

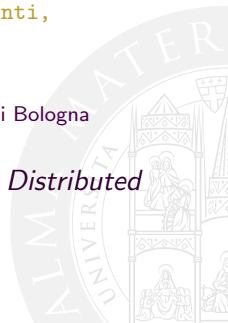
Engineering Micro-intelligence at the Edge of CPCS: Design Guidelines

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- 1 Motivations & Context
- 2 Design Guidelines for Distributing Intelligence
 - Real-time & Fault-tolerance requirements
 - Safety-critical & Big data requirements
 - Scale of interest & Nature of knowledge
 - Embodied computation & Situatedness requirement
- 3 Micro-intelligence in CPCS with LPaaS
- 4 Conclusion & Further Work



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Context

Era of digital CPS Revolution [Rauch et al., 2019, Um, 2019, Waschull et al., 2019]

- reality based on smart technologies
- discovering, storing, processing, learning, analysing, and predicting from huge amounts of environment-collected data
- spread of intelligence in distributed system

Edge computing as a new paradigm

[Chen et al., 2019, Pace et al., 2019, Tang et al., 2017]

- distributing intelligence between the Cloud and the Edge
- addressing CPCS issues such as context-awareness and real-time planning



Motivation & Contribution I

- Research work do not provide for a general software engineering standpoint [Ananthanarayanan et al., 2017, Hu et al., 2019, Tang et al., 2017]
- Criteria, guidelines, and methodologies on *how to design and distribute intelligence* are mostly missing [Cicirelli et al., 2019]



Guidelines for the design of distributed intelligence in CPCS

- symbolic and sub-symbolic combined to produce intelligent behaviour
- deal with the diverse requirements of CPCS
- intelligent environment to complement individuals cognitive process

Motivation & Contribution II

- *micro-intelligence* as the *situated intelligence* of Edge computing
- *Situated Logic Programming* as delivering framework for micro-intelligence in CPCS
- *Logic Programming as a Service* [Calegari et al., 2018b] as technological embodiment



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Design Guidelines for Distributing Intelligence

<i>intelligence</i>	which		where		who		
	symbolic	sub-symbolic	Cloud	Edge	individual	environment	e-institution
no requirement	✓		✓				✓
real-time req.		(✓)		✓		✓	
no requirement	✓		✓				✓
fault-tolerance req.				✓		✓	
no requirement		✓	✓				✓
safety critical req.	✓			✓	✓		
big data		✓	✓				✓
small data	✓			✓		✓	
macro scale		✓	✓				✓
micro scale	✓			✓		✓	
commonsense KB		✓		✓		(✓)	
contextual KB				✓			✓
disembodied			(✓)				✓
embodied		✓		✓		✓	
no requirement		✓	✓				✓
situatedness req.	(✓)			✓		✓	

Design choices (*columns*) and design criteria (*rows*)

Focus on. . .

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Real-time & Fault-tolerance requirements

<i>intelligence</i>	which		where		who		
	symb	sub-symb	Cloud	Edge	individual	env	institution
no requirement real-time	✓	(✓)	✓	✓	✓		✓
no requirement fault-tolerance	✓		✓	✓	✓		✓

CPS strict *real-time* requirements

- preferred sub-symbolic approaches at the Edge (individuals/resources)
- e-institutions enforcing norms and monitoring long-term evolution

fault-tolerance not strictly related to intelligence

- enhanced by *decentralised* approaches of Edge computing
- Cloud is intrinsically a fault-tolerant computational environment but also a bottleneck as well as a single point of failure

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Safety-critical & Big data requirements

<i>intelligence</i>	which		where		who		
	symb	sub-symb	Cloud	Edge	individual	env	institution
no requirement		✓	✓				✓
safety critical	✓			✓	✓		
big data		✓	✓				✓
small data	✓			✓	✓		

CPS usually *safety-critical* system

- preferred symbolic approaches at the Edge (individual responsibility)
- sub-symbolic approaches cannot guarantee no errors
- symbolic techniques can encode strict safety rules to apply no matter what

Big data available?

- sub-symbolic techniques to find relevant patterns (Cloud horsepower)
- exploited by e-institution for long-term planning and predictive adaptation

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Scale of interest & Nature of knowledge

intelligence	which		where		who		
	symb	sub-symb	Cloud	Edge	individual	env	institution
macro scale		✓	✓				✓
micro scale	✓			✓	✓		
commonsense		✓	✓		(✓)		
contextual KB				✓			✓

Scale of interest: *micro vs macro*

- big data best suits Cloud and institutions to power sub-symbolic techniques
 - focus on the macro scale of CPCS
- symbolic approaches at the Edge effective for small data analysis
 - individuals and intelligent environment perform local inference locally

Nature of *knowledge*

- contextual knowledge usually acquired *dynamically* at the Edge of the CPCS
- commonsense knowledge more static → Cloud/Edge depending on criticality

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Embodied computation & Situatedness requirement

<i>intelligence</i>	which		where		who		
	symb	sub-symb	Cloud	Edge	individual	env	institution
disembodied			(✓)				✓
embodied	✓			✓	✓		
no requirement		✓	✓				✓
situatedness req.	(✓)			✓	✓		

embodiment of computation: bound to system *physical nature*

- **embodied** — responsibility of individuals / environment (Edge)
- **disembodied** — e-institutions for encapsulate all the norms (Cloud)

situatedness requirement

- stronger prevalence of symbolic approaches when situatedness *is required*
- by definition, it may correspond to rare occurrences of events out of the normal system operations

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Micro-intelligence in CPCS with LPaaS

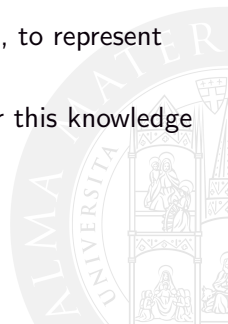
- **micro-intelligence** approach to reify the guidelines in the LPaaS technology
- completing the tile of intelligence in CPCS by acting synergically with sub-symbolic techniques

micro-intelligence [Calegari, 2018]

- scattering small chunks of machine intelligence all over a distributed, situated system, capable of enabling the individual intelligence of any kind of devices
- can be interpreted as the *externalised rationality* of cognitive agents (individual), complementing their own in the sense of Clark and Chambers' *active externalism* [Clark and Chalmers, 1998], and under Hutchins' *distributed cognition* perspective [Hollan et al., 2000]

LPaaS I

- suitable reference architecture for delivering micro-intelligence to the CPCS edge [Calegari et al., 2018a]
- designed according SOA paradigm [Erl, 2005]
- multiple logical theories, scattered in the environment, to represent the local, possibly partial/conflicting KB
- inference capabilities are admissible and available over this knowledge (extending the local KB)



LPaaS II

Guidelines reification

scale of interest intelligence at the *micro* scale of the system

→ enabling local (symbolic) reasoning complementing global (sub-symbolic)

Big / small data synergistically exploit symbolic and sub-symbolic approaches

→ ML for general KB generation (scattered in the Edge) then LPaaS for local reification

fault-tolerance microservices LPaaS architecture to achieve fault tolerance

knowledge nature micro-intelligence rooted in the notion of situatedness

→ LPaaS resolution process intrinsically bound to the computational context

embodied computation micro-intelligence rooted in IoT and inner physical nature

→ LPaaS *ad hoc* API for dealing with sensors and streams of data

situatedness LPaaS as an effective embodiment of the situated LP paradigm

→ LP inference process is itself situated in the spatio-temporal context

→ solve operations dedicated to spatio-temporal issues (timeout, neighbourhood exploration)

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Conclusion

CPS revolution: decentralisation (Cloud/Edge) and need to exploit intelligence on low-level devices for

- distributed processing
- fault tolerance
- low latency
- situated deliberation
- better scalability
- ...

Guidelines for distributing intelligence in CPCS (Cloud/Edge)

Reification of the methodology –providing feasibility– into:

- *micro-intelligence* as the way to distribute chunks of symbolic intelligence at the Edge of CPCS
- *LPaaS* to empower the Edge with knowledge and inference capabilities of computational logic

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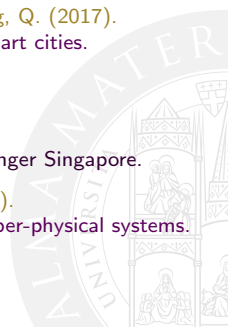
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