Construe: a software solution for the explanation-based interpretation of time series

T. Teijeiro, P. Félix

Abstract

This paper presents a software implementation of a general framework for time series interpretation based on abductive reasoning. The software provides a data model and a set of algorithms to make inference to the best explanation of a time series, resulting in a description in multiple abstraction levels of the processes underlying the time series. As a proof of concept, a comprehensive knowledge base for the electrocardiogram (ECG) domain is provided, so it can be used directly as a tool for ECG analysis. This tool has been successfully validated in several noteworthy problems, such as heartbeat classification or atrial fibrillation detection.

Keywords: Time Series Interpretation, Temporal Abstraction, Abductive Reasoning, ECG delineation, Arrhythmia Recognition, Python, WFDB

1. Motivation and significance

Recently, a novel approach for time series interpretation has been proposed [7], based on the principles of abductive reasoning and conceiving the interpretation task as a process of hypotheses formulation and testing in multiple abstraction levels. This proposal is essentially different from traditional approaches to pattern recognition, which in general pose time series interpretation as a sequence of classification problems in multiple levels, where results from lower levels are taken as the input for higher levels [5]. Standard classifiers behave as deductive systems, and once a decision has been made it cannot be changed or retracted within the same classifier. This causes that errors in the lower level classifiers are propagated upwards, resulting in a system that is weaker than any of the individual components.

An abductive approach, however, features a non-monotonic reasoning paradigm, which supports the amendment of any conclusion at any abstrac-
tion level in the search for the best global explanation of the observed evidence. The strategy is inspired by how humans identify and characterize the patterns appearing in a time series, leveraging both bottom-up and top-down reasoning to provide a joint result. As a consequence, abduction can guess the underlying processes from corrupted data or even in the temporary absence of data, by considering the context information from higher abstraction levels. This achieves greater robustness in the interpretation process and overcomes some of the most important weaknesses of traditional paradigms [7].

These properties made it possible to successfully address two different problems in the domain of automatic electrocardiogram (ECG) analysis. On the one hand, the interpretations provided by Construe are the basis of a new method for heartbeat classification [8] that significantly outperforms any other automatic approaches in the state-of-the-art, and even improves most of the assisted approaches that require expert aid. Also, a combination of Construe with machine-learning algorithms obtained the highest score in the Physionet/Computing in Cardiology 2017 Challenge, outperforming the most popular techniques such as deep learning and random forests [9].

But our main motivation is to expand the use of this method and its adaptation to new problems and domains. In order to encourage this, we provide a free and open source reference implementation oriented to ECG applications. This implementation includes an abstract data model and a set of interpretation algorithms, as well as a knowledge base formalizing the standard clinical criteria for ECG analysis. This knowledge base supports building an interpretation of the ECG trace in the abstraction levels typically adopted in cardiology for explaining the physiological processes that take place in the heart muscle, including the electrical activation/recovery of the atria and the ventricles, and the different rhythm patterns that can be observed over time. Hence, this software can be directly used as an advanced ECG analysis tool, with a similar interface to that of other software packages such as ecg-kit [3] or the WFDB Applications [6].

2. Software description

2.1. Software Functionalities

In short, the Construe project provides a domain-independent framework for the explanation-based interpretation of time series. This framework includes a mechanism for designing abstraction patterns, and an interpretation algorithm that produces an explanation of a time series on the basis of the designed patterns.

Let’s begin with a simple illustration of these concepts. Figure 1 shows an example of an abstraction pattern that formalizes the notion of a normal
heart beat as it can be observed in an ECG signal. Each heartbeat is observed as a sequence of three wave components: The P wave, which represents the electrical activation of the atria; the QRS complex, corresponding to the electrical activation of the ventricles; and the T wave, which is the signature of the electrical recovery of the ventricles. The pattern also defines some temporal constraints in the durations and separations between the endpoints of the waves.

To describe abstraction patterns, the framework relies on two main entities:

- **Observables** `<model.Observable>`: They describe the ontological knowledge of a particular domain in an object-oriented fashion, that is, as a hierarchy of classes. In the example above there are four observables: P wave, QRS Complex, T Wave and Normal heart beat.

- **Abstraction grammars** `<model.PatternAutomata>`: They enable the description of potentially infinite sets of abstraction patterns, setting an explanatory relation between a hypothesis observable (in the example this would be the Normal heart beat) and different temporal arrangements of evidence observables. Formally they are described as right-linear attributed grammars [7], so they provide the same expressiveness as regular expressions. For simplicity, they are implemented as the equivalent finite automata, where non-terminals are replaced by states, and rules are described as transitions between states. These automata support a flexible definition of temporal and value constraints between the evidence and the hypothesis by means of user-defined functions.

For the definition of temporal constraints, the Simple Temporal Problem (STP) model has been adopted [2]. This model allows to constrain
the distance between temporal variables by closed intervals, and supports
a graph-based representation that can be efficiently analyzed in polynomial
time. The knowledge representation model is sufficiently expressive to de-
scribe complex processes such as for example trigeminy arrhythmias [7], and
a tutorial on how to use the knowledge description tools is included in the
project wiki page.

Once a set of abstraction patterns for a specific problem has been defined,
Construe will receive as input a time series and will produce an interpreta-
tion. The interpretation algorithm is based on a heuristic search procedure
inspired by the K-Best-First-Search algorithm [4] that combines a set of
reasoning modes to implement a hypothesize-and-test cycle guided by an at-
tentional mechanism. As a result, the algorithm provides a set of annotated
time intervals with the hypotheses explaining the input time series. Construe
can also work in online mode, processing the signal while it is being acquired.

On the other hand, in its present application as an end-user tool, this
software includes a built-in knowledge-base that supports the interpretation
of multi-lead ECG records in the MIT-BIH format [6]. Given an ECG record,
Construe infers the set of hypotheses that best explain the observed signal.
These resulting hypotheses describe the signal behavior in two abstraction
levels: 1) conduction level, that provides a delineation for the P, QRS, and
T waves; and 2) rhythm level, that gives the sequence of rhythm patterns,
including normal sinus rhythm, bradycardia, tachycardia, extrasystole, cou-
plet, rhythm block, bigeminy, trigeminy, atrial fibrillation, ventricular flutter
and asystole. This result can be exported to a standard annotation file, en-
abling further analysis or visualization with external tools. The interface
has been designed to be compatible with the well-known command-line tools
from the WFDB library [6].

2.2. Software Architecture

Figure 2 shows the main components of the framework, which roughly
correspond to the top-level packages of the project. Each of these components
are described below:

- **inference**: Contains the implementation of the Construe algorithm.
  It is composed by two modules: **searching**, that provides the heuristic
  search method; and **reasoning**, that implements the reasoning modes
  composing the hypothesize-and-test cycle. This component is domain-
  independent.

- **acquisition**: Provides global buffers for the acquisition of the time
  series to be interpreted, with support for online interpretation scenarios.
- **model**: Defines the general data model of the framework. This includes *observables, abstraction patterns, abstraction grammars and interpretations*. A model for the definition of STP networks [2] is also provided.

- **utils**: Miscellaneous utility modules, including signal processing, plotting and data-format manipulation routines.

- **knowledge**: This package provides all the domain-specific knowledge for ECG interpretation, namely the ontology of observables and the automata defining the abstraction patterns supporting all the conduction-level and rhythm-level hypotheses.

### 3. Illustrative Examples

In the search for the best explanation of the initial evidence, *Construe* is able both to ignore part of the evidence or to actively search for missing pieces, according to the known patterns. Figure 3 shows how this ability to discard some evidence makes it possible to obtain useful interpretations from very distorted signals. The figure shows a noisy ECG segment, in which a standard heartbeat detector identifies a number of false positive beats (detections are the vertical lines). After the interpretation, *Construe* concludes that the best explanation for the segment is that it corresponds to a normal rhythm, and that only the lines marked with arrows are actual heartbeats.

On the other hand, in Figure 4 we can see how the active search for missing information allows to find patterns that a common classifier would ignore. The figure shows a ventricular bigeminy pattern, in which every normal heartbeat is followed by an ectopic one, much more wider but with...
smaller amplitude. In this case, a standard annotator misses all but the first of the ectopic beats, so a normal classification would label the segment as an ectopic ventricular beat followed by a sinus bradycardia (low heart rate). However, in Construe the first ectopic beat allows to hypothesize the presence of a possible bigeminy, and then actively look for the missing ectopic beats.

4. Impact

In the short term, the main impact of Construe is expected to come from its function as an ECG interpretation tool, but not only for targeting the typical problems addressed by the automatic ECG processing community (continuous monitoring, outpatient follow-up, etc.). Besides the remarkable results we have already obtained in some noteworthy problems in this area [8, 9], independent users have successfully used Construe as a tool for ECG abstraction and feature extraction in large genome-wide studies to characterize the genetic variations that underlie cardiovascular diseases, aimed at a better understanding of the human physiology [12, 10, 11]. In these studies Construe has been used to interpret tens of thousands of signals with very different properties (at rest, during exercise, with varying lead configurations, etc.), demonstrating the reliability of the algorithm beyond the common validation databases. And most importantly, in these works the interpretation of the ECG is not an end, but a means to reach new research hypotheses that go beyond an immediate individual diagnosis of the heart function.

The key factor behind the reliability of Construe is the non-monotonic nature of the hypothesize-and-test cycle, making it possible to exploit the
complementarity between bottom-up and top-down processing, in order to find the best explanation consistent with the evidence. As in perception, ECG interpretation is assumed to be mostly bottom-up, although top-down processing has proven to be decisive to cope with noise, artifacts or ambiguities in the signal. Thus, in the longer term, we expect that the main impact of this software will be to spread the use of non-monotonic reasoning techniques for the abstraction of temporal information. This is especially suited for scenarios requiring a continuous interpretation of low quality sensory data, and that are particularly frequent in emerging Internet of Things (IoT) contexts [1].

5. Conclusions

The Construe software aims to provide a framework for the development of knowledge-based solutions oriented to time series interpretation according to an abductive reasoning scheme. This framework defines a general data model for knowledge representation and a set of domain-independent interpretation algorithms, and it has been successfully tested on different problems in the ECG domain.

The main advantages of this approach are 1) the explainability of the models and of the interpretation results, a key advantage to gain the trust of human experts; and 2) the robustness to the presence of noise and artifacts, which makes it adequate for poorly controlled interpretation environments.

As for the evolution of this project, besides deepening into the interpretation of biological signals to address more complex problems and to include new signal types and multi-parameter signals, efforts will be devoted to the integration of machine learning strategies for knowledge definition and adaptation, as well as to the improvement of the computational performance of the algorithms in special-purpose architectures. Also, we are confident that the generality of this framework will allow the scientific community to find new problems and domains of application.

Acknowledgements

This work was supported by the Xunta de Galicia and the European Regional Development Fund (ERDF) under Grant No. 2016-2019-ED431G/08, and by the Human Brain Project (HBP) SGA2 (GA No. 785907).
References

[1] F. Alam, R. Mehmood, I. Katib, N. N. Albogami, and A. Albeshri. Data Fusion and IoT for Smart Ubiquitous Environments: A Survey. *IEEE Access*, 5:9533–9554, 2017.

[2] M. Dechter, J. Meiri, and J. Pearl. Temporal constraint networks. *Artificial Intelligence*, 49:61–95, 1991.

[3] A. Demski and M. Llamedo. ecg-kit: a Matlab Toolbox for Cardiovascular Signal Processing. *Journal of Open Research Software*, 4(1), 2016.

[4] S. Edelkamp and S. Schrödl. *Heuristic Search: Theory and Applications*. Morgan Kaufmann, 2011.

[5] F. Ganz, D. Puschmann, P. Barnaghi, and F. Carrez. A Practical Evaluation of Information Processing and Abstraction Techniques for the Internet of Things. *IEEE Internet of Things Journal*, 2(4), 2015.

[6] G. B. Moody. WFDB Applications Guide, 10th edition. [http://www.physionet.org/physiotools/wag/](http://www.physionet.org/physiotools/wag/) 2014. [Online; accessed 05/06/2019].

[7] T. Teijeiro and P. Félix. On the adoption of abductive reasoning for time series interpretation. *Artificial Intelligence*, 262:163–188, 2018.

[8] T. Teijeiro, P. Félix, J. Presedo, and D. Castro. Heartbeat classification using abstract features from the abductive interpretation of the ECG. *IEEE Journal of Biomedical and Health Informatics*, 22(2), 2018.

[9] T. Teijeiro, C. A. García, D. Castro, and P. Félix. Abductive reasoning as the basis to reproduce expert criteria in ECG atrial fibrillation identification. *Physiological Measurement*, 39(6), 2018.

[10] Yordi J. van de Vegte, Pim van der Harst, and Nick Verweij. Heart Rate Recovery 10 Seconds After Cessation of Exercise Predicts Death. *Journal of the American Heart Association*, 7(8), 2018.

[11] N. Verweij, J.W. Benjamins, M.P. Morley, Y. van de Vegte, A. Teumer, T. Trenkwalder, W. Reinhard, T. P. Cappola, and P. van der Harst. The genetic makeup of the electrocardiogram. *bioRxiv preprint*, 2019.

[12] N. Verweij, Y. J. Van De Vegte, and P. Van Der Harst. Genetic study links components of the autonomous nervous system to heart-rate profile during exercise. *Nature Communications*, 9(1):898, 2018.
Required Metadata

Current code version

| Nr. | Code metadata description                                      | Please fill in this column                                                      |
|-----|---------------------------------------------------------------|--------------------------------------------------------------------------------|
| C1  | Current code version                                         | v2.1                                                                           |
| C2  | Permanent link to code/repository used for this code version | [https://github.com/citiususc/construe/archive/v2.1.zip](https://github.com/citiususc/construe/archive/v2.1.zip) |
| C3  | Legal Code License                                           | AGPL v3                                                                         |
| C4  | Code versioning system used                                  | git                                                                             |
| C5  | Software code languages, tools, and services used            | Python 3                                                                         |
| C6  | Compilation requirements, operating environments & dependencies | - Python 3 installation with the following packages:                             |
|     |                                                               |   • sortedcontainers                                                           |
|     |                                                               |   • numpy                                                                      |
|     |                                                               |   • python-dateutil                                                             |
|     |                                                               |   • scipy                                                                      |
|     |                                                               |   • scikit-learn v0.18.1                                                       |
|     |                                                               |   • [PyWavelets](https://github.com/citiususc/construe)                        |
|     |                                                               |   • matplotlib                                                                 |
|     |                                                               |   • networkx                                                                   |
|     |                                                               |   • [pygraphviz](https://github.com/citiususc/construe)                        |
| C7  | If available Link to developer documentation/manual         | [https://github.com/citiususc/construe](https://github.com/citiususc/construe) |
| C8  | Support email for questions                                  | tomas.teijeiro@epfl.ch                                                          |

Table 1: Code metadata.
## Current executable software version

| Nr. | (Executable) software metadata description | Please fill in this column |
|-----|-------------------------------------------|---------------------------|
| S1  | Current software version | v2.1 |
| S2  | Permanent link to executables of this version | [https://github.com/citiususc/construe/archive/v2.1.zip](https://github.com/citiususc/construe/archive/v2.1.zip) |
| S3  | Legal Software License | AGPL v3 |
| S4  | Computing platforms/Operating Systems | GNU/Linux |
| S5  | Installation requirements & dependencies | - Python 3 installation with the following packages:  
  • [sortedcontainers](https://pypi.org/project/sortedcontainers/)  
  • [numpy](https://numpy.org/)  
  • [python-dateutil](https://python-dateutil.readthedocs.io/en/stable/)  
  • [scipy](https://scipy.org/)  
  • [scikit-learn v0.18.1](https://scikit-learn.org/stable/)  
  • [PyWavelets](https://pypi.org/project/PyWavelets/)  
  • [matplotlib](https://matplotlib.org/)  
  • [networkx](https://networkx.github.io/)  
  • [pygraphviz](https://pypi.org/project/pygraphviz/)  
  
- WFDB Software package  
- Graphviz |
| S6  | Link to user manual | [https://github.com/citiususc/construe](https://github.com/citiususc/construe) |
| S7  | Support email for questions | tomas.teijeiro@epfl.ch |

Table 2: Software metadata.