Composite Event Recognition for Maritime Monitoring

Manolis Pitsikalis\textsuperscript{1}, Alexander Artikis\textsuperscript{2,1}, Richard Dreo\textsuperscript{3}, Cyril Ray\textsuperscript{3,4}, Elena Camossi\textsuperscript{5} and Anne-Laure Jousselme\textsuperscript{5}

\textsuperscript{1}Institute of Informatics & Telecommunications, NCSR Demokritos, Athens, Greece
\textsuperscript{2}Department of Maritime Studies, University of Piraeus, Greece
\textsuperscript{3}Naval Academy Research Institute, Brest, France, \textsuperscript{4}Arts et Metiers ParisTech, France
\textsuperscript{5}Centre for Maritime Research and Experimentation (CMRE), NATO, La Spezia, Italy

http://cer.iit.demokritos.gr
Composite Event Recognition

Event Recognition System

CE Definitions

Streams of SDEs

Recognised CEs

INPUT ▶ RECOGNITION ▶ OUTPUT ■
Composite Event Recognition for Maritime Monitoring
Run-Time Event Calculus (RTEC):

- Guides data-driven reasoning using domain-knowledge.
- High-level language facilitating interaction with domain experts.
- Built-in rules for temporal reasoning.
- Formal, declarative semantics.
- Scalable to high-velocity data streams.
- Direct routes to machine learning.
Event Calculus

• A **logic programming language** for representing and reasoning about events and their effects.

• Key components:
  - **event** (typically instantaneous).
  - **fluent**: a property that may have different values at different points in time.

• Built-in representation of **inertia**:
  - $F = V$ holds at a particular time-point if $F = V$ has been *initiated* by an event at some earlier time-point, and not *terminated* by another event in the meantime.
# Run-Time Event Calculus (RTEC)

<table>
<thead>
<tr>
<th>Predicate</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>happensAt(E, T)</code></td>
<td>Event (E) occurs at time (T)</td>
</tr>
<tr>
<td><code>initiatedAt(F = V, T)</code></td>
<td>At time (T) a period of time for which (F = V) is initiated</td>
</tr>
<tr>
<td><code>terminatedAt(F = V, T)</code></td>
<td>At time (T) a period of time for which (F = V) is terminated</td>
</tr>
<tr>
<td><code>holdsFor(F = V, I)</code></td>
<td>(I) is the list of the maximal intervals for which (F = V) holds continuously</td>
</tr>
<tr>
<td><code>holdsAt(F = V, T)</code></td>
<td>The value of fluent (F) is (V) at time (T)</td>
</tr>
<tr>
<td><code>union_all([J_1, \ldots, J_n], I)</code></td>
<td>(I = (J_1 \cup \ldots \cup J_n))</td>
</tr>
<tr>
<td><code>intersect_all([J_1, \ldots, J_n], I)</code></td>
<td>(I = (J_1 \cap \ldots \cap J_n))</td>
</tr>
<tr>
<td><code>relative_complement_all(I', [J_1, \ldots, J_n], I)</code></td>
<td>(I = I' \setminus (J_1 \cup \ldots \cup J_n))</td>
</tr>
<tr>
<td><code>deadline[UE](F = V, T)</code></td>
<td>(F = V) is terminated after (T) timepoints (\text{(Unless Extended)})</td>
</tr>
</tbody>
</table>
Run-Time Event Calculus (RTEC)

<table>
<thead>
<tr>
<th>Predicate</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>happensAt(E, T)</code></td>
<td>Event $E$ occurs at time $T$</td>
</tr>
<tr>
<td><code>initiatedAt(F = V, T)</code></td>
<td>At time $T$ a period of time for which $F = V$ is initiated</td>
</tr>
<tr>
<td><code>terminatedAt(F = V, T)</code></td>
<td>At time $T$ a period of time for which $F = V$ is terminated</td>
</tr>
<tr>
<td><code>holdsFor(F = V, I)</code></td>
<td>$I$ is the list of the maximal intervals for which $F = V$ holds continuously</td>
</tr>
<tr>
<td><code>holdsAt(F = V, T)</code></td>
<td>The value of fluent $F$ is $V$ at time $T$</td>
</tr>
<tr>
<td><code>union_all([J_1, \ldots, J_n], I)</code></td>
<td>$I = (J_1 \cup \ldots \cup J_n)$</td>
</tr>
<tr>
<td><code>intersect_all([J_1, \ldots, J_n], I)</code></td>
<td>$I = (J_1 \cap \ldots \cap J_n)$</td>
</tr>
<tr>
<td><code>relative_complement_all(I', [J_1, \ldots, J_n], I)</code></td>
<td>$I = I' \setminus (J_1 \cup \ldots \cup J_n)$</td>
</tr>
<tr>
<td><code>deadline[UE](F = V, T)</code></td>
<td>$F = V$ is terminated after $T$ timepoints (Unless Extended)</td>
</tr>
</tbody>
</table>
# Run-Time Event Calculus (RTEC)

<table>
<thead>
<tr>
<th>Predicate</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>happensAt(E, T)</code></td>
<td>Event $E$ occurs at time $T$</td>
</tr>
<tr>
<td><code>initiatedAt(F = V, T)</code></td>
<td>At time $T$ a period of time for which $F = V$ is initiated</td>
</tr>
<tr>
<td><code>terminatedAt(F = V, T)</code></td>
<td>At time $T$ a period of time for which $F = V$ is terminated</td>
</tr>
<tr>
<td><code>holdsFor(F = V, I)</code></td>
<td>$I$ is the list of the maximal intervals for which $F = V$ holds continuously</td>
</tr>
<tr>
<td><code>holdsAt(F = V, T)</code></td>
<td>The value of fluent $F$ is $V$ at time $T$</td>
</tr>
<tr>
<td><code>union_all([J₁, ..., Jₙ], I)</code></td>
<td>$I = (J₁ \cup \ldots \cup Jₙ)$</td>
</tr>
<tr>
<td><code>intersect_all([J₁, ..., Jₙ], I)</code></td>
<td>$I = (J₁ \cap \ldots \cap Jₙ)$</td>
</tr>
<tr>
<td><code>relative_complement_all(I', [J₁, ..., Jₙ], I)</code></td>
<td>$I = I' \setminus (J₁ \cup \ldots \cup Jₙ)$</td>
</tr>
<tr>
<td><code>deadline[UE](F = V, T)</code></td>
<td>$F = V$ is terminated after $T$ timepoints</td>
</tr>
<tr>
<td></td>
<td>(Unless Extended)</td>
</tr>
</tbody>
</table>
Run-Time Event Calculus (RTEC)

<table>
<thead>
<tr>
<th>Predicate</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>happensAt($E$, $T$)</td>
<td>Event $E$ occurs at time $T$</td>
</tr>
<tr>
<td>initiatedAt($F = V$, $T$)</td>
<td>At time $T$ a period of time for which $F = V$ is initiated</td>
</tr>
<tr>
<td>terminatedAt($F = V$, $T$)</td>
<td>At time $T$ a period of time for which $F = V$ is terminated</td>
</tr>
<tr>
<td>holdsFor($F = V$, $I$)</td>
<td>$I$ is the list of the maximal intervals for which $F = V$ holds continuously</td>
</tr>
<tr>
<td>holdsAt($F = V$, $T$)</td>
<td>The value of fluent $F$ is $V$ at time $T$</td>
</tr>
<tr>
<td>union_all($[J_1, \ldots, J_n]$, $I$)</td>
<td>$I = (J_1 \cup \ldots \cup J_n)$</td>
</tr>
<tr>
<td>intersect_all($[J_1, \ldots, J_n]$, $I$)</td>
<td>$I = (J_1 \cap \ldots \cap J_n)$</td>
</tr>
<tr>
<td>relative_complement_all($I'$, $[J_1, \ldots, J_n]$, $I$)</td>
<td>$I = I' \setminus (J_1 \cup \ldots \cup J_n)$</td>
</tr>
<tr>
<td>deadline[UE]($F = V$, $T$)</td>
<td>$F = V$ is terminated after $T$ timepoints (Unless Extended)</td>
</tr>
</tbody>
</table>
CE Definitions in the RTEC

CE definition:

\[
\text{initiatedAt}(CE, T) \leftarrow \text{happensAt}(E_{ln}, T), \\
\text{[conditions]}
\]

\[\ldots\]

\[
\text{initiatedAt}(CE, T) \leftarrow \text{happensAt}(E_{ln_i}, T), \\
\text{[conditions]}
\]

\[
\text{terminatedAt}(CE, T) \leftarrow \text{happensAt}(E_{T_1}, T), \\
\text{[conditions]}
\]

\[\ldots\]

\[
\text{terminatedAt}(CE, T) \leftarrow \text{happensAt}(E_{T_j}, T), \\
\text{[conditions]}
\]

CE recognition:
CE Definitions in the RTEC

CE definition:

\[
\text{initiatedAt}(CE, T) \leftarrow \text{happensAt}(E_{ln1}, T), \quad \text{happensAt}(E_{lni}, T), \quad \text{happensAt}(E_{tn1}, T), \quad \text{happensAt}(E_{tnj}, T).
\]

\[
\text{terminatedAt}(CE, T) \leftarrow \text{happensAt}(E_{ln1}, T), \quad \text{happensAt}(E_{lni}, T), \quad \text{happensAt}(E_{tn1}, T), \quad \text{happensAt}(E_{tnj}, T).
\]

CE recognition:
CE Definitions in the RTEC

CE definition:

\[
\text{initiatedAt}(CE, T) \leftarrow \text{happensAt}(E_{In_i}, T), \quad \text{happensAt}(E_{T_i}, T), \quad \text{[conditions]}
\]

\[
\text{terminatedAt}(CE, T) \leftarrow \text{happensAt}(E_{T_1}, T), \quad \text{happensAt}(E_{T_j}, T), \quad \text{[conditions]}
\]

CE recognition:

[Diagram showing time line with events and conditions]
CE Definitions in the RTEC

CE definition:

\[
\text{initiatedAt}(CE, T) \leftarrow \text{happensAt}(E_{ln_i}, T), \quad \text{[conditions]}
\]

\[
\text{initiatedAt}(CE, T) \leftarrow \text{happensAt}(E_{ln_j}, T), \quad \text{[conditions]}
\]

\[
\ldots
\]

\[
\text{terminatedAt}(CE, T) \leftarrow \text{happensAt}(E_{T_1}, T), \quad \text{[conditions]}
\]

\[
\text{terminatedAt}(CE, T) \leftarrow \text{happensAt}(E_{T_j}, T), \quad \text{[conditions]}
\]

CE recognition: \(\text{holdsFor}(CE, I)\)

\[
\text{time}
\]

\[
0
\]
initiatedAt(drifting(Vessel), T) ←
happensAt(velocity(Vessel, ←, CoG, TrHd), T),
angleDiff(CoG, TrHd, Ad),
threshold(v_{ad}, V_{ad}), Ad > V_{ad},
holdsAt(underWay(Vessel), T).

terminatedAt(drifting(Vessel), T) ←
happensAt(velocity(Vessel, ←, CoG, TrHd), T),
angleDiff(CoG, TrHd, Ad),
threshold(v_{ad}, V_{ad}), Ad \leq V_{ad}.

terminatedAt(drifting(Vessel), T) ←
happensAt(end(underWay(Vessel)), T).
initiatedAt(trawlingMovement(Vessel), T) ←
  happensAt(change_in_heading(Vessel), T),
vesselType(Vessel, fishing),
holdsAt(withinArea(Vessel, fishing), T).
deadlineUE(trawlingMovement(Vessel), MinT).

holdsFor(trawling(Vessel), I) ←
  holdsFor(trawlingMovement(Vessel), Itc),
  holdsFor(trawlSpeed(Vessel), It),
  intersect_all([It, Itc], I_i),
threshold(v_trawl, V_trawl),
intDurGreater(I_i, V_trawl, I).
Maritime Pattern Hierarchy

- withinArea
  - anchoredOrMoored
  - loitering
  - stopped
  - rendezVous
  - pilotBoarding
  - lowSpeed
  - tuggingSpeed
  - tugging
  - sarSpeed
  - sarMovement
  - sar
  - highSpeedNC
  - trawlSpeed
  - sar
  - trawlingMovement
  - trawling
  - changingSpeed
  - movingSpeed
  - underWay
  - drifting
Empirical Evaluation
## Empirical Evaluation

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Brest, France</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (months)</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Vessels</td>
<td>5K</td>
<td>34K</td>
</tr>
<tr>
<td>AIS signals</td>
<td>18M</td>
<td>55M</td>
</tr>
<tr>
<td>Critical points</td>
<td>4.6M</td>
<td>17M</td>
</tr>
<tr>
<td>Fishing areas</td>
<td>263</td>
<td>1K</td>
</tr>
<tr>
<td>Natura 2000 areas</td>
<td>1K</td>
<td>6K</td>
</tr>
<tr>
<td>Ports</td>
<td>222</td>
<td>2201</td>
</tr>
<tr>
<td>Spatio-temporal events</td>
<td>811K</td>
<td>7M</td>
</tr>
</tbody>
</table>
## Empirical Evaluation

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Brest, France</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (months)</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Vessels</td>
<td>5K</td>
<td>34K</td>
</tr>
<tr>
<td>AIS signals</td>
<td>18M</td>
<td>55M</td>
</tr>
<tr>
<td>Critical points</td>
<td>4.6M</td>
<td>17M</td>
</tr>
<tr>
<td>Fishing areas</td>
<td>263</td>
<td>1K</td>
</tr>
<tr>
<td>Natura 2000 areas</td>
<td>1K</td>
<td>6K</td>
</tr>
<tr>
<td>Ports</td>
<td>222</td>
<td>2201</td>
</tr>
<tr>
<td>Spatio-temporal events</td>
<td>811K</td>
<td>7M</td>
</tr>
</tbody>
</table>
Precision based on expert feedback

<table>
<thead>
<tr>
<th>Composite Event</th>
<th>TP</th>
<th>FP</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>anchoredOrMoored(Vessel)</td>
<td>3067</td>
<td>4</td>
<td>0.999</td>
</tr>
<tr>
<td>trawling(Vessel)</td>
<td>29</td>
<td>0</td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>tugging(Vessel)</td>
<td>117</td>
<td>0</td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>pilotBoarding(Vessel_1, Vessel_2)</td>
<td>80</td>
<td>0</td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>rendezVous(Vessel_1, Vessel_2)</td>
<td>52</td>
<td>2</td>
<td>0.963</td>
</tr>
</tbody>
</table>

One month of the Brest dataset.
## Compression effects on accuracy

<table>
<thead>
<tr>
<th>Composite Event</th>
<th>Brest $F_1$-Score</th>
<th>Europe $F_1$-Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>highSpeedNC($Vessel$)</td>
<td>0.989</td>
<td>0.989</td>
</tr>
<tr>
<td>anchoredOrMoored($Vessel$)</td>
<td><strong>1.000</strong></td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>drifting($Vessel$)</td>
<td>0.999</td>
<td>-</td>
</tr>
<tr>
<td>trawling($Vessel$)</td>
<td>0.994</td>
<td>0.998</td>
</tr>
<tr>
<td>tugging($Vessel_1$, $Vessel_2$)</td>
<td>0.994</td>
<td>0.951</td>
</tr>
<tr>
<td>pilotBoarding($Vessel_1$, $Vessel_2$)</td>
<td><strong>1.000</strong></td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>rendezVous($Vessel_1$, $Vessel_2$)</td>
<td><strong>1.000</strong></td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>loitering($Vessel$)</td>
<td><strong>1.000</strong></td>
<td><strong>1.000</strong></td>
</tr>
<tr>
<td>sar($Vessel$)</td>
<td>0.998</td>
<td>0.988</td>
</tr>
</tbody>
</table>
Performance Evaluation: Brest, France

![Map of Brest, France](image)

- **Average number of input entities (in thousands):**
  - Enriched AIS Stream
  - Critical Point Stream

- **Average recognition time (sec):**
  - Enriched AIS Stream
  - Critical Point Stream

The graphs show the relationship between window size (in hours) and the two metrics. As the window size increases, the average number of input entities and average recognition time also increase.
Performance Evaluation: Europe

![Graph showing performance evaluation for Europe.]
Summary

Composite Event Recognition system for maritime monitoring:
  • with formal specifications of effective maritime patterns,
  • evaluated by domain experts using real data,
  • and proven to be capable of real-time CER.

Current work:
  • data fusion (AIS in conjunction with SAR images, radar etc),
  • and detection of dark targets.

The dataset of recognised composite events is available here:
https://zenodo.org/record/2557290

Join us in the demo session or visit our site below:
https://cer.iit.demokritos.gr/cermm