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A systematic review to merge discourses: Interoperability, integration and cyber-physical systems

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ABSTRACT

Cyber-physical systems (CPS) are developed through the cooperation of several engineering disciplines. Powerful software tools are utilized by each individual discipline, but it remains challenging to connect these into tool chains for increased efficiency. To support this endeavour, the literature on interoperability assessment was surveyed to identify concepts valuable to transfer from the interoperability to the tool integration research field.

Implementation options, types of interoperability and domains described in interoperability assessment models were concepts identified as directly transferable. To avoid the problems with uptake that plague the models identified, visual analytics is suggested as a vehicle for the transfer. Furthermore, based on the use of non-functional properties as an underlying motivation for these models, cost, performance and sustainability are suggested as a common base for future research in both discourses.

1. Introduction

The term Cyber-Physical Systems (CPS) is defined by Lee [30] as: "Integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa". The application of CPS technology has been actively studied in domains such as aviation, transportation, robotics, defence and critical infrastructure [52]. Integrated tools are increasingly important in these domains, with the construction of modern CPS requiring seamless integration of development, business and manufacturing tools [32]. The discourse regarding this *tool integration* is commonly limited to technology [53] and platforms/standards, such as the Eclipse platform, the Open Services for Lifecycle Collaboration standard and the IEEE standard for CASE tool interconnections [25]. Large European Union projects such as CRYSTAL, CORDIS, SPRINT, iFEST and EMC^2 have similarly spent large efforts on technology such as the Semantic Web and Linked Data. However, the tool integration technology discussion rests on a part of the tool integration discourse that focuses on how to conceptually understand tool integration, focusing on taxonomies, lists of important aspects, reference models, classification schemes, etc. Detailed summaries are provided by Wicks and Dewar [53] and Asplund and Törngren [2].

The *interoperability* research field originates from a different community, but shares many discussion topics with the discourse on tool integration. Like the tool integration research field, interoperability has also garnered an increasing interest in the research community since the 1970s. This has resulted in a growing share of research literature related to interoperability, as shown in Fig. 1. However, despite what appears to be clear motivation for connecting these research fields, they remain disparate. This raises the question whether there are some fundamental differences in the conceptual base of the two fields, or if they can come together in the future – for instance, by learning from each other´s basic models and schemes.

This merge might be of extra interest to research in tool integration, where - despite the conceptualization discourse being active for more than 4 decades – the associated classification schemes and context descriptions remain high-level and vague [2]. There are no well-defined methods to guide tool chain developers, engineers, analysts, decision makers or other stakeholders towards understanding the current status of tool chain integration even though this is essential to identify priorities, dependencies and the right decisions towards a more integrated development process. Therefore, the purpose of this study is to review the fundamentals of *interoperability assessment* approaches, with an aim towards transferring valuable insights from the interoperability to the tool integration research field. The emphasis is on basic models in both research fields, with the added limitation of considering what would be of most value in the context of CPS development. To this end, a *systemic literature survey* was conducted according to a protocol that allows for the survey to be replicated.

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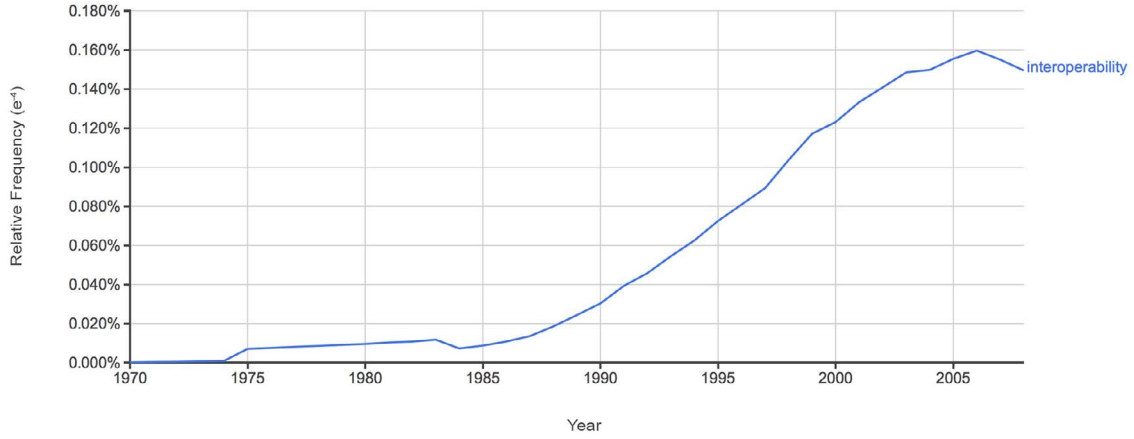

Fig. 1. The relative frequency, in percentage over time, corresponding to the "interoperability" keyword. Generated by the Google Books results for the keyword "interoperability" through use of the Ngram Viewer [35].

This protocol is explained in detail in the next section along with essential terminology related to interoperability. The review findings are described in Section 3 together with descriptions of a few selected interoperability assessment models. In Section 4, a detailed analysis of these models is laid out identifying related problems in the context of interoperability research. Section 5 builds on the previous sections, discussing both what would be most valuable to transfer in the context of CPS development, and how the identified problems can be overcome in the process. The paper concludes with a reiteration of the primary results of the study.

2. Systematic literature review

This section describes important terminology related to interoperability, and defines the protocol used for the systemic literature review.

2.1. Interoperability definitions and types

Interoperability is a multidimensional concept, which comprises several perspectives and approaches from different communities in various application domains. Today various terminologies exist in the literature: Ford et al. [18] listed 34 distinct interoperability *definitions*. The most popular definitions are found below. In our review, we have used Definition 4, since it fits with the highly heterogeneous nature of CPS development [9] with regard to stakeholders, tools, engineering disciplines, etc.

(1) "The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together." [13];
(2) "The ability for a system or a product/service to work with other systems or products/services without special effort of the user." [24];
(3) "The ability of an Enterprise to interact with other Enterprises, not only on an Information Technology point of view, but also on organizational and semantic points of view. This interaction must be flexible and be developed at the lowest cost." [15]; and
(4) "The ability of two or more systems or components to exchange and use the exchanged information in a heterogeneous network." [20].

Moreover, Ford et al. [18] identified 64 different interoperability *types*. Fig. 2 shows the 10 most popular with numbers referring to how many times a particular type of interoperability was defined in literature.

We have acknowledged all of the interoperability types listed in Fig. 2 in this study, using the definitions below to avoid ambiguity in regard to CPS development:

- *System interoperability* is the ability of systems to operate together, with systems defined in line with the generic "combination of interacting elements organized to achieve one or more stated purposes" [23].
- *Technical interoperability* is the ability achieved by communication and electronic systems when information or services can be exchanged directly and satisfactorily between them and/or their users [14].
- *Enterprise interoperability* is concerned with interoperability between organizational units or business processes, either within a large distributed enterprise or within a network of enterprises [7].
- *Functional interoperability* is the capability to reliably exchange information without error [6].
- *Programmatic interoperability* is the ability of a set of communicating entities engaged in acquisition management activities to exchange specified acquisition management information and operate on that acquisition management information according to specified, agreed-upon operational semantics [44].
- *Operational interoperability* is a relation between/among actors cooperating to achieve a common goal, an overall, mutual capability necessary to ensure successful and efficient cooperation [38].
- *Process interoperability* is a property referring to the ability of diverse business processes to work together, to "inter-operate" [49].
- *Information interoperability* is the ability of processes and systems to effectively exchange and use information services [36].
- *Data interoperability* is defined as the ability of data (including documents, multimedia content, and digital resources) to be universally accessible, reusable, and comprehensible by all transaction parties (in a human-to-machine and machine-to-machine basis), by addressing the lack of common understanding caused by the use of different representations, different purposes, different contexts, and different syntax-dependent approaches [39].
- *Constructive interoperability* is the ability of organizations responsible for constructing or maintaining a system to cooperate [37].

2.2. Method

We adopted Kitchenham's [28] procedure for conducting systematic literature reviews, including addressing the following topics in order: research questions, search processes, inclusion criteria, exclusion criteria, quality assessment, data collection and data analysis. The academic papers, theses and reports included in this literature review have thus been read with an eye towards answering two main research