in space;
2. To examine the role of artificial intelligence in autonomous navigation technologies in space.

II. LITERATURE REVIEW

The study by Xiong et al. (2024) established that autonomous optical navigation in estimating a spacecraft's velocity while in Earth orbit is a required advancement. The study proposed the "novel autonomous optical navigation method" to improve navigation. This method involves a star camera placed on a spacecraft that collects measurements in a line-of-sight (LOS), with the focus being the number of non-cooperative space targets whose vectors are not precisely known ahead of time of contact. The proposed *novel autonomous optical navigation method* is meant to improve the "*Q-Learning Extended Kalman Filter*", thereby obtaining accurate motions for both the space targets and spacecraft using the measurements by the LOS direction. LOS can accurately acquire the direction of space targets if an additional advanced star camera is used. During the movement of a spacecraft, its position, attitude, and velocity are obtained using the star camera while the space targets and stars are simultaneously observed.

Zhang et al. (2024) studied using autonomous rubber-tapping robots installed with trajectory prediction decision mechanisms to navigate forests. The use of the navigation decision mechanism deals with obtaining coordinates of target points (OCTP), selecting the next coordinate (SNC), generating additional coordinates (GAC), and finally optimising planned paths (OPP). Using mechanisms, robots increase their autonomy in predicting their next target based on their current position and actual operating logic during their navigation within forested environments, with an overall rationality effectiveness of 92.14% for path planning.

Li et al. (2025) studied the 3D point cloud optimisation method using an octree data structure as a solution to autonomous navigation and a replacement to the 3D LiDAR's contribution towards autonomous navigation of the robots called orchard mobile. According to the study, the 3D point cloud optimisation method advances mapping and spatial indexing and introduces the octree data segmentation features and structure. According to the survey, sparsity and density in the point cloud mapped by the 3D orchard get adaptively divided, and key information about the orchard is retained. Regarding path planning, the octree nodes random tree expansion and improved algorithm proposed by the octree. The results of the tests revealed a score of -76.32% reduction of point cloud data points within a map. The robot improved the RRT algorithm significantly when dealing with path generation time, curvature, sampling point utilisation, and path length. Lateral tracking errors improved with a decrease in the resolution of octree nodes. For example, 0.20 m resolution achieved 0.079 m lateral tracking error, indicating strong path tracking.

Gao et al. (2024) studied the implementation of an unsupervised homography network. The purpose of the technology was the interframe motion lander estimation (position, attitude, and velocity) using an inertial measurement information/measurement model and a state recursive model. The results of the simulation showed that the tool was effective. Zhao et al. (2024) studied using SLAM-driven autonomous navigation instead of traditional algorithms. According to the algorithm, SLAM enhanced precision in autonomous navigating robots with less than a 5% error rate.

Duarte et al. (2024) studied cameras and active sensors with their advancements in AI navigation algorithm to increase on-board visible wavelength as a docking sensor and on-orbit servicing (OOS). According to the study, these sensors reduce dependency on lidars. To improve navigation, several Convolutional Neural Networks (CNN) form a benchmark for generating synthetic data that drive docking manoeuvres applied in the International Space Station (ISS). Haj et al. (2024) studied the incorporation of Nvidia Jetson Nano AI control systems. Using advanced mechanical, software, and electrical components, rovers can withstand harsh conditions in places

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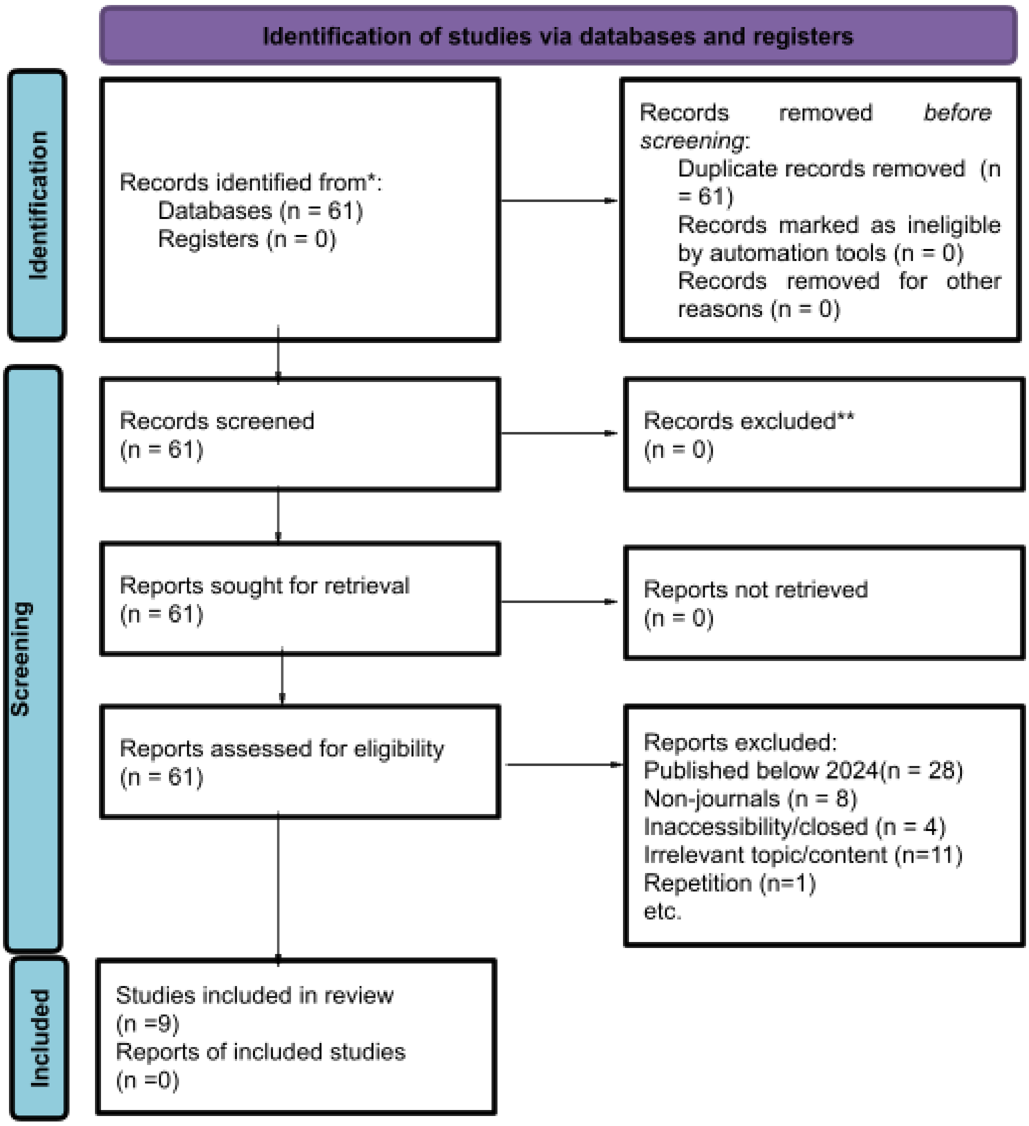
like Mars, powered by MATLAB's RRT AI planner, to optimise navigation systems and path planning.

Ying et al. (2024) studied the inadequacy of the Kalman filter using multi-sensor autonomous navigation with intelligent information fusion to operate launch vehicles. To improve navigation, the study proposed using Artificial Neural Networks (ANNs) to connect data with trajectory parameters. The tracking, control system and telemetry provide accurate launch vehicles after every flight. The experiment results showed that ANNs improve navigation performance compared to the Kalman filter.

III. MATERIALS AND METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines guided this study section (Flow Chart 1) below.



Source: McKenzie et al. (2021)

Figure 1: PRISMA 2020 flow diagram for new systematic reviews, which included searches of databases and registers only

3.1 Eligibility Criteria

The inclusion criteria were as follows: Sources should be published in journals. The publishing should have happened between 2024 and 2025. The sources should be open-access, making them available to the public on the most used search platform worldwide. Finally, the sources should be relevant to the topic and objectives of this

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study. The exclusion criteria are Older Sources, i.e., 2023 backwards. Sources that are anything other than open-source published journals, meaning no reports, unpublished theses, numerical data from statistics websites, and websites in general. After assessing various sources totaling 61, this study excluded 52, remaining with 9 (nine) sources used for the systematic review.

3.2 Information Sources

The study used the extraction form provided in Table 1 to identify suitable sources that led to the findings reported in this study. The extraction was therefore considered as the data collection tool for this study.

Table 1: Extraction Form

Study ID	Inclusion criteria	Exclusion criteria	Selected /Not Selected	Was the author contacted for additional outcome data	Contact record	Date last searched/ consulted.
	[ ] Published 2024-2025 [ ] Journal (type) [ ] Open source [ ] Relevant	[ ] Published 2023 backwards [ ] Non-journal (type) [ ] Inaccessible [ ] Irrelevant		[ ] Yes, positive response [ ] Yes, but no response [ ] No [ ] It was N/A		

Source: Author (2024)
Outcome Key: [✓] Yes, [×] No

3.3 Search Strategy

The researcher used qualitative, desktop, and systematic review research designs to identify scholarly articles from journal publishing websites. The search included: "Types of Autonomous Navigation Technologies in Space – journal" and "Role of Artificial Intelligence in Autonomous Navigation Technologies in Space – journal." The study directly searches the internet using Google browser and Google Scholar). The source filtering was limited to the extraction form (Table 1).

3.4 Selection Process

The data sources and findings were selected based on what the study extracted from the data collection form (Table 1). All 9 (nine) sources met the inclusion criteria for the review. The researcher and four research assistants (reviewers) reviewed the sources by screening for quality and context suitable for this study. The supervisor, a professor in Artificial Intelligence and mechatronics at Cambridge University validated and confirmed the suitability of the studies selected for systematic review. Independent reviewers conducted the review process through anonymous peer review (meaning the absence of influence from the authors and the absence of knowledge about the author). During the entire process, the review discouraged using automation tools.

3.5 Data Collection Process

An extraction form was used to collect data. The sources of data were 9 (nine) journals. First, the researcher identified the topic of the study. The researcher then identified the objectives of the study. The researcher used the following search phrases to obtain the required data sources: "Types of Autonomous Navigation Technologies in Space – journal" and "Role of Artificial Intelligence in Autonomous Navigation Technologies in Space – journal." The researcher searched the internet using Google and Google Scholar search bars. The search resulted in a total of 61 journals. The researcher then used the extraction form in Table 1 to further evaluate the

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data sources. The researcher was guided by the PRISMA 2020 flow diagram proposed by McKenzie et al. (2021) to highlight the exclusion criteria for selecting the sources. After exclusion, the researcher was left with a total of 9 (nine) sources. The researcher then hired 4 (Four) reviewers to validate the selected sources to be reviewed and analysed for the study. Upon confirmation that the data collection sources were suitable, the researcher collected and analysed the findings.

3.6 Study Risk of Bias Assessment

The study was limited to findings from 9 (nine) sources out of 61. This produced a potential bias caused by the exclusion criteria used. It was necessary to use the exclusion criteria to minimise the use of old sources considered outdated information. This does not mean that older sources lacked important information, risking the study's findings from being adequate and inclusive.

To assess the risk of bias, the researcher applied the Robvis method. Robvis visualises the risk of bias. It is an open-source web app that evaluates the risk of biased figures and provides a synthesis workflow in R-studio. The researcher backed up the process by conducting a peer review manually. The study employed 4 (four) reviewers who certified and selected the 9 (nine) sources independently.

3.7 Effect Measures

The effect measures were determined using the Odds Ratio (OR) synthesis. The odds Ratio (OR) estimates the odds of "Event A" divided by the odds of "Event B". The results were interpreted as follows: OR values near 1 meant the approximate effects were almost identical for groups A and B. In reverse, OR values far from 1 meant a lower identicality of the two events (A and B). This study achieved an OR equal to 0.7, considered adequate regarding the identicalness of the 9 (nine) sources. This meant the 9 (nine) sources adequately complemented each other with a high level of reliability, thus giving this study the go-ahead to conduct the systematic review.

3.8 Synthesis Methods

Table 1 was used to determine the number of sources being used for the study. A total of 9 (nine) sources were reviewed and found eligible. Data collection used secondary sources such as scholarly articles and analysed using qualitative analysis. Qualitative analysis was a thematic data coding that sought common trends and themes from the chosen sources.

3.9 Reporting Bias Assessment

The risk of bias assessment involved using the Robvis methods during the inclusion and exclusion criteria.

3.10 Certainty Assessment

To determine confidence levels related to the sources set aside for data collection, the research used Cronbach's alpha to test the reliability of the extraction form. It established an alpha value above 0.7, which was considered sufficient. This allowed the researcher to proceed to the next step, data analysis.

3.11 Study Selection

The study collected data from two recommended studies by the supervisor at Cambridge University and reviewers of the list provided by the researcher, as presented in Table 1. Out of 61 studies, only 9 (nine) qualified to inform the systematic review. The other 52 studies were disqualified based on the exclusion criteria.

3.12 Study Characteristics

This systematic review is characterised by published journals between 2024 and 2025, considered open sources, with relevant information regarding the topic and objectives of this study.

3.13 Risk of Bias in Studies

Risks of bias were assessed using Cochrane's review criteria. The criteria work in stages: selecting, detecting, and reporting bias. Selecting bias deals with questioning/disapproving data sourcing, amounting to more than 50% of

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reviewers considering it inadequate. Detection bias deals with questioning/disapproving data sources by over 50% of reviewers and the other 50% of reviewers approving; therefore, it reports adequacy of 50%. Finally, reporting bias deals with approved data sources by more than 50% of reviewers (defining the adequacy as close to 100%). Each paper was evaluated as "Low Risk" (+), "High Risk" (-), or "Unclear Risk", as provided in Table 2.

Table 3: Risk of bias in studies

Code	References	Protocol results	Selection bias	Detection bias	Reporting bias	Risk of Bias
1	Xiong et al (2024)	83.33%	+	?	+	Low Risk
2	Zhang et al. (2024)	83.33%	+	?	+	Low Risk
3	Alizadeh and Zhu (2024)	83.33%	+	?	+	Low Risk
4	Li et al. (2025)	83.33%	+	?	+	Low Risk
5	Gao et al. (2024)	83.33%	+	?	+	Low Risk
6	Zhao et al. (2024)	83.33%	+	?	+	Low Risk
7	Duarte, et al. (2024)	83.33%	+	?	+	Low Risk
8	Haj, et al (2024)	83.33%	+	?	+	Low Risk
9	Ying, et al. (2024)	83.33%	+	?	+	Low Risk

Source: Taghizad (2024)

Table 2 revealed that most of the sources of information were picked with a low risk of bias, making them adequate for data analysis.

IV. RESULTS

Xiong et al. (2024) offer insight into improving the Curiosity and Perseverance rovers' real-time adaptability and limited autonomy. According to the study, using novel autonomous optical navigation technology, line-of-sight (LOS) techniques, and star cameras can improve the accuracy of measuring and implementing the velocity of space targets. If this is applied, the rovers can perform precise navigation in real-time independent of Earth-based control limited by communication delays. Implementing the three systems will improve Mars rovers' autonomous estimation of navigating complex terrains and adjusting trajectories. By combining AI- with optical navigation methods, rovers built in the future will achieve more precision during obstacle avoidance and target selection. The star tracker optical device uses star patterns to determine the rovers' space orientation. On the other hand, LOS use celestial objects and visual landmarks in relative positioning.

Zhang et al. (2024) explained the need to adopt Selecting the Next Coordinate (SNC), Obtaining Coordinates of Target Points (OCTP), Generating Additional Coordinates (GAC) technology, and optimising planned paths (OPP). By applying these approaches, the Mars rovers are expected to achieve the highest level of rationality and effectiveness when conducting path-planning missions. Adapting these advancements will also reduce dependency on Earth-based control. Using mission objectives and environmental data, the RL-based Selecting the Next Coordinate (SNC) can autonomously determine the following rover navigations in real time. The challenges facing the

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Curiosity and Perseverance rovers include deep reliance on Earth-based control and pre-programmed paths that delay missions. To deal with this, RL is required to help the rovers adapt to the dynamic environments by selecting coordinates.

Alizadeh's and Zhu's (2024) study can be used to build the On-Orbit Servicing (OOS) robotics towards improving Mars rovers. According to Alizadeh and Zhu (2024), OOS depends on advanced machine learning and neural network performances, enabling Mars rovers to conduct precise and safe manipulation, controls, object estimation, and path planning. These capabilities include handling uncertainties, fuel-optimized trajectories, docking manoeuvres, and collision avoidance. Applying similar AI-driven systems to Mars rovers could significantly enhance their ability to autonomously navigate complex terrains, avoid hazards, and optimise scientific operations. The On-Orbit Servicing (OOS) can improve the capabilities of Curiosity and Perseverance robots' maintenance and refuelling. The challenges facing the rovers include hardware degradation and limited fixed energy supplies. Robotic maintenance and refuelling can replenish power sources (i.e., plutonium-238 connected to RTGs) and replace worn components to address this.

Li et al. (2025) this study shares how 3D point cloud optimisers that use octree data structures can offer valuable improvements to Mars exploration rovers. According to Li et al. (2025), 3D point cloud optimisation and octree data segmentation are tools for advancing mapping, path planning and spatial indexing conducted by autonomous robots like the Mars rover. With the help of this approach, traditional systems like 3D LiDAR can be replaced. The other systems that can be used include the Rapidly-exploring Random Tree (RRT) algorithms and the random tree expansion for path planning efficiency. Therefore, this advances the Mars rover's ability to navigate autonomously while mapping complex Martian terrains. Octree's 3D point cloud optimisers include the OctoMap and the Point Cloud Library (PCL). These techniques apply hierarchical octree data to process, store, and analyse 3D imagery data. The Octrees divide 3D spaces into small recursive cubes called voxels, reducing storage complexity. Challenges facing the Curiosity and Perseverance rovers are their reliance on 2D maps and, to some extent, weak 3D data characterised by navigation errors when mapping complex terrain. The Octree systems offer real-time 3D obstacle detection and mapping to address this.

Gao et al. (2024) studied unsupervised homography networks for inter-frame motion estimation of position, velocity, and attitude. The study also explained using the state recursive and inertial measurement models. Simulations of the tool have witnessed an advancement of motion estimation precision in the navigation of robots in dynamic environments, and this includes addressing the need to advance Mars rovers' ability to adjust trajectories and motion autonomously and in real time. The challenge that Curiosity and Perseverance face includes relying on pre-programmed paths. Using the models as a solution can address this situation. State recursive (i.e., Kalman filters) and inertial measurement models offer a robust pose estimation, while the homography networks advance visual odometry.

Zhao et al. (2024) studied Simultaneous Localization and Mapping (SLAM) in autonomous navigation and demonstrated how SLAM navigation advances precision in robots and lowers error rates as opposed to traditional algorithms. SLAM is highly accurate and applicable to localising and mapping complex environments. SLAM can advance Mars rovers' autonomous navigation and exploration capacities by creating real-time maps while simultaneously determining their position inside the maps. Through this, the rover can navigate unpredictable and hazardous Martian territory with limited communication, making Earth's human guidance impossible. The challenges facing the Curiosity and Perseverance rovers include delayed Earth control and pre-loaded maps that delay or limit adaptability. To address this, the SLAM enables autonomous navigation in real-time by offering 3D mapping at high resolution.

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et al. (2024) studied advancements in cameras, sensors, and AI algorithms for navigation. They demonstrated how integrating advanced cameras and sensors using Convolutional Neural Networks (CNNs) AI algorithms advances navigation and docking accuracy. According to the study, Convolutional Neural Network (CNN) advancements make proper onboarding of visible wavelength, real-time recognition of objects, and spatial mapping. The challenge facing the Curiosity and Perseverance rovers has been the reliance on Earth-based control and pre-programmed instructions. These challenges have led to delayed decision-making caused by communication lag (i.e., 4–24 minutes). With the advancement in Neural Networks such as CNNs, it is established that decision-making will be in real-time and, thus, an increase in autonomous navigation. The other challenge facing the Curiosity and Perseverance rovers is the limited onboard power processing that restricts the analysis of complex terrain within actual time. Therefore, using sensor data and integrating CNNs can increase transformers' processing speed and high-resolution images. This will increase the accuracy of classifying terrain types and hazard detection with mote.

Haj et al. (2024) studied the Nvidia Jetson Nano AI controller integrated with the Rapidly-exploring Random Tree (RRT) in MATLAB. According to the study, Nvidia Jetson Nano with RRT in planner rover optimises autonomous navigation through path planning trajectory generation, thereby increasing obstacle avoidance. As previously found, the challenge facing Curiosity and Perseverance rovers is the need for backup regarding the existence of an Earth-base controller and a pre-programmed path, which led to suboptimal routes and delays. Applying the Jetson Nano and RRT technologies solves this problem by providing real-time processing of path planning.

Ying et al.'s (2024) study leads to the proposal of using multi-sensor navigation fused with intelligent information, in particular, applying Artificial Neural Networks (ANNs). According to the survey, using ANNs connects data and trajectory parameters, a combination that advances the tracking, controlling, and launch of robotic vehicles. The challenge facing Curiosity and Perseverance rovers includes pre-programmed instructions incapable of real-time performance. ANNs are a solution as they provide fast, real-time decision-making and learning.

V. DISCUSSION

The study aimed to systematically review advancements in autonomous navigation in space through artificial intelligence about the limitations challenging space exploration by the Curiosity and Perseverance rovers.

Xiong et al. (2024) proposed using novel autonomous optical navigation technology, line-of-sight (LOS) techniques, and star cameras. In support of the findings, Johnson et al. (2024) revealed that star tracker navigation reduces up to 50% of positioning errors compared to gyroscope systems and is immune to environmental disturbances, including sand and dust storms, which serve well on Mars. On the other hand, LOS navigation and star trackers ensure highly accurate navigation in challenging conditions. Smith et al. (2025) combined the two technologies and established that there will be improved path-planning accuracy of rovers of up to 40% in the Martian dust storms environment.

Zhang et al. (2024) proposed the use of the Selecting the Next Coordinate (SNC), the Obtaining Coordinates of Target Points (OCTP), the Generating Additional Coordinates (GAC), and optimising planned paths (OPP). Tomljenovic et al. (2024) support the finding by demonstrating how RL-SNC reduces travel time (i.e., by 30%) and lowers energy consumption (i.e., by 20%) when compared to past methods.

Alizadeh and Zhu (2024) proposed the adoption of the On-Orbit Servicing (OOS) robotics. According to Zhang et al. (2024), the OOS extends rover missions for up to 10 years, continuing their scientific exploration.

Li et al. (2025) suggested the application of 3D point cloud optimisers using octree data structures and rapidly exploring random Tree (RRT) algorithms and random tree expansion.

The study is supported by Serdel et al. (2024), who found that using OctoMaps improves rovers' navigation with up to 40% accuracy when simulations of Martian environments are conducted.

Gao et al. (2024) proposed the application of the unsupervised homography networks using the state recursive models and the inertial measurement models. In support of this, Annu et al. (2024) found that this technology reduces localisation errors by up to 50% during the simulation of rovers in Martian terrain.

The study by Zhao et al. (2024) proposed using the Simultaneous Localization and Mapping (SLAM). Alizadeh and Zhu (2024) found that SLAM improved rover navigation accuracy by 60% and reduced mission delays by 30% in simulated Martian terrains.

The study by Duarte et al. (2024) proposed the use of the Convolutional Neural Networks (CNNs) algorithms. In support, Thakker et al. (2023) revealed that RL navigation systems reduce mission delays by up to 40% as opposed to traditionally used system programs by NASA. Mathematically, CNNs advance autonomous navigation by >94.61% accuracy regarding terrain classification (Solomon & Agnes, 2024).

The Haj et al. (2024) study suggested using the Nvidia Jetson Nano AI controller with the Rapidly-exploring Random Tree (RRT) in MATLAB. The finding was supported by Lee et al. (2024), who revealed that the presented combination of technologies reduces travel time by 35% and lowers energy consumption by up to 25%, as established by results from a simulation of rovers in a Martian environment.

Ying et al. (2024) proposed applying artificial neural networks (ANNs). In link to the finding, Sharma et al. (2024) established that ANNs advance the accuracy of terrain classification by up to 30% and lower navigation errors by up to 40% when a simulation of rovers in the Martian environments was conducted.

VI. CONCLUSION

The study aimed to systematically review advancements in autonomous navigation in space through artificial intelligence about the limitations challenging space exploration by the Curiosity and Perseverance rovers. The study studied advancements in cameras, sensors, and AI algorithms for navigation. The solutions presented include the use of modern neural networks, reinforcement learning (RL), genetic algorithms (GAs), and quantum computing algorithms. Xiong et al. (2024) proposed using novel autonomous optical navigation technology, line-of-sight (LOS) techniques, and star cameras. Zhang et al. (2024) proposed the use of the Selecting the Next Coordinate (SNC), the Obtaining Coordinates of Target Points (OCTP), the Generating Additional Coordinates (GAC), and optimising planned paths (OPP). Alizadeh and Zhu (2024) proposed the adoption of the On-Orbit Servicing (OOS) robotics. Li et al. (2025) suggested the application of 3D point cloud optimisers using octree data structures and rapidly exploring random Tree (RRT) algorithms and random tree expansion. Gao et al. (2024) proposed the application of the unsupervised homography networks using the state recursive models and the inertial measurement models. The study by Zhao et al. (2024) proposed using the Simultaneous Localization and Mapping (SLAM). The study by Duarte et al. (2024) proposed the use of the Convolutional Neural Networks (CNNs) algorithms. The Haj et al. (2024) study suggested using the Nvidia Jetson Nano AI controller with the Rapidly-exploring Random Tree (RRT) in MATLAB. Ying et al. (2024) proposed applying artificial neural networks (ANNs). All the applications were significant knowledge that this study recommended for advancing rover vehicles in the future of Mars exploration. The study hopes these technologies can be simulated comprehensively to benefit scientific planetary exploration.

List of Abbreviations

3D: Three-Dimensional
AI: Artificial intelligence
ANNs: Artificial Neural Networks
CNN: Convolutional Neural Network

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CNN:	Convolutional Neural Networks
GAC:	Generating Additional Coordinates
GAC:	Generating Additional Coordinates
LiDAR:	Light Detection and Ranging
LOS:	Line-of-Sight
MATLAB:	Matrix Laboratory
NASA:	National Aeronautics and Space Administration
OCTP:	Obtaining Coordinates of Target Points
OOS:	On-Orbit Servicing
OPP:	Optimizing Planned Paths
PRISMA:	Preferred Reporting Items for Systematic Reviews and Meta -Analyses
Q:	Quality
RL:	Reinforcement learning
RRT:	Rapidly-exploring Random Tree
RTGs:	Real-Time Gross Settlement
SLAM:	Studied Simultaneous Localization and Mapping
SNC:	Selecting the Next Coordinate

VII. DECLARATIONS

Ethics approval and consent to participate

A systematic review was used as the research design. Systematic reviews are findings obtained using secondary sources previously researched. In this case, the study investigated the advancement of autonomous navigation in space through artificial intelligence. The study was keen to ensure ethical approval, citing credible sources, authors and data.

Consent for Publication

The second author, a professor of AI-related studies at Cambridge University, supervised the first author. Therefore, the study sought the supervisor's consent to publish this research. The supervisor was then acknowledged as the co-author.

Availability of data and material

The study used a systematic review approach to collect and analyse secondary data. The method used published online open-access journals between 2024 and 2024, considered public information and accessible to public platforms.

Conflicts of Interest

The researcher was biased due to the topic, "Advancement in Autonomous Navigation in Space through Artificial Intelligence: A Systematic Review". The authors practice artificial intelligence-related careers. Because of this, the researchers ignored complementing and alternative fields attached to the topic. Therefore, some findings showed bias against other fields of knowledge unrelated to artificial intelligence. There were competing interests between the reviewers and the author, mainly because of their differences in experiences and careers. Because of these, changes to the main manuscript were intensive to streamline the published document to meet the conflicting thoughts, thereby making them uniform.

Funding

The author fully funded the study. The finances included family contributions.

Authors' contributions

Financing the project, A.I.; Supervising the project, A.I.; Study conceptualisation, P.L.; methodology, A.I.; validation, P.L.; formal analysis, A.I.; investigation, A.I.; resources, A.I.; data curation A.I.; writing—original draft preparation, A.I.; writing—review and editing, A.I.; and P.L.; project administration, A.I.; funding acquisition, A.I. All authors read, and agreed to move on with the published version of this manuscript.

ACKNOWLEDGEMENTS

I wish to extend my thanks to the reviewers assigned to ensure the validity of this paper. I also thank my parents for financing the writing of this paper and its subsequent publishing

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APPENDICES

Appendix 1 Graphic Abstract

Graphic Abstract

Integrating Artificial Intelligence for Enhanced Fault Detection in Power Transmission Systems: A Smart Grid Approach

Overview	Design and methods	Findings
Since the first trip to Mars, rovers have been used to conduct scientific experiments. The use of rovers continues to date due to Mars being uninhabitable for humans at this state and time. Despite the invention of Mars rovers, there have been many limitations challenging space exploration, even with improvements seen in the Curiosity and Perseverance rovers. The objectives of the study were to; - determine the types of autonomous navigation technologies in space, and - examine the role of artificial intelligence in autonomous navigation technologies in space.	Qualitative, desktop, and systematic review research designs. Data was collected from secondary sources, which were purely open-access online journals. A total of 61 journals were searched as the target population. The study then conducted judgmental sampling, which resulted in the use of 9 out of 61 journals. The PRISMA guidelines guided the sampling process. The study used an extraction form to collect data.	Star tracker navigation reduces positioning errors and environmental disturbances from sand and dust storms. LOS navigation and star trackers ensured highly accurate navigation in challenging conditions for path-planning accuracy. SNC, OCTP, GAC, and OPP reduce travel time and lower energy consumption. OOS robotics can extend rover missions up to 10 years. 3D OctoMaps improves rovers' navigation accuracy. Unsupervised homography networks, state recursive, and inertial measurement models reduce localisation errors. SLAM can improve navigation accuracy and reduce mission delays. RL navigation systems reduce mission delays. CNN algorithms advance autonomous navigation accuracy in terms of terrain classification. Nvidia Jetson Nano AI controller and RRT in MATLAB reduce travel time and lower energy consumption. ANN advances the accuracy of terrain classification and lowers navigation errors.

Source: Author (2025)

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