Aligning, Interoperating, and Co-executing Air Traffic Control Rules Across PSOA RuleML and IDP

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Outline

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ATC KB

- ATC KB (Air Traffic Control Knowledge Base) builds on top of ATC Regulations concerning the *separation minimum*

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ICAO Wake Turbulence Categorization

Light — MTOM of 7000 kg or less.

Medium — MTOM of greater than 7000 kg, but less than 136000 kg.

Heavy — MTOM of 136000 kg or greater.

Super — A separate designation that currently only refers to the Airbus A380 (MTOM 575000 kg, ICAO designation `A388`).

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ICAO Weight Categories and Associated Separation Minima

ICAO separation standards (nautical miles)

		Follower			
		Super	Heavy	Medium	Light
Leader	Super	MRS	6	7	8
	Heavy	MRS	4	5	6
	Medium	MRS	MRS	MRS	5
	Light	MRS	MRS	MRS	MRS

MRS: Minimum Radar Separation.

Outline

PSOA RuleML Rule Languages

- **P**ositional-**S**lotted **O**bject-**A**pplicative (**PSOA**) RuleML integrates table-like relationships and graph-like frames into **p***ositional-***s***lotted* **o***bject-***a***pplicative* (**psoa**) *terms*
- Three anchor languages: datalog, hornlog, (naf)folog(eq)
- The often used *single-dependent-tuple independent-slot special case of psoa terms*, oidless or oidful, has these forms ($n \geq 0$ and $k \geq 0$):

$$\textbf{Oidless}: \quad \texttt{f(}\texttt{t}_1 \ldots \texttt{t}_n\ \texttt{p}_1\texttt{->}\texttt{v}_1 \ldots \texttt{p}_k\texttt{->}\texttt{v}_k\texttt{)} \tag{1}$$

$$\textbf{Oidful}: \quad \texttt{o\#f(}\texttt{t}_1 \ldots \texttt{t}_n\ \texttt{p}_1\texttt{->}\texttt{v}_1 \ldots \texttt{p}_k\texttt{->}\texttt{v}_k\texttt{)} \tag{2}$$

Examples in ATC KB

```
:AircraftIcaoCategory(:a388 icao:Super)
:be9l#:Aircraft(:mtow->9300.0)
```

- we focus on either $n = 0$ for – oidless – *frameships* and – oidful – *framepoints*,
- or $k = 0$ for – oidless – *relationships*

IDP

- **IDP** is both the name of a *Knowledge Based System* and the *declarative language* used to create the Knowledge Base
- The **Knowledge Based Paradigm** advocates a strict separation between domain knowledge gathered in the Knowledge Base, and various possible inferences to use this knowledge to solve specific problems
- IDP can deal both with **rules** and **constraints**
- The IDP language adds types, aggregates and **inductive definitions** to classic FO

Examples in ATC KB

```
{!id:  IcaoCategory(id) = Light <- mtom(id) =< 7000.}
{Separation = MRS <- IcaoCategory(Leader) = Light.}
```

Outline

ATC KB in PSOA and IDP : Alignment

Signature declaration :

- Explicit vocabulary in IDP
- In PSOA RuleML there is no separate signature declaration

Specifications

PSOA RuleML

```
Forall ?a ?w (
  :AircraftIcaoCategory(?a icao:Light) :-
    And(?a#:Aircraft(:mtom->?w)
        math:lessEq(?w 7000))  )
Forall ?a ?w (
  :AircraftIcaoCategory(?a icao:Heavy) :-
    And(?a#:Aircraft(:mtom->?w)
        math:greaterEq(?w 136000)
        not:Naf(:AircraftIcaoCategory
                    (?a icao:Super))
) )
%% Sample Aircraft Facts %%

:be91#:Aircraft(:mtom->4218.41
                :mtow->9300.0
                :wingspan->45.92
                :appSpeed->100.0)

:a388#:Aircraft(:mtom->575000.0
                :mtow->1267658.0
                :wingspan->261.65
                :appSpeed->145.0)
```

IDP Aligned

```
vocabulary V {
    type Mtom isa int
    type Aircraft isa string
    MTOM(Aircraft,Mtom)
        ... }


theory T:V{
    !a[Aircraft] w[Mtom]:
    AircraftIcaoCategory(a, Light) <=
        MTOM(a,w)
            & w =< 7000.
    !a[Aircraft] w[Mtom]:
    AircraftIcaoCategory(a, Heavy) <=
        MTOM(a,w)
                & 136000 =< w
                & a ~= a388
                & a ~= a38f.

structure S1 : V {
    //specific value assignments:
    Leader = {a388}
    Follower = {be91}
    ...

    //aircraft data
    MTOM = {be91, 4218; a388, 575000}
    MTOW = {be91, 9300; a388, 1267658}
    WingSpan = {be91, 45; a388, 261}
    AppSpeed = {be91, 100; a388, 145}
}
```

IDP Definition

```
vocabulary V {
    type Icao constructed from {Light, Medium,
                                Heavy, Super}
    type AeroplaneID isa string
    IcaoCategory(AeroplaneID) : Icao
    mtom(AeroplaneID) : Mass
        ... }
theory T:V{
  { !id: IcaoCategory(id) = Light <-
        mtom(id) =< 7000.
    !id: IcaoCategory(id) = Medium <-
        7000 < mtom(id) =< 136000.
    !id: IcaoCategory(id) = Heavy <-
         (136000 < mtom(id)) &
         IcaoCategory(id) ~= Super.
    IcaoCategory("a388") = Super.
    IcaoCategory("a38f") = Super.  }


structure S : V {
    AeroplaneID = {
    a388        ;
    a500        ;
    sgup        }

    mtom =      {
    a380        ,       137000  ;
    a500        ,       3175.15 ;
    sgup        ,       77110.7 }
```

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Expressing relations

- Possibility to use n-ary functions and relations in IDP
- Atom dimensions in PSOA RuleML : OIDless/OIDful, independent/dependent, slotted/tupled

Specifications

PSOA RuleML

```
Forall ?a ?w (
  :AircraftIcaoCategory(?a icao:Light) :-
    And(?a#:Aircraft(:mtom->?w)
        math:lessEq(?w 7000))  )
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        not:Naf(:AircraftIcaoCategory
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%% Sample Aircraft Facts %%

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```

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        ... }


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structure S1 : V {
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    MTOM = {be91, 4218; a388, 575000}
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        ... }
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        7000 < mtom(id) =< 136000.
    !id: IcaoCategory(id) = Heavy <-
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Negation as failure:

- Does not exist in IDP
- Exists in PSOA RuleML

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        MTOM(a,w)
            & w =< 7000.
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                & 136000 =< w
                & a ~= a388
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    !id: IcaoCategory(id) = Heavy <-
         (136000 < mtom(id)) &
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Using the Knowledge Bases

- Focus on possible world models in IDP
- Answers obtained by query answering in PSOA RuleML

Specifications

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    mtom =      {
    a380        ,       137000  ;
    a500        ,       3175.15 ;
    sgup        ,       77110.7 }
```

Interoperation and Co-Execution

A partial translation can be realized:

- PSOA's relationship – *Oidless*: $\texttt{f(t}_1 \ldots \texttt{t}_n\texttt{)}$ `:AircraftIcaoCategory(:a388 icao:Super)`

$\Rightarrow$ Relation in IDP : `AircraftIcaoCategory(a388,Super)`

Interoperation and Co-Execution

A partial translation can be realized:

- PSOA's framepoint – *Oidful* : `o#f(`$\mathtt{p}_1$`->`$\mathtt{v}_1$ ... $\mathtt{p}_k$`->`$\mathtt{v}_k$`) :be91#:Aircraft(:mtom->4218.41)`

$\Rightarrow$ Mimicked with binary relations in IDP : `MTOM(be91,4218)`

Interoperation and Co-Execution

A partial translation can be realized:

- PSOA's frameship – *Oidless* : $\texttt{f(p}_1\texttt{->v}_1\ \ldots\ \texttt{p}_k\texttt{->v}_k\texttt{)}$
  `:icaoSeparation(:leader->?l :follower->?f :miles->?d)`

$\Rightarrow$ Function in IDP :
`IcaoSeparation(Leader, Follower) : MilesDistance`

Interoperation and Co-Execution

A partial translation can be realized:

- PSOA's frameship – *Oidless* : `f(`$\mathtt{p}_1$`->`$\mathtt{v}_1$ ... $\mathtt{p}_k$`->`$\mathtt{v}_k$`)`
  `:icaoSeparation(:leader->?l :follower->?f :miles->?d)`

$\Rightarrow$ Function in IDP :
`IcaoSeparation(Leader, Follower) : MilesDistance`

Co-execution with the purpose of:

- Checking and validating the outcome of the respective applications
- Complementing the top-down processing of PSOATransRun with bottom-up processing of IDP
- Efficiently distribute tasks over systems

Outline

Inconsistencies within Regulations (1)

RECAT Regulations

Category D. Aircraft capable of MTOW of less than 300,000 pounds and wingspan greater than 125 ft and less than or equal to 175 ft; or aircraft with wingspan greater than 90 ft and less than or equal to 125 ft.

Category F. Aircraft capable of MTOW of less than 41,000 pounds and wingspan less than or equal to 125 ft, or aircraft capable of MTOW less than 15,500 pounds regardless of wingspan, or a powered sailplane.

Inconsistencies within Regulations (1)

RECAT Regulations

Category D. Aircraft capable of MTOW of less than 300,000 pounds and wingspan greater than 125 ft and less than or equal to 175 ft; or aircraft with wingspan greater than 90 ft and less than or equal to 125 ft.

Category F. Aircraft capable of MTOW of less than 41,000 pounds and wingspan less than or equal to 125 ft, or aircraft capable of MTOW less than 15,500 pounds regardless of wingspan, or a powered sailplane.

Inconsistency

Any aircraft capable of MTOW of less than 41,000 pounds with wingspan greater than 90 ft and less than or equal to 125 ft will be categorized in both **D** and **F** categories

Inconsistencies within Regulations (1)

RECAT Regulations

Category D. Aircraft capable of MTOW of less than 300,000 pounds and wingspan greater than 125 ft and less than or equal to 175 ft; or aircraft with wingspan greater than 90 ft and less than or equal to 125 ft.

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PSOA RuleML Query

```
And(:AircraftRecatCategory(?a ?X) :AircraftRecatCategory(?a ?Y)
    External(isopl:generic_not_eq(?X ?Y)))
Answer(s):
?a=<...#dc3>  ?X=<...#D> ?Y=<...#F>
?a=<...#dhc4> ?X=<...#D> ?Y=<...#F>

...
```

Inconsistencies within Regulations (1)

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IDP

```
{!id :  Recat(id) = D <- 125 >= wingspan(id) > 90.
 !id :  Recat(id) = F <- (...)  & 125 >= wingspan(id).}
```

- No query is needed, `unsatisfiable` message will be displayed
  - not possible to find a model that satisfies all constraints
  - difficult to find the exact inconsistency in a theory

Inconsistencies within Regulations (2)

RECAT Regulations, later revision

Category D. . . . or aircraft capable of a MTOW greater than 41,000 pounds with a wingspan greater than 90 ft and less than or equal to 125 ft.

Category F. Aircraft capable of MTOW of less than 41,000 pounds and wingspan less than or equal to 125 ft, or aircraft capable of MTOW less than 15,500 pounds regardless of wingspan, or a powered sailplane.

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Category F. Aircraft capable of MTOW of less than 41,000 pounds and wingspan less than or equal to 125 ft, or aircraft capable of MTOW less than 15,500 pounds regardless of wingspan, or a powered sailplane.

Incompleteness

Any aircraft capable of MTOW of exactly 41,000 pounds with wingspan greater than 90 ft and less than or equal to 125 ft will never be categorized

- No real-life example
- Dassault Falcon 2000, MTOW: 41,000 pounds, wingspan 63 ft

Inconsistencies within Regulations (2)

RECAT Regulations, later revision

Category D. . . . or aircraft capable of a MTOW greater than 41,000 pounds with a wingspan greater than 90 ft and less than or equal to 125 ft.

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PSOA RuleML

Discovery by adding "witness" aircraft representing corner cases

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IDP

- Use of the definition notation : all cases need to be covered

```
Unsatisfiable Number of models:  0
```

- Use of material implication : random category will be assigned to "witness" aircraft

Outline

Additional developments to the ATC KB

Order four aircraft in such a way that the total separation is minimized

Optimization

```
term totalSeparation:V{
    sum{ac: Leader = ac V Follower1 = ac V Follower2 = ac V
    Follower3 = ac : Separation(ac,Next(ac))}
}
procedure main() {
    printmodels(minimize(T, S, totalSeparation))
}
```

Dependent-Slot ATC KB Version

PSOA RuleML explicitly specifies for each descriptor (tuple, slot) whether it is to be interpreted *dependent on* (under the perspective of) the predicate in whose scope it occurs:

- It permits atoms atoms with dependent slots, denoted by "+>" (instead of "->" for independent slots)
- This supports advanced data and knowledge representation where, for the same OID, a slot name can have different fillers depending on a predicate (in the example: `wtc`, wake turbulence category)

Example in ATC KB

- Perspective-providing predicates: `IcaoRegulated` vs. `FaaRegulated`

```
:a225#:IcaoRegulated(wtc+>icao:Heavy)
:a225#:FaaRegulated(wtc+>faa:Super)
```

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Conclusions

ATC KB in IDP and PSOA RuleML

- We discussed the alignment of both specifications and the implications of modeling choices that are involved in this
- Inconsistencies in the original regulations were discovered
  - this demonstrates the added value of combining two separate systems to formalize the same knowledge

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IDP and PSOA RuleML

- A partial interoperation is possible for facts and rules
- Co-execution: the advantages of each system can be exploited from within a combined application
  - optimization, in the constraint-based system IDP
  - disambiguation of slots via their dependence, in the graph-based system PSOA RuleML

Future Work

PSOA and IDP Alignment

- Align additional KBs
  - examine the constructs used in these KBs and define the complete intersection of PSOA and IDP constructs

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PSOA and IDP Interoperation

- Round-trippable translation between increasing subsets of the two languages
- Further development of the systems
  - support for a separated vocabulary in PSOA RuleML
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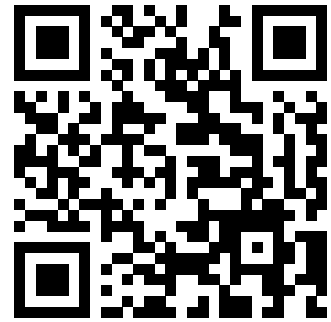
ATC KB; a standard use case

- additional languages for formalizing the ATC KB
- a shared resource, e.g., of a multi-agent environment

Download the specification:

- ATC KB in IDP:
  https://gitlab.com/mderyck/atc-kb-idp/



- ATC KB in PSOA RuleML:
  http://users.ntua.gr/mitsikas/ATC_KB/

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mitsikas@central.ntua.gr