Towards Interpretable Case-Based Reasoning for Acoustic Signal Classification under Low-Data Constraints

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Abstract

This PhD thesis investigates the adaptation of Case-Based Reasoning (CBR) to the classification of complex marine bioacoustic signals under limited-data conditions, with a particular focus on cetacean vocalizations. While deep learning approaches dominate bioacoustic analysis, they generally require large annotated datasets and provide limited interpretability, which restricts their applicability in expertise-driven domains such as ethology.

This work explores a hybrid neuro-symbolic framework, the Iterative Signals Base System (ISBS), in which acoustic events are represented as structured cases combining acoustic descriptors with expert annotations. ISBS is based on the principles of Iterative Knowledge Base Systems (IKBS), where cases are progressively enriched as new knowledge becomes available.

Neural components are intended to support sound detection and feature extraction, while symbolic reasoning enables case-based classification through similarity-based retrieval.

Preliminary experiments on 518 annotated acoustic events evaluate coarse classification into acoustic domains. Preliminary results suggest that the proposed representation is promising in low-data settings while preserving interpretability through explicit descriptor-based reasoning.

This PhD thesis aims to consolidate the proposed framework by improving case representation, studying descriptor relevance, and investigating neuro-symbolic extensions. In the longer term, it will contribute to the structured representation of cetacean vocalizations for progressive knowledge-base construction.

Keywords

Case-Based Reasoning, Marine Bioacoustics, Neuro-Symbolic Reasoning, Acoustic Signal Classification, Knowledge Representation, Interpretability

1. Introduction

The classification of acoustic signals is a key challenge in many fields, particularly in bioacoustics, where it supports the monitoring and study of marine mammals [1, 2]. Cetacean vocalizations provide valuable information for species identification, behavioral analysis, and environmental monitoring.

Recent advances rely heavily on deep learning approaches, particularly convolutional neural networks applied to spectrogram representations [3, 4, 5]. Although these methods achieve strong performance on large-scale datasets, they generally require substantial annotated data and provide limited interpretability, which restricts their use in ecological contexts where expert validation is essential.

Case-Based Reasoning (CBR) offers an alternative paradigm that is inherently interpretable and particularly suited to low-data settings [6]. CBR relies on the reuse of past experiences represented as cases, enabling decision-making based on explicit similarity with previously observed situations.

This PhD thesis investigates how Case-Based Reasoning can support the interpretable classification of complex acoustic signals under limited-data conditions. More specifically, it explores a neuro-symbolic perspective in which learning and symbolic reasoning complement one another for the analysis of cetacean vocalizations.

> *How can Case-Based Reasoning be adapted to enable interpretable and efficient classification of complex acoustic signals under conditions of limited annotated data?*

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2. Background and Positioning

2.1. Acoustic Signal Classification

Automatic acoustic signal classification has evolved from classical pattern recognition techniques, including Dynamic Time Warping (DTW), Hidden Markov Models (HMMs), Gaussian Mixture Models (GMMs), and correlation-based approaches [7, 8, 9], to deep learning methods based on convolutional neural networks operating on spectrogram representations [3, 4, 10]. Although these methods achieve high performance, they generally require large annotated datasets and offer limited interpretability, which restricts their applicability in ecological contexts where expert validation remains essential [5].

2.2. Case-Based Reasoning for Complex Acoustic Data

Case-Based Reasoning (CBR) solves new problems by retrieving and adapting solutions from similar previously encountered cases [6]. Its explicit similarity-based reasoning naturally provides interpretability, making CBR particularly attractive for low-data applications. Beyond its traditional domains, CBR has been applied to heterogeneous and complex data [11], including acoustic signal analysis through case-based sonogram classification [12] and fault diagnosis [13]. More recently, hybrid CBR–deep learning approaches have demonstrated the complementarity between learned representations and similarity-based reasoning [14, 15, 16].

2.3. Neuro-Symbolic Reasoning for Bioacoustics

Neuro-symbolic Artificial Intelligence combines the representation learning capabilities of neural networks with the transparency of symbolic reasoning. In the proposed framework, neural models support sound detection and feature extraction, while CBR exploits structured cases for interpretable similarity-based classification. Rather than replacing expert knowledge, neural components are intended to enrich case representations and facilitate the progressive construction of knowledge bases.

2.4. Knowledge Representation and Ontologies

A major challenge concerns the formal representation of cetacean vocalizations. Although numerous acoustic descriptors have been proposed, no widely adopted ontology exists for their signal-based description, resulting in heterogeneous annotation schemes that limit interoperability and knowledge reuse. This research therefore investigates a signal-oriented ontology describing acoustic descriptors, contextual metadata, and expert annotations to support consistent case representation and the progressive construction of an interpretable knowledge base.

3. Proposed Research Direction: ISBS

This research investigates the *Iterative Signals Base System* (ISBS), an adaptation of the Iterative Knowledge Base System (IKBS) [17] to acoustic signal classification. ISBS represents cetacean vocalizations as structured cases that are progressively enriched as new knowledge becomes available. As illustrated in Figure 1, acoustic recordings are segmented into vocalization events from which temporal, spectral, cepstral, and autocorrelation descriptors are extracted and combined with metadata and expert annotations to build structured cases suitable for reasoning.

The current implementation performs case retrieval using a k-nearest neighbors (k-NN) strategy within the IKBS framework. The emphasis is therefore placed on the representation and organization of acoustic knowledge rather than on designing a novel similarity measure.

Each newly validated vocalization directly enriches the case base without requiring complete retraining, making ISBS particularly suitable for domains where annotated data remain scarce.

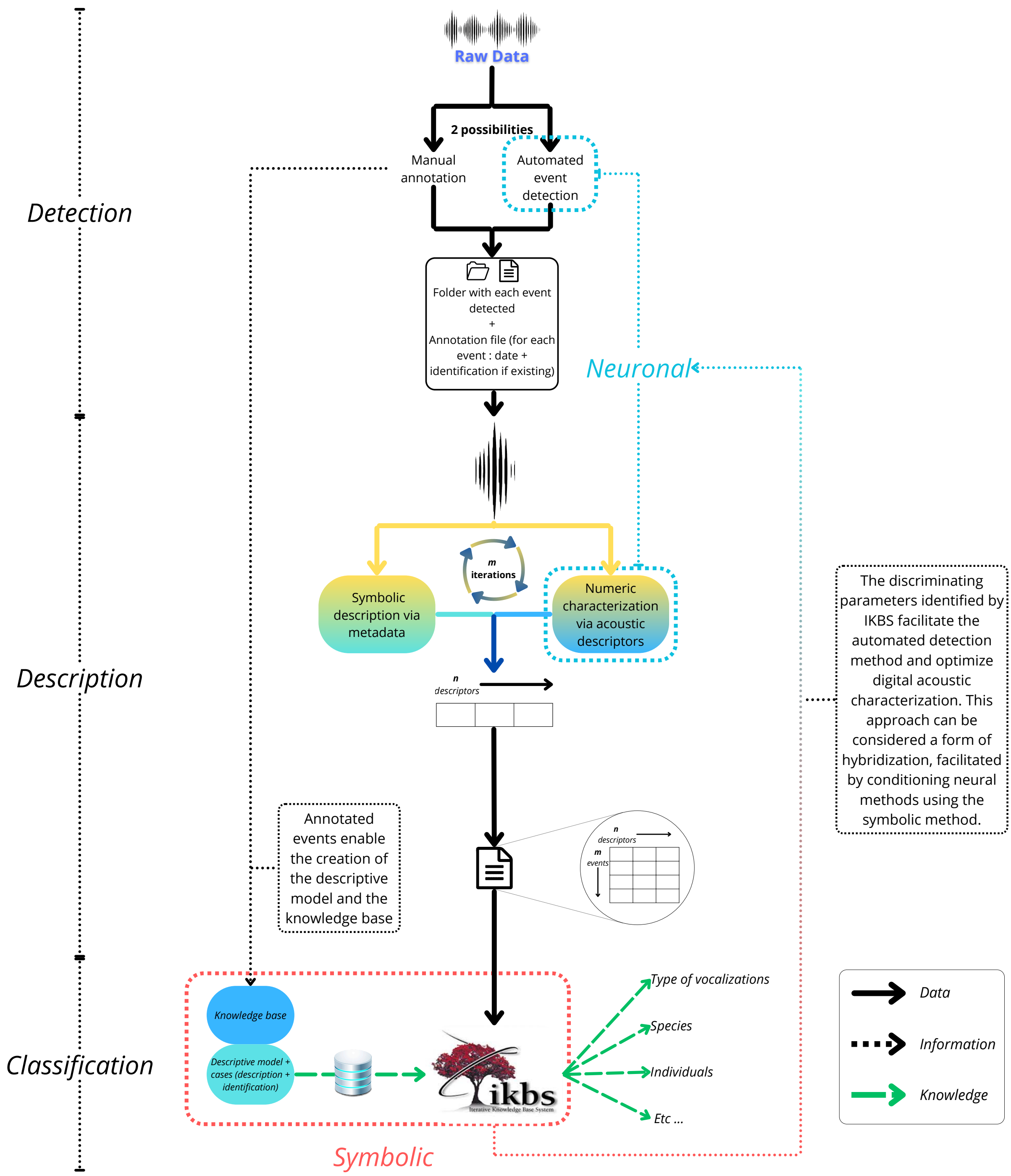

Figure 1: Overview of the proposed ISBS framework linking acoustic signal acquisition, descriptor extraction, case representation, and similarity-based classification within an iterative knowledge management process.

Although the current implementation relies on manually extracted descriptors, the long-term objective is to integrate neural methods for sound detection and descriptor extraction while preserving the transparency of symbolic case-based reasoning.

More broadly, this research investigates how cetacean vocalizations should be represented and organized within a knowledge base to support interpretable acoustic classification. A long-term objective is the development of a dedicated ontology providing a shared semantic framework for vocalizations, descriptors, and associated expert knowledge.

4. Preliminary Results

The current implementation of ISBS was evaluated on a proof-of-concept dataset extracted from the Watkins Marine Mammal Sound Database [18]. The dataset contains 518 manually annotated acoustic events and was designed to assess the feasibility of the proposed framework under realistic low-data conditions.

The evaluation considers coarse acoustic-domain classification (*harmonic*, *impulsive*, *stationary*, and their combinations) rather than fine-grained species or vocalization recognition, providing an initial validation of the proposed case representation.

Each acoustic event is represented as a hybrid case combining numerical descriptors with symbolic metadata and expert annotations. Classification is performed through k-nearest neighbors (k-NN) retrieval within the IKBS framework, with the best performance obtained for $k = 3$.

Table 1
Preliminary classification results.

Metric	Value
Overall accuracy	94.52%
Strict accuracy	87.26%
Relative accuracy	92.97%
Best k	3

The results indicate that the proposed representation captures meaningful acoustic similarities despite the limited size of the case base. More importantly, classification remains fully interpretable since each prediction is justified by retrieved cases and explicit descriptor similarities.

These experiments constitute an initial proof of concept rather than a definitive evaluation. Future work will extend the case base, evaluate ISBS on larger and more heterogeneous datasets, compare it with state-of-the-art approaches, and investigate finer-grained vocalization classification while preserving interpretability.

5. Research Challenges

The preliminary results demonstrate the feasibility of representing cetacean vocalizations as structured cases within the ISBS framework. However, several scientific and methodological challenges remain before such an approach can support robust, interpretable, and scalable acoustic classification.

Vocalization Characterization The first challenge concerns the characterization of cetacean vocalizations. Numerous acoustic descriptors can be extracted from marine mammal sounds, yet their respective ability to describe, discriminate, and generalize across vocalization types remains poorly understood. Identifying the most informative descriptors and organizing them into coherent case representations is therefore essential for building an effective knowledge base.

Knowledge Base Construction A second challenge is the progressive construction of a reusable knowledge base dedicated to cetacean vocalizations. Beyond storing acoustic descriptors, such a knowledge base must integrate contextual information and expert knowledge while ensuring consistency as new vocalizations are incorporated. In the longer term, this work will contribute to the formalization of an ontology providing a common semantic framework for representing vocalizations and their associated knowledge.

Neuro-Symbolic Integration. The proposed framework adopts a neuro-symbolic perspective in which neural methods support sound detection and descriptor extraction, whereas symbolic reasoning exploits the resulting structured knowledge for interpretable classification. Designing an effective interaction between these complementary paradigms while preserving transparency constitutes a major research challenge.

Evaluation and Scalability Finally, the proposed methodology must be evaluated beyond proof-of-concept experiments. This includes assessing its robustness on larger and more diverse datasets, comparing it with state-of-the-art approaches, and investigating its applicability to passive acoustic monitoring and other acoustic signal analysis domains.

6. Research Plan and Expected Contributions

The doctoral research will progress through three successive phases. First, the representation of acoustic events will be refined by studying descriptor relevance and improving case representation. Second, the knowledge base will be extended while investigating neuro-symbolic approaches in which neural methods assist sound detection and descriptor extraction and CBR provides interpretable reasoning. Finally, the framework will be evaluated on larger datasets, supported by a dedicated ontology of cetacean vocalizations, and assessed for transferability to other acoustic signal analysis domains.

The expected contributions are:

- a methodology for representing cetacean vocalizations using structured acoustic descriptors;
- an adaptation of the Iterative Knowledge Base System (IKBS) to interpretable acoustic signal classification through the ISBS framework;
- a knowledge representation supporting the progressive construction of acoustic case bases;
- a neuro-symbolic framework combining neural processing with interpretable Case-Based Reasoning;
- experimental protocols for evaluating interpretable classification under low-data conditions.

7. Conclusion

This doctoral research investigates how Case-Based Reasoning can contribute to the interpretable classification of cetacean vocalizations under low-data conditions. Rather than competing directly with deep learning approaches, the proposed ISBS framework explores a complementary neuro-symbolic perspective in which explicit acoustic descriptors, expert knowledge, and incremental case acquisition support transparent reasoning.

Preliminary proof-of-concept results demonstrate the feasibility of representing vocalizations as structured cases within an IKBS framework and highlight the potential of CBR for marine bioacoustics, while also identifying several research directions concerning vocalization characterization, knowledge representation, ontology construction, and neuro-symbolic integration.

Ultimately, this work aims to provide a reusable methodology for building interpretable acoustic knowledge bases that can support the description, classification, and identification of cetacean vocalizations while remaining transferable to other acoustic signal analysis domains.

Declaration on Generative AI

During the preparation of this manuscript, the author used ChatGPT (OpenAI) exclusively to improve the grammar, style, and readability of the text. The research questions, methodology, software implementation, experiments, analysis, and conclusions were developed by the author, who reviewed and edited the manuscript and takes full responsibility for its content.

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