



DEFENSE / CYBER / SECURITY

ACOUSTIC DETECTION OF UNDERWATER MINES

Benchmark vs. Logistic Regression, Random Forests, Boosted Trees & Neural Networks

Use Case 10/2022 (v2.2) • xtractis.ai

? PROBLEM DEFINITION

PROBLEM	How to automatically, efficiently and transparently diagnose underwater mines from sonar echoes?
GOALS	<ul style="list-style-type: none"> ☑ Identify the frequency bands involved in the detection of underwater mines and enhance knowledge by helping submarine staff and acoustic experts understand the causal relationships between specific frequency bands, their combination, and the presence of a mine. ☑ Help to design a virtual "Golden Ear" (expert in underwater acoustics) operating 24/7/365 with the same quality of decision, or to design by simulation undetectable mines. ☑ Assist the military profession in making an earlier and more reliable decision, thanks to rapid, systematic, and explainable detection process with limited sensors.
REFERENCE DATA	<ul style="list-style-type: none"> ▶ Observations: 208 sonar echoes obtained by bouncing sonar signals off obstacles, at various angles and under various conditions, divided into 176 cases for Training/Validation, and 32 cases for External Test. Source: Terry Sejnowski, R. Paul Gorman, University of California - San Diego, Allied-Signal Aerospace Technology Center - Columbia, [http://archive.ics.uci.edu/ml]. Dataset: Dua, D. and Graff, C. (2019). UCI Machine Learning Repository [http://archive.ics.uci.edu/ml]. Irvine, CA: University of California, School of Information and Computer Science ▶ Predictive Variables: 60 Potential Predictors are measures included in [0 ; 1] characterizing the energy in a specific frequency band, integrated over a period [Energy in frequency band 1, 2...]. ▶ Variable To Predict: Detected object type [ROCK / MINE].

MODEL TYPE	Regression	Multinomial Classification	Binomial Classification	Scoring
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✓ XTRACTIS SOLUTION

PROCESS	Reference Data	INDUCTION + Reverse-Engineering ¹	XTRACTIS Top-Model	New Cases	DEDUCTION	Automated Decision (supporting experts' decision)
SOFTWARE ROBOTS		XTRACTIS® GENERATE			XTRACTIS® PREDICT	+ Prediction Report (for decision explainability)

RESULTS	<ul style="list-style-type: none"> ☑ Intelligible Predictive Top-Model: Decision system composed of 23 unchained gradual rules, each rule using some of the 29 variables that XTRACTIS identified as predictors. ☑ Robust Predictive Top-Model: Good performance on External Test. ☑ Operational Efficient System: Real-time predictions up to 70,000 decisions/s., offline or online (API).
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TOP-MODEL INDUCTION

INDUCTION PARAMETERS

We launch 2,000 inductive reasoning strategies; each strategy is applied on 40 different 5-fold-partitions of the Training/Validation dataset to get a reliable assessment of the descriptive and predictive performances. Each strategy thus generates 200 unitary models called **Individual Virtual Expert (IVE)**, and whose decisions are aggregated with 3 possible operators into a **College of Virtual Experts (CVE)**. Among the 6,000 CVE, the top-CVE with the best predictive performance remains complex (60 predictors shared by 1,989 rules).

We then apply 2,000 induction strategies to the same single Training (34%)/Validation (33%)/Test (33%) partition of a synthetic dataset: 35,200 new cases simulated by deduction from the top-CVE, around the 176 cases but distinct from these original cases. This XTRACTIS Reverse-Engineering¹ process induces 2,000 IVE. The top-IVE selected is as efficient as the top-CVE, but intelligible (29 predictors shared by 23 rules).

Total number of induced unitary models
402,000 IVE

Criterion for the induction optimization
F₁-Score

Validation criterion for the top-model selection
F₁-Score

Duration of the process (Induction Power FP64)
~25 hours (1 Tflops)

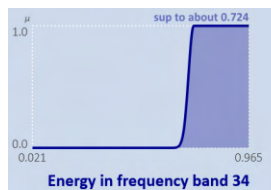
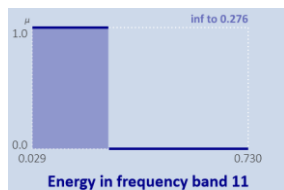
STRUCTURE

Intelligibility

The top-IVE model combines the 29 predictors automatically selected by XTRACTIS into 23 rules. Its Structure Report reveals all the internal decision logic and ensures that the human expert understands the model. This decision system is a *white-box* model that can be audited by the domain expert and certified by the regulator before its deployment to end-users.

PREDICTORS

- ▶ 29 energy measures in frequency bands out of 60
- ▶ Ranked by impact significance (1 strong, 9 medium & 19 weak signals):
#1 Energy in frequency band 11
#2 Energy in frequency band 34
/ #3 /... / #29
- ▶ Labeled by fuzzy and crisp classes
Examples: **crisp interval** "inf to 0.276";
fuzzy interval "sup to about 0.724"



RULES

- ▶ 23 connective fuzzy rules without chaining (aggregated into 2 disjunctive fuzzy rules)
- ▶ 2 to 6 predictors per rule (on average, 3.9 predictors per rule)
- ▶ Example: **fuzzy rule R1** uses 3 predictors, and concludes "ROCK". 22 other rules complete this model, including 1 binary rule.

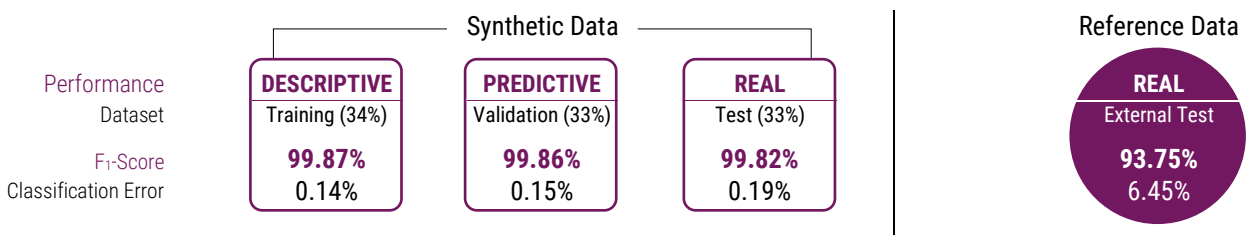
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IF Energy in frequency band 11 IS inf to 0.276
AND Energy in frequency band 34 IS sup to about 0.724
AND Energy in frequency band 45 IS about [0.088 ; 0.312]
THEN Detected Object IS ROCK
    
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PERFORMANCE

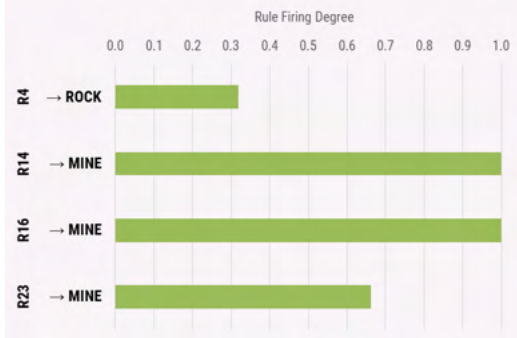
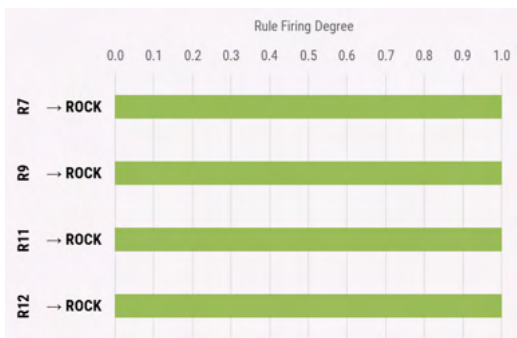
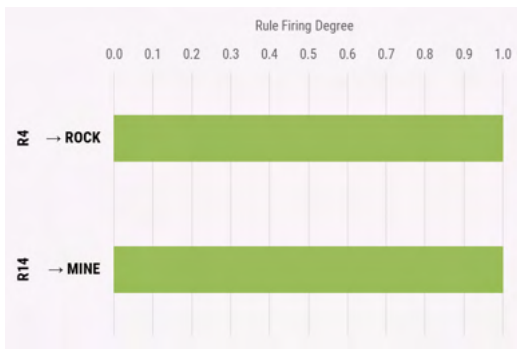
Robustness

The top-IVE performances, measured in Training/Validation/Test on synthetic data, then in External Test on reference data, guarantee the model's predictive and real performances.




Xtractis Top-Model: Intelligible AND Good Predictive Capacity

PREDICTIONS FOR 3 CASES FROM THE EXTERNAL TEST SET






CASE (not used in Training/Validation)	DEDUCTIVE INFERENCE OF RULES	DECISION																																
<p>ECHO #133 (actual value = MINE)</p> <table border="1"> <tr><td>Energy in frequency band 8</td><td>0.422</td></tr> <tr><td>Energy in frequency band 9</td><td>0.574</td></tr> <tr><td>Energy in frequency band 11</td><td>0.349</td></tr> <tr><td>Energy in frequency band 12</td><td>0.170</td></tr> <tr><td>Energy in frequency band 15</td><td>0.422</td></tr> <tr><td>Energy in frequency band 16</td><td>0.531</td></tr> <tr><td>Energy in frequency band 19</td><td>0.191</td></tr> <tr><td>Energy in frequency band 20</td><td>0.832</td></tr> <tr><td>Energy in frequency band 21*</td><td>1.000</td></tr> <tr><td>Energy in frequency band 22</td><td>0.408</td></tr> <tr><td>...</td><td>...</td></tr> <tr><td>Energy in frequency band 47</td><td>0.133</td></tr> <tr><td>Energy in frequency band 49</td><td>0.106</td></tr> <tr><td>Energy in frequency band 53</td><td>0.0081</td></tr> <tr><td>Energy in frequency band 54</td><td>0.0303</td></tr> <tr><td>Energy in frequency band 55</td><td>0.0190</td></tr> </table>	Energy in frequency band 8	0.422	Energy in frequency band 9	0.574	Energy in frequency band 11	0.349	Energy in frequency band 12	0.170	Energy in frequency band 15	0.422	Energy in frequency band 16	0.531	Energy in frequency band 19	0.191	Energy in frequency band 20	0.832	Energy in frequency band 21*	1.000	Energy in frequency band 22	0.408	Energy in frequency band 47	0.133	Energy in frequency band 49	0.106	Energy in frequency band 53	0.0081	Energy in frequency band 54	0.0303	Energy in frequency band 55	0.0190	<p>Real Time</p> <p>For this signal, 4 rules are triggered: R14 and R16 at 1.000, R23 at 0.662, and R4 at 0.318.</p> <p>The other 19 rules are not activated.</p> 	<p>NUMBER OF TRIGGERED RULES 4 / 23</p> <p>FUZZY PREDICTION { MINE 1.000, ROCK 0.318 }</p> <p>FINAL PREDICTION { MINE }</p> <p>The system delivers a correct detection compared to the acoustic expert / experiment:</p> <p>MINE ⚠️</p>
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<p>ECHO #74 (actual value = ROCK)</p> <table border="1"> <tr><td>Energy in frequency band 8</td><td>0.095</td></tr> <tr><td>Energy in frequency band 9</td><td>0.079</td></tr> <tr><td>Energy in frequency band 11</td><td>0.126</td></tr> <tr><td>Energy in frequency band 12</td><td>0.083</td></tr> <tr><td>Energy in frequency band 15</td><td>0.151</td></tr> <tr><td>Energy in frequency band 16</td><td>0.140</td></tr> <tr><td>Energy in frequency band 19</td><td>0.299</td></tr> <tr><td>Energy in frequency band 20</td><td>0.325</td></tr> <tr><td>Energy in frequency band 21</td><td>0.380</td></tr> <tr><td>Energy in frequency band 22</td><td>0.566</td></tr> <tr><td>...</td><td>...</td></tr> <tr><td>Energy in frequency band 47</td><td>0.090</td></tr> <tr><td>Energy in frequency band 49</td><td>0.045</td></tr> <tr><td>Energy in frequency band 53</td><td>0.0072</td></tr> <tr><td>Energy in frequency band 54</td><td>0.0113</td></tr> <tr><td>Energy in frequency band 55</td><td>0.0012</td></tr> </table>	Energy in frequency band 8	0.095	Energy in frequency band 9	0.079	Energy in frequency band 11	0.126	Energy in frequency band 12	0.083	Energy in frequency band 15	0.151	Energy in frequency band 16	0.140	Energy in frequency band 19	0.299	Energy in frequency band 20	0.325	Energy in frequency band 21	0.380	Energy in frequency band 22	0.566	Energy in frequency band 47	0.090	Energy in frequency band 49	0.045	Energy in frequency band 53	0.0072	Energy in frequency band 54	0.0113	Energy in frequency band 55	0.0012	<p>Real Time</p> <p>For this signal, 4 rules are triggered: R7, R9, R11 and R12 at 1.000.</p> <p>The other 19 rules are not activated.</p> 	<p>NUMBER OF TRIGGERED RULES 4 / 23</p> <p>FUZZY PREDICTION { ROCK 1.000, MINE 0.000 }</p> <p>FINAL PREDICTION { MINE }</p> <p>The system delivers a correct detection compared to the acoustic expert / experiment:</p> <p>ROCK 👍</p>
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<p>ECHO #134 (actual value = MINE)</p> <table border="1"> <tr><td>Energy in frequency band 8</td><td>0.268</td></tr> <tr><td>Energy in frequency band 9</td><td>0.566</td></tr> <tr><td>Energy in frequency band 11</td><td>0.5</td></tr> <tr><td>Energy in frequency band 12</td><td>0.258</td></tr> <tr><td>Energy in frequency band 15</td><td>0.452</td></tr> <tr><td>Energy in frequency band 16</td><td>0.458</td></tr> <tr><td>Energy in frequency band 19</td><td>0.533</td></tr> <tr><td>Energy in frequency band 20</td><td>0.901</td></tr> <tr><td>Energy in frequency band 21</td><td>0.994</td></tr> <tr><td>Energy in frequency band 22</td><td>0.369</td></tr> <tr><td>...</td><td>...</td></tr> <tr><td>Energy in frequency band 47</td><td>0.077</td></tr> <tr><td>Energy in frequency band 49</td><td>0.078</td></tr> <tr><td>Energy in frequency band 53*</td><td>0.039</td></tr> <tr><td>Energy in frequency band 54</td><td>0.0294</td></tr> <tr><td>Energy in frequency band 55</td><td>0.0175</td></tr> </table>	Energy in frequency band 8	0.268	Energy in frequency band 9	0.566	Energy in frequency band 11	0.5	Energy in frequency band 12	0.258	Energy in frequency band 15	0.452	Energy in frequency band 16	0.458	Energy in frequency band 19	0.533	Energy in frequency band 20	0.901	Energy in frequency band 21	0.994	Energy in frequency band 22	0.369	Energy in frequency band 47	0.077	Energy in frequency band 49	0.078	Energy in frequency band 53*	0.039	Energy in frequency band 54	0.0294	Energy in frequency band 55	0.0175	<p>Real Time</p> <p>For this situation, only 2 conflicting rules are triggered: R4 and R14 at 1.000.</p> 	<p>NUMBER OF TRIGGERED RULES 2 / 23</p> <p>FUZZY PREDICTION { ROCK 1.000, MINE 1.000 }</p> <p>FINAL PREDICTION REFUSAL</p> <p>The system cannot decide between the 2 classes so it refuses to decide; this is the only Refusal prediction from the External Test cases. This Refusal could be a warning if the decision system runs in real-time.</p> <p>More training data with situations near this echo profile should strengthen the model in this decision space area.</p>
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*Predictor value outside the variation range of the model (< 0.01 % OOR for case #133 and 8.92 % OOR for case #134) but inside the allowed extrapolation range. Xtractis will refuse to give a result for an extrapolation far from the allowed extrapolation range. It is one situation of the "Refusal" prediction.

TOP-IVE BENCHMARK

	XTRACTIS 	LOGISTIC REGRESSION	RANDOM FOREST	BOOSTED TREES	NEURAL NETWORK
MODELS RELEASE	2022/09	2022/10	2021/12	2021/12	2022/02
ALGO VERSION	XTRACTIS GENERATE 12.2.43406	Python 3.9.10; Scikit-learn 1.1.2	Python 3.6; LightGBM 2.2.2	Python 3.6; LightGBM 2.2.2	Python 3.6; TensorFlow 2.6.2 Keras 2.6.0
CROSS-VALIDATION TECHNIQUE	40x5 folds for each CVE model Then 1-Split Validation for each IVE model (for the reverse engineering of top-CVE): 34% Training; 33% Validation; 33% Test	40x5 folds for each CVE model	40x5 folds for each CVE model	40x5 folds for each CVE model	40x5 folds for each CVE model
NUMBER OF EXPLORED STRATEGIES²	2,000 induction strategies for the CVE on Training / Validation data 2,000 induction strategies for the IVE on simulated data	2,000 ML strategies on Training / Validation data	800 ML strategies on Training / Validation data	800 ML strategies on Training / Validation data	2,000 ML strategies on Training / Validation data
NUMBER OF MODELS	6,000 CVE + selection of the top-CVE 2,000 IVE (for the reverse engineering of top-CVE) + selection of the top-IVE	2,000 CVE + selection of the top-CVE 1 top-IVE	800 CVE + selection of the top-CVE 1 top-IVE	800 CVE + selection of the top-CVE 1 top-IVE	2,000 CVE + selection of the top-CVE 1 top-IVE

TOP-IVE STRUCTURE

NUMBER OF PREDICTORS (out of 60 Potential Predictors)	29	51	55	58	60
DECISION STRUCTURE	System with 23 unchained fuzzy rules (or 2 disjunctive fuzzy rules)	1 linear equation	27 trees; 369 binary rules	48 chained trees; 503 binary rules	3 hidden layers; 74 hidden nodes
MODEL INTELLIGIBILITY (& DECISION EXPLAINABILITY)	 3.9 predictors per rule on average; only a few rules are triggered at a time.	 Linear equation with 51 coefficients	 Lots of predictors and rules	 Tree #N corrects the error of the N-1 previous trees	 Unintelligible synthetic variables

TOP-IVE REAL PERFORMANCE (External Test)

	<i>Random³</i>					
Classification Error	47.90%	6.45%	31.25%	15.63%	18.75%	12.50%
Sensitivity		93.75%	76.47%	88.24%	76.47%	88.24%
Specificity		93.33%	60.00%	80.00%	86.67%	86.67%
PPV		93.75%	68.42%	83.33%	86.67%	88.24%
NPV		93.33%	69.23%	85.71%	76.47%	86.67%
F₁-Score	55.17%	93.75%	72.22%	85.72%	81.25%	88.24%
Refusals	N/A	3.13%	N/A	N/A	N/A	N/A
MODEL ROBUSTNESS		#1	#5	#3	#4	#2

¹ Given the small number of reference cases of this dataset, the XTRACTIS Reverse-Engineering (CVE→IVE) is necessary to get a robust AND intelligible model.

² All CVE and IVE models are optimized according to their validation F₁-Score. The XTRACTIS top-CVE and top-IVE are selected according to their validation F₁-Score while checking that it remains close to their training F₁-Score. The ML/LoR CVE top-models are selected according to the mean value of their F₁-Score in validation. Each ML/LoR top-IVE is obtained by applying the respective ML/LoR top-CVE strategy on 100% of the Training/Validation data.

³ Baseline performances that models must exceed to perform better than chance (P-value = 0.001; 100,000 models generated by random permutation of the output values).

More Use Cases:
xtractis.ai/use-cases/