Title:

Use of Technologically and Topologically Related Surfaces (TTRS) geometrical theory for Mechatronic Ontology

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Introduction:

Today, very few research studies have focused on the integration and importance of geometrical knowledge consistency management in the conceptual design for the selection of promising solution concepts related to their 3D component positioning and physical behavioral constraints. As the geometrical data can be multiple and varied, they actually depend on the model they are used in. When considering the mechatronic systems design, geometry challenges mainly relate to their high physical integration, be it to increase their compactness (that needs to be evaluated through metrics), or to take into account multi-physical couplings due to the proximity of components. The definition of a suitable ontology including the geometrical point of view is then required in order to ensure the geometrical data consistency in such a complex mechatronic system design thanks to a Model-Based System Engineering (MBSE) approach. Indeed, semantic knowledge-based engineering can efficiently support an automatic consistent products design. In order to meet these objectives, it is then necessary to describe the geometrical properties of the mechatronic system as of the early design stage to select a suitable concept, but also to ensure their consistency from the requirements specification phase to the verification phase (with the traceability of the selected geometrical concept 3D architecture). In this paper, the integration of the TTRS (Technologically and Topologically Related Surfaces) geometrical modeling theory into a mechatronic ontology is presented, in order to ensure geometrical data consistency during the conceptual design stage. Finally, its implementation in an electric powertrain case study are performed.

TTRS modeling:

The TTRS [3] theory represents and classifies surfaces. TTRS defines an algebraic group structure. Any surface or association of the real surfaces of an object is related to a kinematic invariance class named TTRS. There are 7 classes of TTRS classified according to increasing degrees of freedom (DOF). These classes are: spherical, planar, cylindrical, helical, revolute, prismatic, and complex. For each class, it is possible to associate one Minimal Reference Geometric Element (MRGE) that is the minimal combination of the following simpler geometric objects, named Reduced Geometric Element (RGE): plane, line and point. This reduced geometrical representation allows an easier object positioning in Euclidian space. Finally, the TTRS modelling also manages the composition of other TTRS and their relative positioning. Actually, it allows the positioning and orientation of MRGEs by using 13 geometrical constraints between them [8].

TTRS also allows the management of constraints between different parts of an assembly to take into consideration the kinematic joint between these parts, notably for tolerancing. They are then called Pseudo-TTRS [7], the constraint between the MRGE of the parts are the same as in the TTRS theory.

TTRS theory presents many advantages for geometric modelling, since it includes both the modelling of components and their positioning (through the consideration of their surfaces), which facilitates its implementation in a SysML extension. Another advantage of this theory is that GPS (Global Product Specifications) standards [12][13] are based on it. These standards are already implemented in many CAD software like CATIA V5, allowing users to formalize positioning constraints with the same “logics”. Finally, this approach allows to create all kinds of geometry, be it simple and complex, so that it suits any geometry whatever the complexity.

Mechatronic challenges for ontology definition

The design of mechatronic systems is particularly challenging because of their high functional integration, multi-domain and multi-physical aspects, and other corresponding couplings [9][11].

Indeed, they are characterized by the synergic interactions between their components from different technological domains, as they integrate mechanics, electronics, automation and information technologies. These interactions enable these systems to achieve more functionalities (due to couplings) than the sum of the functionalities of their components considered independently. Individual parts also incorporate more functions in an increasingly highlyintegrated package (“cross-functional integration”) [1], which results in an increasing number of components to be integrated in a compact volume, in which various physical fields interact and create multi-physical couplings [9]. For example, Pérez-Grande & al. show that the compactness is a current optimization criterion for an aircraft environmental control system [16], and Ooshima & al. underline the issue of multi-physical interactions for the optimization of the size of a system [15].

Therefore, these challenges imply to take into account, as soon as possible, component geometry and positioning to design these complex mechatronic systems. Integrating geometrical considerations in the early stages of mechatronic design first means to provide a support to easily supply the same geometry specifications to each domain technical team (geometrical requirements of the system and its components or geometrical constraints of relative position between components). Then, it allows tracing whether these requirements are fulfilled by the different potential 3D architectures. As the physical integration of mechatronic systems is one major issue of their design, it requires to be considered as one of the criteria of the decision-making process, to select the convenient system architecture. The definition of such physical integration metrics (based on these criteria) requires to know the components simplified geometry and their relative positioning, from the conceptual design stage [18].

Additionally, the high integration of the mechatronic systems leads to an increasing number of desired and undesired interactions among the components. Undesired interactions are the disturbances, mainly due to multi-physical couplings between components, which can affect the behavior of the entire system. However, due to the lack of 3D data in the early design stage, the multi-physical behavior of mechatronic systems is usually not studied before the detailed design phase, and its modeling is thus based on time consuming finite elements methods. Actually, it would be interesting to assess 3D potential physical architectures, under multi-physical constraints, from the conceptual phase, in order to decrease the risk of the late expensive changes occurring during further design phases, and consequently to reduce the global design time [4].

Finally, all these mechatronic challenges regarding geometric modeling require a knowledge formalization to describe features such as the structure and the behavior of complex technical products in a clear and consistent way. The topological (graph-based) representation of the system is useful to define the (hierarchical) structure of components and their interconnection laws, be it geometrical or physical.

In fact, according to the semantic complexity of mechatronic design, dictionary, thesaurus and taxonomy are not sufficient to express, formalize and structure all the knowledge entities described in such a semantic environment. Thus, an ontology modeling will ease the specifications of complex concepts and relationships required for the mechatronic design. It will help to automatically define a coherent knowledge-based engineering design process of mechatronic products, by providing powerful means of analysis (of problem, of their causes, of their solutions), to support the knowledge sharing and reuse, and also the planning, coordination and control of complex product/process activities.

Related Works

As an ontology defines a common vocabulary for those who need to share information in a domain, the usage of ontologies and corresponding expert system software is a major issue for the mechatronic design process.

Welp & al. propose a semantic web service platform for a knowledge-based design of mechatronic systems [19], by integrating the design environment and using software agents, since ontologies also include machine-interpretable definitions of basic concepts in specific domains and relations between them. They use the semantic web technology to intelligently deal with web contents [20] and they define three knowledge levels: the ontology layer, the metadata layer and the information layer. Their mechatronic ontology is based, on one hand, on four basic elements (actuator, sensors, information processing and mechanical basic system) and on the other hand on two basic forms of interfaces (energy-dominated interfaces and signal dominated interfaces).

Other studies have focused on the semantically based description of the information and product data exchange during the conceptual mechatronic design process. Hehenberger & al were particularly interested in the use of ontology as a means of inconsistencies detection and tracking during the design changes, notably for the design/process planning integration [10].

Considering existing ontologies for the 3D modeling, few studies have actually dealt with the geometry domain. They mainly address the semantic representation of 3D contents [2][17]. Other authors describe some spatial ontologies, which deal with space for geographical interests [6]. Furthermore, Liang & al. propose a port ontology for conceptual design that includes form attributes classes related to the geometry. They associate a CAD feature to a form feature including a form attribute linked to its location, in order to make possible the specification of a partial geometry definition (points, curves and surfaces) [14].

Finally, none of the previous studies have dealt with an ontology integrating the geometrical knowledge from the early phases of the conceptual design, and its specific challenges related to the physical integration of mechatronic systems.

Our proposal: *TTRS theory as a part of the mechatronic ontology.*

The knowledge needs to be structured according to a semantic representation [7]. For example, we define a mechatronic ontology with seven concepts and thirteen relationships, as described on Fig. 1. The concepts and their relationships describe then the relevant knowledge of mechatronic design, as previously presented.

To facilitate the understanding of the developed ontology, Fig. 2 presents the general semantic field of an ontology used for the modeling, and its instantiation in the case of the TTRS geometrical point of view.

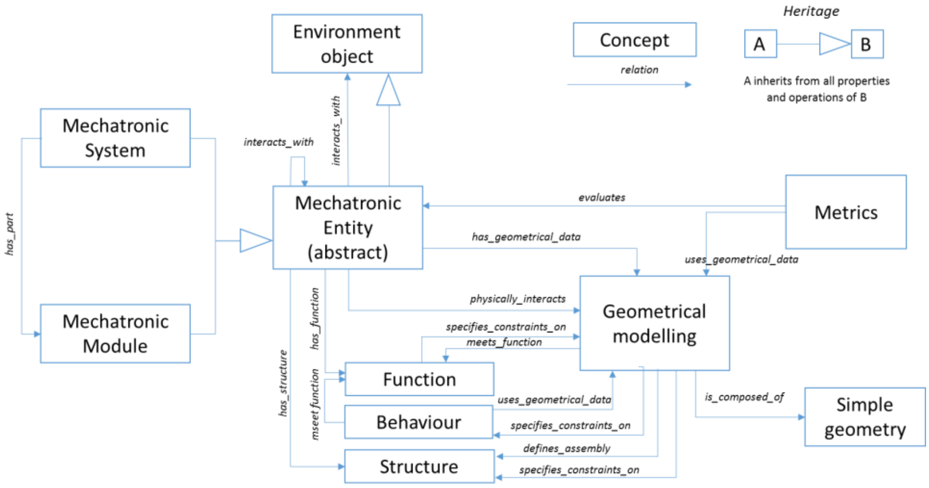


Fig. 1: Mechatronic Ontology with TTRS.

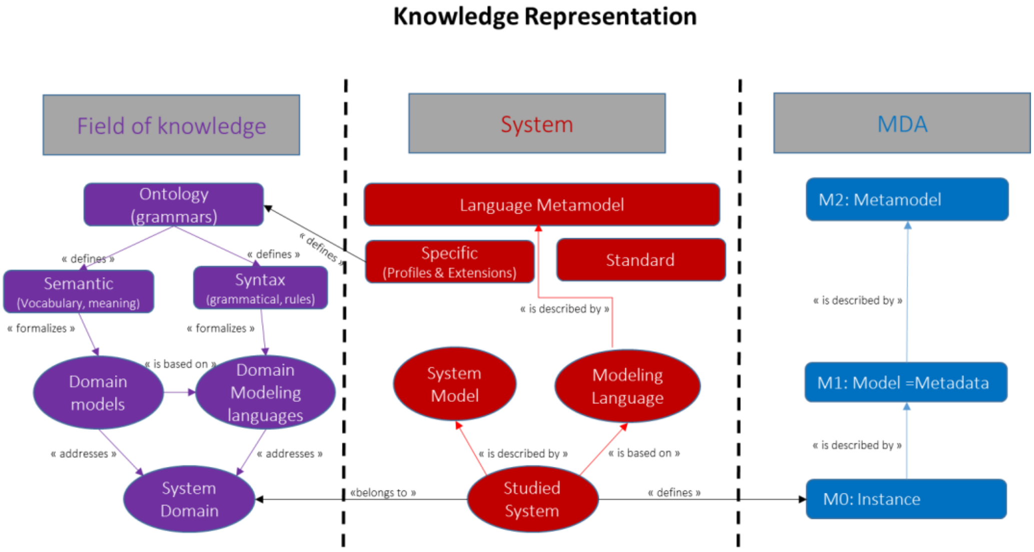


Fig. 2: Semantic field of a modelling ontology applied to our approach.

Fig. 3 presents how the use, for the different conceptual stage modelling, of the TTRS ontology (which can be considered as an “upper/generic ontology”), allows to keep the geometry knowledge consistency, notably through successive model transformations. This will ensure to meet the geometrical specifications and corresponding data traceability, and then to facilitate the verification automation.

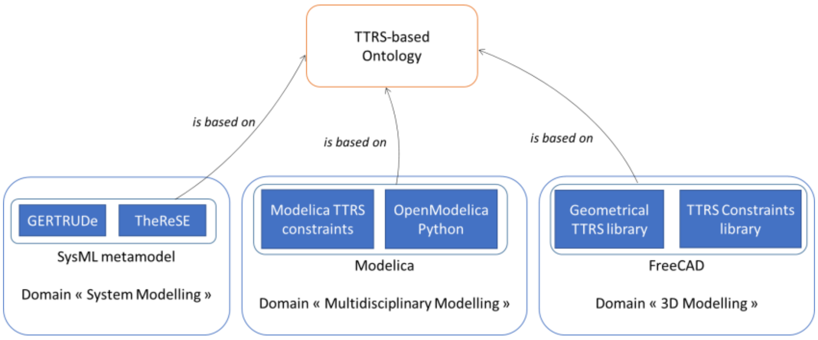


Fig. 3: Geometrical knowledge consistency through the use of the TTRS ontology during model transformations process.

- Case study application: EPT

Case study description

To illustrate this approach, and to see how ontology can help to ensure geometrical consistency of such mechatronic systems design, we choose the scenario of the 3D architecture of an electric power train (EPT) for bus vehicles, mounted on a chassis. Regarding geometrical specifications about the minimal volume, two architectures have been considered:

- The first architecture consists of one geared motor, one inverter, one electronics control unit and one differential gear.
- The second one differs from the first one by two motors and two inverters (one by wheel), but it does not need the differential gear any longer.

Case study modelling

On Figure 4 both architectures are detailed, thanks to the developed GERTRUDe SysML extension [5]. Components represented by blocks are stereotyped with “Component”: each block is associated with a simplified geometry and its corresponding dimensions can be specified in the predefined unit. The relative positioning (position and orientation) of components can be specified by the TTRS constraints, between their respective Minimal Reference Geometrical Element (MGRE). Finally, the geometrical metric to calculate the compactness of the system is also defined by a constraint block.

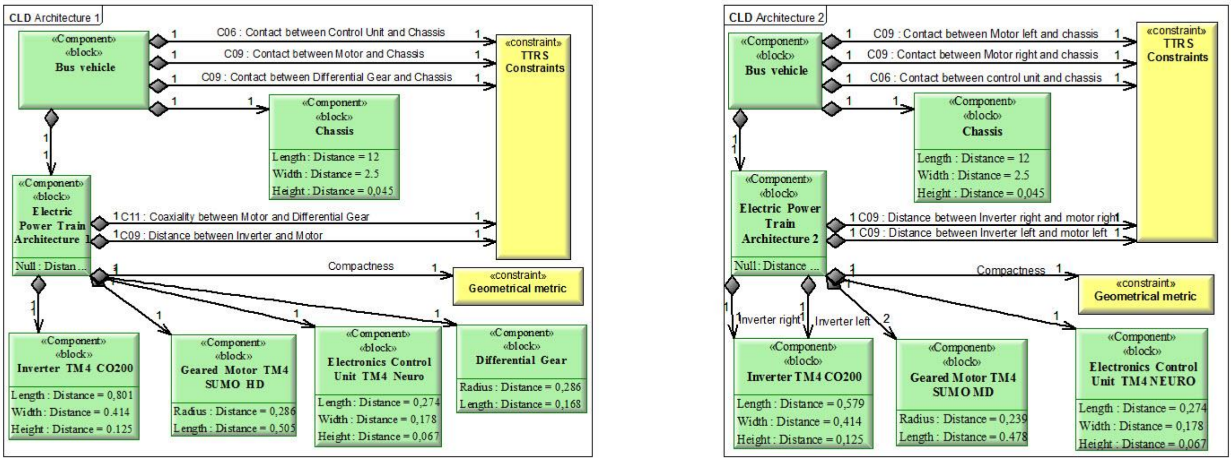


Fig. 4: Alternative EPT spatial architectures in SysML with GeRTRUDE.

Then, 3D modeling is automatically generated in FreeCAD (Fig. 5), thanks to the developed SAMOS platform based on model transformations [3], which implements the developed ontology.

After performing the geometric metric giving the compactness of each architecture [18], as the first one is lighter and slightly more compact, we choose this architecture to carry out the thermal modeling.

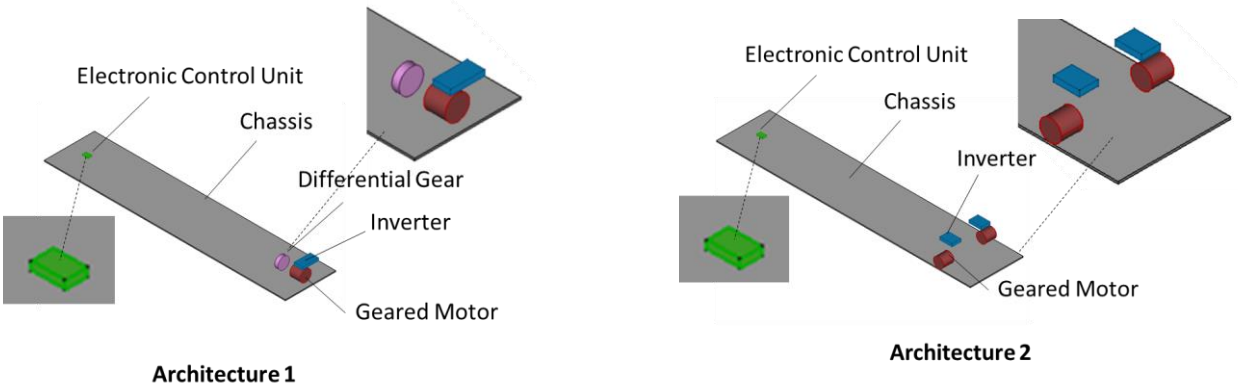
For this thermal behavior modeling, performed thanks to the developed TheReSE SysML extension [4] (based also on this ontology) and then Modelica, we need four additional components: a fan and three pipes to complete the 3D architecture.

Ontology validation of the case study

The developed ontology for the geometrical knowledge for mechatronic systems based on the TTRS theory has been implemented in the data models of the GERTRUDe and TheReSE SysML extensions, to specify the simplified geometry and relative positioning constraints of the components of both EPT architectures and to trace the final 3D architecture resulting from the thermal modeling in Modelica back to the System model. The evolving geometrical knowledge during this conceptual phase has been kept consistent, since the corresponding model transformation processes (between SysML, Modelica and FreeCAD models) have been carried out between geometrical data models based on the same (TTRS-based) ontology.

Conclusions:

After having presented the TTRS theory and described mechatronics design complex challenges, we have proposed a geometrical ontology, based on the TTRS theory, to be included in a mechatronic design ontology. This approach allows to automatically ensure the consistency of geometrical knowledge all along the conceptual design stage, from the specifications to the verification (traceability), accordingly to MBSE approach. This ontology has been validated through the effective development of model transformation processes between the different modelling using geometrical data. Moreover, it has been applied to a scenario of the architecture choice of an Electric Power Train, including many geometrical issues related to mechatronic system design aside from previous MBSE challenges, such as physical integration and related compactness metric, thermal modeling for multi-physics.



Architecture 1

Architecture 2

Fig. 5: Generated 3D modeling of the different architectures.

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