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Use of technologically and topologically related surfaces (TTRS) geometrical theory for mechatronic design ontology

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ABSTRACT
This paper presents the MBSE challenges related to the conceptual design of mechatronic systems and especially the need to ensure geometrical knowledge consistency. To tackle this issue, we propose to define an ontology based on the TTRS (Technologically and Topologically Related Surfaces) geometrical modeling. We implement it in the Protégé environment and validate it through the modeling process of an Electric Power Train, including many additional geometrical issues related to mechatronic system design, such as physical integration and the related compactness metric and the thermal modeling for multi-physical couplings. Geometrical knowledge consistency has been ensured through a model transformation between SysML and FreeCAD, using Python.

KEYWORDS
Ontology; semantic modeling; mechatronic design; geometrical modeling

1. Introduction

Today, very few research studies on conceptual design have focused on the integration and importance of geometrical knowledge consistency management when selecting promising solution concepts related to their component 3D positioning and physical behavioral constraints. As geometrical data can be multiple and various, they indeed depend on the model they are used in. When considering 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, it is implemented in an Electric Power Train case study.

2. Context

2.1. Geometrical consistency needed for mechatronic conceptual design

This section describes why ensuring geometry consistency is important for mechatronic conceptual design.

The design of mechatronic systems is particularly complex because of their high functional integration, multi-domain and multi-physical aspects, and other corresponding couplings [11][17]. Indeed, such systems 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 mechatronic 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 highly-integrated package ("cross-functional integration") [1], which results in an increasing number of components to be integrated in a compact volume, in

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which various physical fields interact and create multi-physical couplings [11]. For example, Pérez-Grande & al. show that compactness is a current optimization criterion for an aircraft environmental control system [27], and Ooshima & al. underline the issue of multi-physical interactions for the optimization of the size of a system [24]. 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, from the conceptual design stage, the simplified geometry and relative positioning of components [33]. Additionally, the high integration of 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) that 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 not usually studied before the detailed design phase, and its modeling is thus based on time consuming finite elements methods. However, assessing the 3D spatial architectures, under multi-physical constraints, from the conceptual design phase will definitely decrease the risk of the late expensive changes occurring during further design phases, and consequently reduce the global design time [5].

To meet this challenge and support the design of these complex mechatronic systems, it is necessary to take into account the components geometry and positioning as soon as possible, as of the conceptual design stage, by proposing an approach to evaluate the 3D architecture under geometrical and physical constraints.

Therefore, system architects first need to easily supply the same geometry specifications to all domain technical teams. These can be either geometrical requirements of the system and its components or some geometrical constraints of relative positions between them.

Then, designers have to analyze and compare them, prior to selecting the optimal one, by usually performing some preliminary physical behavior simulations. Still as the simplest assessment of any physical behavior relies on the orientation and distance between the components or even on some dimensional data [32], designers usually need to consider geometry as soon as possible in the design life cycle (notably during the conceptual design phase) in order to evaluate physical interactions. For example, in the case of Measures of Performances (MoP), some geometrical relationships like physical laws including shape factors, are usually required for preliminary behavioral simulations of physical alternative architectures, in order to evaluate their performance relating to the considered MoP [13].

Finally, it is also necessary to trace whether initial (geometrical and physical) requirements are fulfilled by the various potential 3D designed architectures.

To address these challenges, we have proposed a MBSE approach to build a seamless process during the conceptual design phase for a consistent transmission of the 3D geometrical data Fig. 1 [7]. The corresponding platform implementation has to guarantee that all representations of the system - in the System model for the specifications, in multi-disciplinary modeling for physic behavioral simulation or in 3D environment for 3D architecting - will be consistent.

Finally, the implementation of such an approach previously requires a geometry knowledge formalization to describe features, such as the structure and the behavior of such complex systems, in a clear and consistent way. The topological (graph-based) representation of the system could then be useful to define the hierarchical structure of components and their interconnection laws, be it geometrical or physical, but it is not sufficient to define the corresponding semantic. In fact, according to the semantic complexity of mechatronic design, even dictionaries, thesauri and taxonomies are not enough to express, formalize and structure all the knowledge entities described in such a semantic environment. Thus, an ontology modeling, based on a geometrical theory adapted to conceptual design, will ease the definitions of complex concepts and relationships required for mechatronic design. It will help to automatically describe a coherent knowledge-based engineering design process of mechatronic products, by providing powerful means of analysis (of problems, of their causes, of their solutions), to support knowledge sharing and reuse, and also planning, coordination and control of the complex product design process activities.

2.2. TTRS modeling

The Technologically and Topologically Related Surfaces (TTRS) theory represents and classifies surfaces [10]. Classes of TTRS refer to the symmetry-based classification of surfaces and relate to their kinematic invariance. Then, any surface or association of the real surfaces of an object is related to a kinematic invariance class named TTRS class. There are 7 classes of TTRS classified according to their increasing degrees of freedom (DOF). These classes are: spherical, planar, cylindrical, helical, revolute, prismatic, and complex. For example, the revolute class characterizes all invariant to rotation forms such as a circle, a torus or cone. Adding one degree of freedom, we can obtain another surface class, such as the cylindrical.

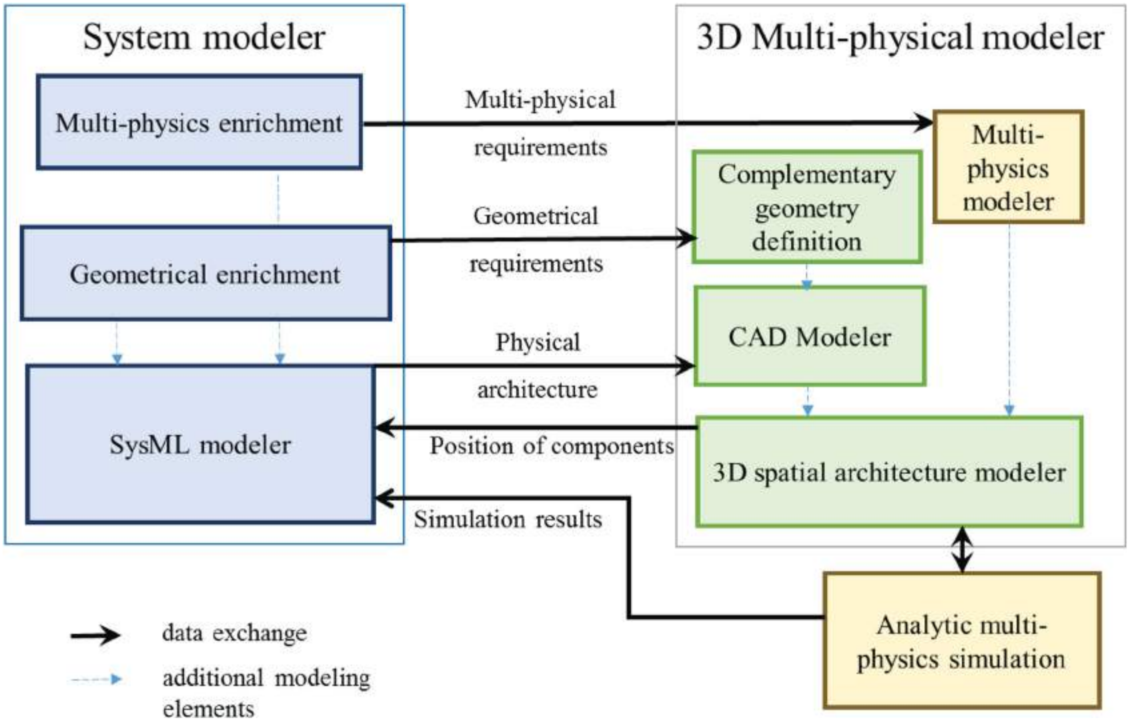
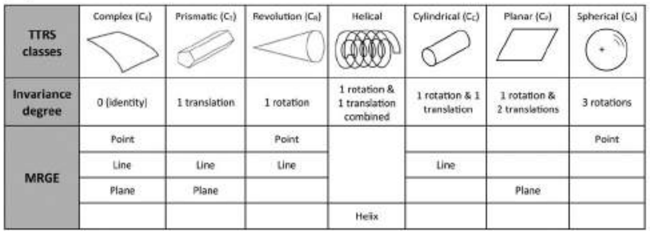


Figure 1. Overview of the global approach [4].

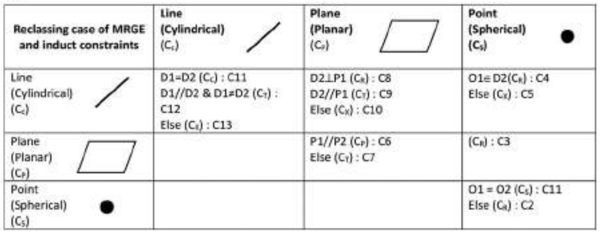
Table 1. (a) Definition of TTRS and MRGE and (b) their relative TTRS constraints.

(a)



TTRS classes	Complex (C_X)	Prismatic (C_T)	Revolution (C_R)	Helical	Cylindrical (C_C)	Planar (C_P)	Spherical (C_S)
Invariance degree	0 (identity)	1 translation	1 rotation	1 rotation & 1 translation combined	1 rotation & 1 translation	1 rotation & 2 translations	3 rotations
MRGE	Point		Point				Point
	Line	Line	Line		Line		
	Plane	Plane				Plane	
				Helix			

(b)



Reclassing case of MRGE and induct constraints	Line (Cylindrical) (C_C)	Plane (Planar) (C_P)	Point (Spherical) (C_S)
Line (Cylindrical) (C_C)	D1=D2 (C_C) : C11 D1//D2 & D1≠D2 (C_T) : C12 Else (C_X) : C13	D2⊥P1 (C_R) : C8 D2//P1 (C_T) : C9 Else (C_X) : C10	O1∈D2(C_R) : C4 Else (C_X) : C5
Plane (Planar) (C_P)		P1//P2 (C_P) : C6 Else (C_T) : C7	(C_R) : C3
Point (Spherical) (C_S)			O1 = O2 (C_S) : C11 Else (C_R) : C2

For each class, it is possible to associate one Minimal Reference Geometric Element (MRGE) (Fig. 2) that is the minimal combination of the following simpler geometric objects, named Reduced Geometric Elements (RGE): plane, line and point, since only these three geometrical entities are necessary to describe the previous 7 classes. For example, the cone belongs to the revolute class. We may resume it with a point and a straight line. This reduced geometrical representation facilitates object positioning in the Euclidian space.

Finally, as TTRSs define an algebraic group structure, TTRS modeling also manages the composition of other TTRS and their relative positioning [31]. An example is when building a component based on a cone and a cylinder, while considering the coincidence between their symmetry axis (D1 = D2), the reclassed TTRS results in a revolute TTRS, whose MRGE is point and line.

Moreover, when analyzing each MRGE, we can find that the MRGE of identity, revolute, prismatic and helical classes are associations of sphere, cylindrical and planar classes. Then, when restricting TTRS classes to only these three TTRS classes, only 13 constraints between their MRGEs are enough for their positioning and orientation (Tab. 1).

Additionally, TTRS can also manage constraints between different parts of an assembly in order to define the kinematic joint between these parts, notably for tolerancing considerations. They are then called Pseudo-TTRS [9] and the constraints between the MRGE of the parts are the same as in the TTRS theory.

The TTRS theory presents many advantages meeting the previous described needs, since it includes both the modeling of components and their positioning (when considering their surfaces) that is required be it to specify geometrical requirements, to spatially position components in a 3D environment, and finally support the corresponding geometrical information necessary for physical simulation. Another advantage of this theory

Figure 2. MRGE generation for TTRS modeling.

is that GPS (Global Product Specifications) standards [18][19] are based on it. These standards are already implemented into 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 or complex, so that it suits any geometry whatever its initial complexity level.

Finally, it is particularly appropriate for the conceptual design stage, since conceptual design requires a simple and quick means to have an overview of the spatial distribution of simplified components of a given architecture, to support the choice of the best concept (that fulfills system model requirements). Therefore, the abstraction level of TTRS theory is very useful, since most of components geometries can be simplified in a simple geometry having a kinematic invariance symmetry. Besides, the kinematic invariance is very useful in a 3D environment to recommend the displacement direction to follow to meet some geometrical or physical requirements.

2.3. *Ontologies 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 [34], 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 [35] 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 an ontology as a means of inconsistencies detection and tracking during the design changes, notably for the design/process planning integration [16].

Considering existing ontologies for the 3D modeling, few studies have specifically addressed the geometry knowledge mentioned earlier. They have mainly dealt with the semantic representation of 3D contents [3][28]. Other authors describe some spatial ontologies, regarding space for geographical interests [8]. 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) [22]. They address geometry and transfer flows (energy, material, signal) compatibility, without describing how to deal with some geometrical and interactive physical constraints that may also be quantified.

Finally, none of the previous studies has dealt with an ontology integrating the geometrical knowledge from the early phases of the conceptual design, and its specific challenges related to the assessment of 3D multi-physical integration of mechatronic systems.

3. Our approach

The aim of our approach is to consider the TTRS theory as the support of the geometrical knowledge within the mechatronic ontology, in order to notably ensure its consistency during the conceptual design stage.

3.1. *Definition process of the mechatronic design ontology*

The fundamental objective when defining an ontology is integrating knowledge of numerous information sources and various viewpoints. Indeed, beneficial interactions between mechatronics domains are actively pursued in order to boost the performance of new products, even if leading to an increasing complexity of their design [26]. Conceptual stage starts from the specification of requirements and aims at providing a support to decide on the feasibility of a given system architecture, before proceeding to its detailed design [23]. Conceptual phase modeling elements may be represented as a graph-like structure [29]. A typical topological representation of the design of such a system could be represented by the Fig. 3.

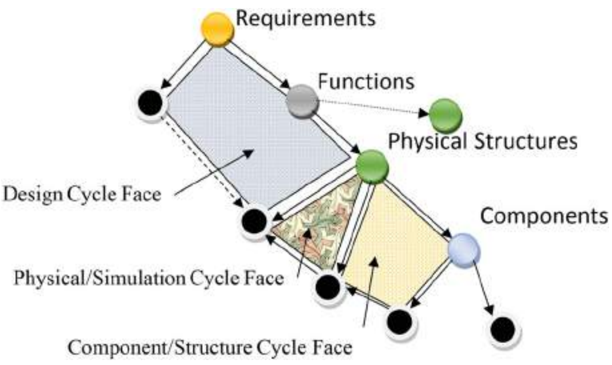


Figure 3. Topological representation of system design [6,29].

This figure shows the interdependency links of modeling data, according to the view addressed.

Indeed, during the conceptual design, it is usual to define rough and simple dimensioning models by an appropriate reduction of more complex systems. The first impact is then to consider simple geometry of components, which permits to evaluate, through metrics, different 3D spatial architectures alternatives, taking into account some geometrical constraints or other physical behavior requirements. Besides, a mechatronic system structure has a component-dominated topology, since a mechatronic system can be decomposed into some systems and then into modules. A mechatronic system concept is related to an environment which can also be a mechatronic system (e.g. robots). Finally, the Function-Behavior-Structure modeling of a system allows to cover different views of complex systems [15].

When considering the 4-layer metamodeling architecture of MDA (Model Driven Architecture) [12], the metamodeling defines an ontology of concepts for a domain, as well as the vocabulary and grammatical rules of a modeling language. A domain ontology formally describes concepts, relationships among concepts and constraints which are used in the metamodel and model definition. Thus, the ontology is the content theory that specifies the concepts and their relations used in a specific knowledge.

To facilitate the understanding of the developed ontology, Fig. 4 presents our view of the ontology-related notions.

Moreover, when designing a mechatronic system, designers implicitly apply their aggregated knowledge to the new concept, without being aware of what other designers will consider as design rules, functional requirements, etc. Then it is also important to formalize the integration of the already existing ontologies. This integration can be made at different levels: by combining two existing ontologies (mapping or inter-ontology mapping), or even by inserting content from an ontology to another [20][21].

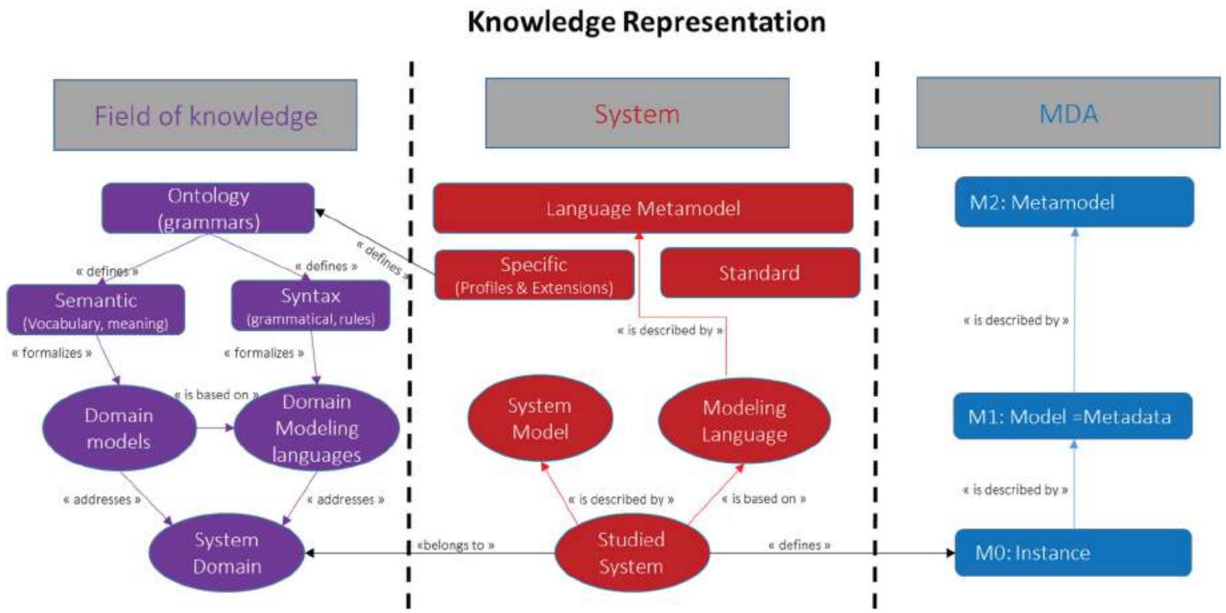


Figure 4. Ontology and related notions.

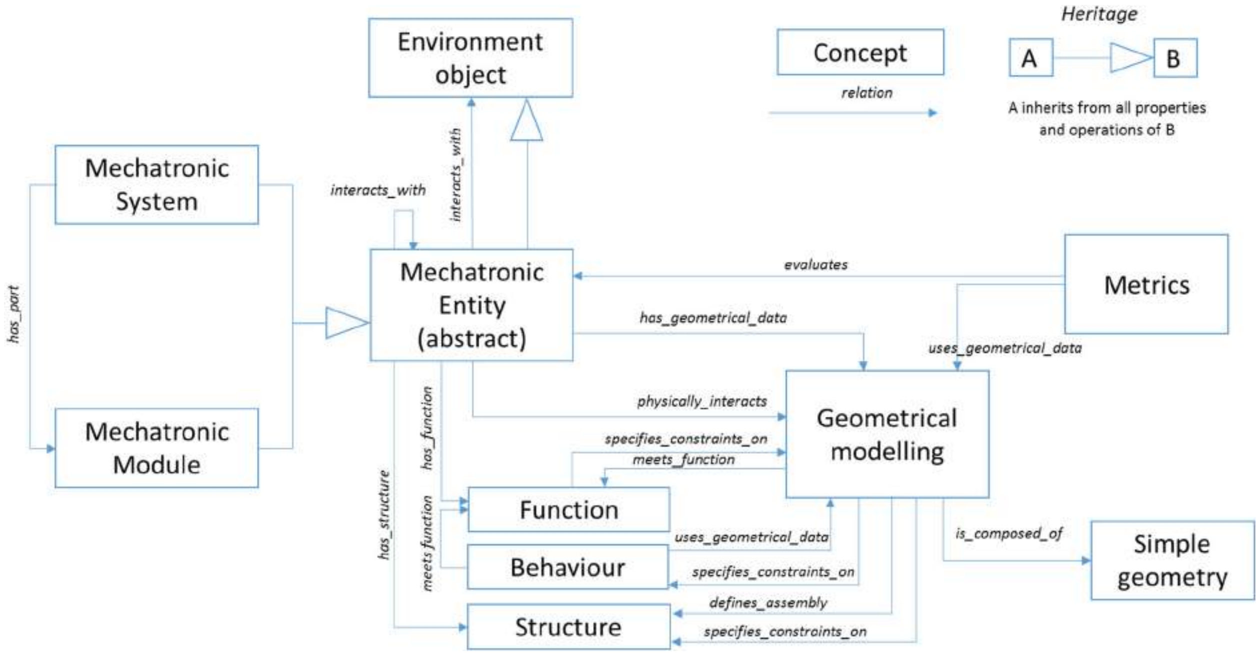


Figure 5. Mechatronic Design Ontology Definition.

The developed ontology contains the basic mechatronic systems knowledge for the conceptual design phase. The concepts and their relationships describe then the relevant knowledge of mechatronic design, as previously presented. This knowledge needs to be structured according to a semantic representation. For example, we define a mechatronic design ontology with ten concepts and thirteen different relationships, as described on Fig. 5.

3.2. TTRS theory integration

Our approach is that the previous geometrical modeling is supported by the TTRS theory. Fig. 6 presents the corresponding TTRS-based geometrical modeling ontology.

The mechatronic entity, which can be made of other mechatronic modules (sub-systems), is composed of one TTRS (corresponding to its whole surface), which can itself comprise some TTRS (some elementary infinite surfaces) (Fig. 7). Finite surface has its own resulting TTRS.

A mechatronic entity has finite dimensions defined by some dimensional parameters.

Whatever the considered level, each TTRS relates on one kinematic invariance of a “TTRS Class”: kinematic invariance is represented through a 6-dimensional vector (3 for each translation invariance and 3 for each rotational invariance). Each TTRS class defines its corresponding MRGE (Minimal Reference Geometrical Elements). The relative position of TTRS to another is defined by one or more constraints. These positioning constraints, derived from Tab. 1, are defined between the MRGE of the two TTRS considered. The 3D parameters, requested for the representation of the mechatronic entity volume in a 3D Euclidean space, are defined by the position and the orientation of each RGE contained in the MRGE of the considered TTRS.

3.3. Ontology-based geometrical consistency implemented in SAMOS

In this section, we explain how the implementation of the previous ontology in software tools allows to ensure the consistency of geometry knowledge, for 3D architecting and physical behavior simulation, under geometrical and physical constraints, of mechatronic system during the conceptual design.

Conceptual design of mechatronic systems is a decisive phase when the simulation teams have an interest in quickly pre-validating spatial architectures from the physical architecture proposed by the system architects. Indeed, they need to evaluate the physical behavior resulting from the high integrated 3D architecture of mechatronic systems. Still, this step could be very difficult, since they have no dedicated means and tools to manage geometry consistency all along the preliminary design phase. In order to help them to efficiently achieve this task, the theoretical formalization of our approach (through the developed ontology) will provide a consistent integration of the geometry knowledge all

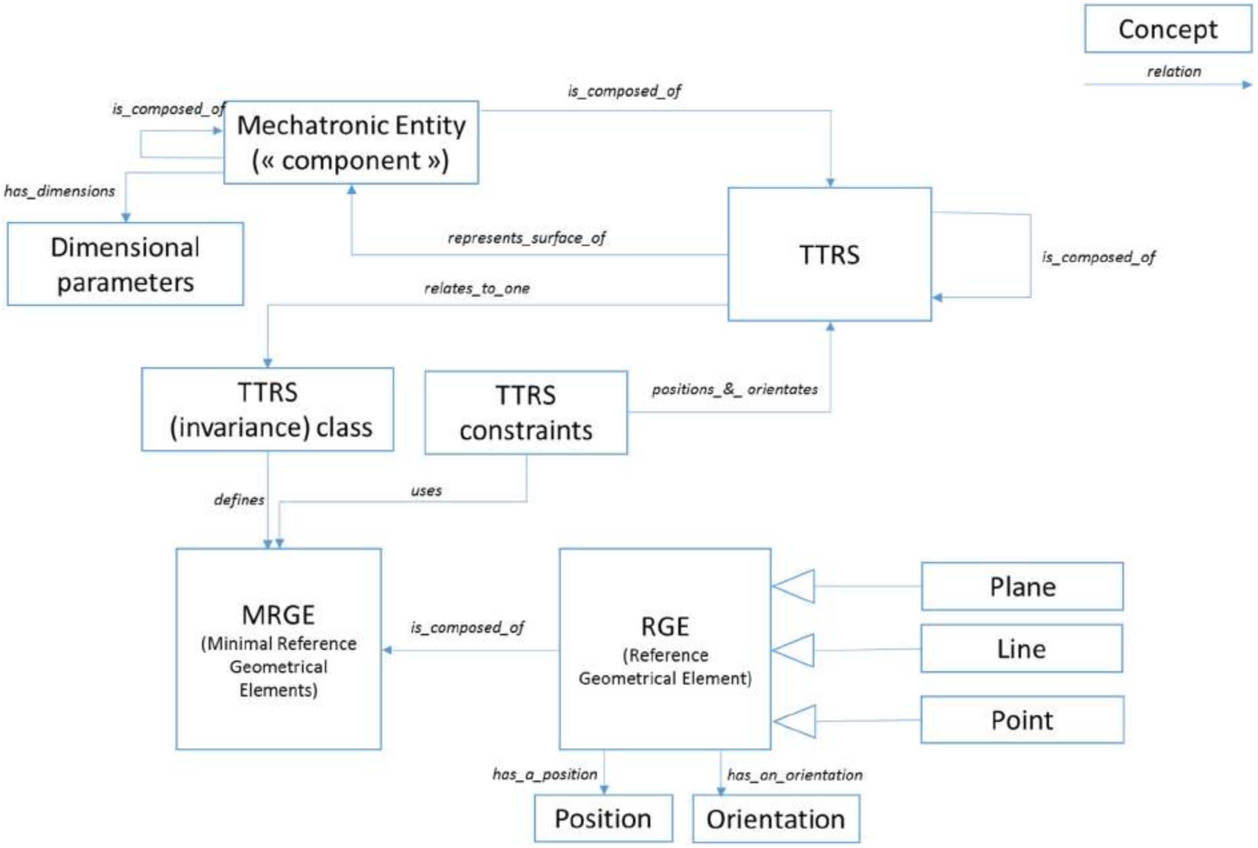


Figure 6. TTRS-based geometrical modeling ontology.

along the conceptual design. The corresponding model transformation platform, named SAMOS (Spatial Architecture based on Multi-physics and Organization of Systems), then ensures a seamless geometrical consistency and traceability from the requirements to the further design stages [4]. Besides, as the simplest assessment of any physical behavior requires prior knowledge of the components position, investigating the geometry-related physical interactions during the conceptual design phase will avoid selecting a 3D physical architecture with unmanageable unwanted multi-physical behaviors.

As a MBSE process needs an abstraction of the system, we have investigated on how to use it to create a consistent link between the geometrical data of the abstraction level of the system model and the graphical view of a 3D sketch required to better perform the conceptual design of the system, and notably the preliminary physical behavior modeling.

The SysML (Systems Modeling Language) language has been chosen, as we require a language which allows specifying all requirements and system architectures, whatever the discipline or technical team. This language was initiated by the International Council on Systems Engineering (INCOSE) to support MBSE and has been defined by an OMG (Object Management Group) specification since 2006. A common approach to formalize an ontology in a system modeling language is to propose some UML profiles or SysML extensions. A profile in the UML provides a generic extension mechanism to customize UML models for particular domains and platforms. Accordingly, our prior developments have consisted in enriching the system model with geometrical and physical data and their corresponding constraints, by providing two SysML extensions based on the TTRS theory: GERTRUDe (Geometrical Extension Related to TTRS Reference for a Unified Design) for geometrical aspects [6] and TheReSE: Thermics Related SysML Extension, for thermal modeling.[5]. The data model of these extensions, based on the developed ontology, is presented in Fig. 8.

The second part of the SAMOS platform, is based on a 3D environment that is more adapted to the simulation teams' tasks. Indeed, they need to test different 3D architectures of components by quickly simulating their corresponding physical behavior, in order to pre-validate those which meet the requirements issued from the system modeling, while dealing with simplified geometry of

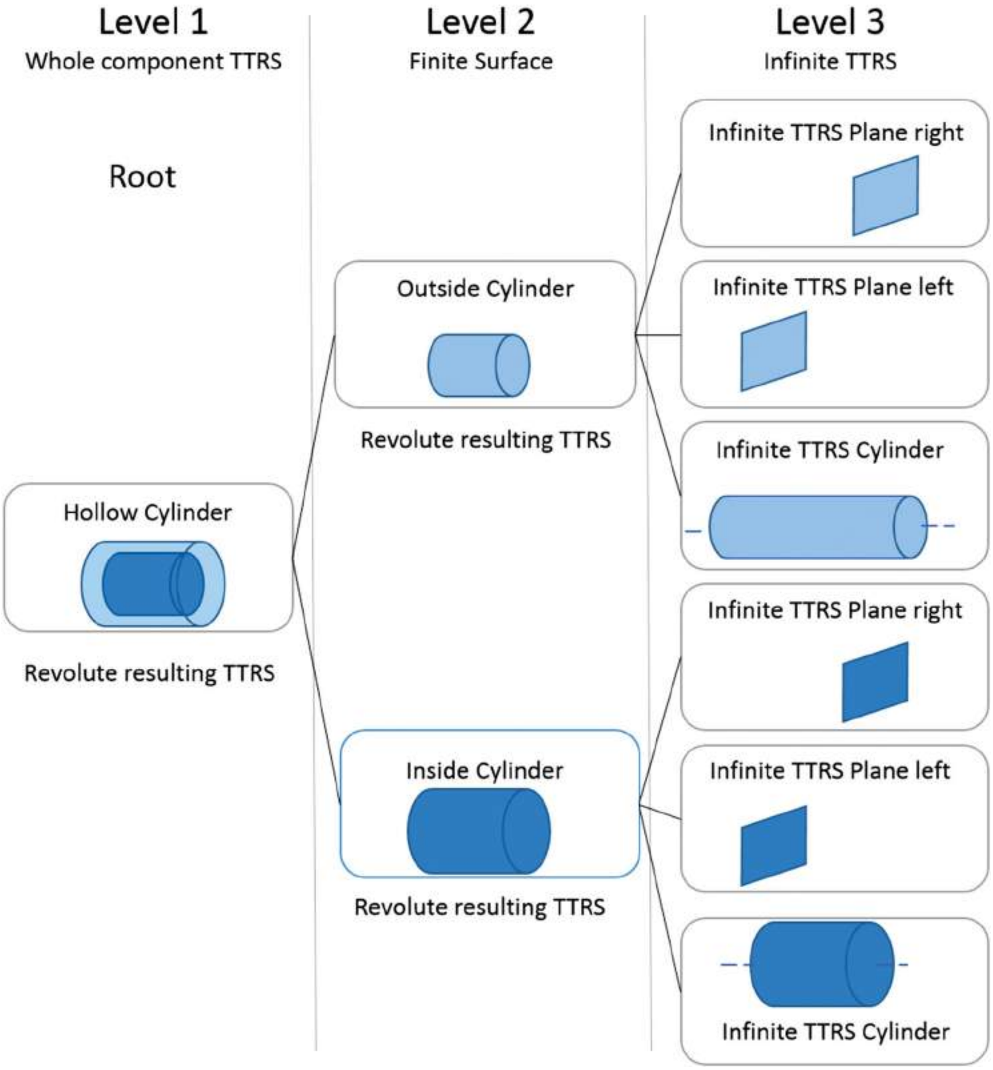


Figure 7. TTRS decomposition levels.

components and some hypotheses to simplify for example thermal behavior by analytical equations. Then these simulation results, corresponding to a specific 3D geometry architecture of components, need to be traced back in the system model.

Firstly, from the geometrical point of view, this model transformation has to ensure that the creation of a new geometry in the SysML model automatically generates the same action in the corresponding CAD model, and vice versa, without any additional development. Model transformation operators often work at the M2 metamodel level, by manipulating instances of metamodel constructs (from GERTRUDe and a CAD tool metamodels). A metamodel (M2) is a model that defines the language which is used in a model (M1) of the real world (M0). A metamodel (M2) conforms to a language whose abstract syntax is represented by a reflexive (that conforms to itself) metametamodel (M3). The OMG standard is the Meta Object Facility or MOF. The proposed approach is described on Fig. 9.

The chosen tools for the experimentation of our approach are Artisan studio 7.4 [2] for SysML modeling and FreeCAD [14] for CAD modeling. The interface used for the transformation platform has been implemented in the Python language. The detailed description of the model transformation process will be presented in [7].

Considering the physical behavior modeling and simulation, we are working on the thermal modeling: with the prior development of the TheReSE extension [5], and by taking into account the impact of the developed TTRS-based ontology on the formalization of thermal behavior equations (for conduction, convection and radiation) [7]. To model interacting components through which the physical flow passes between two components, TheReSE proposes a stereotyped block called “Media”. Media is a component with all its TTRS-based

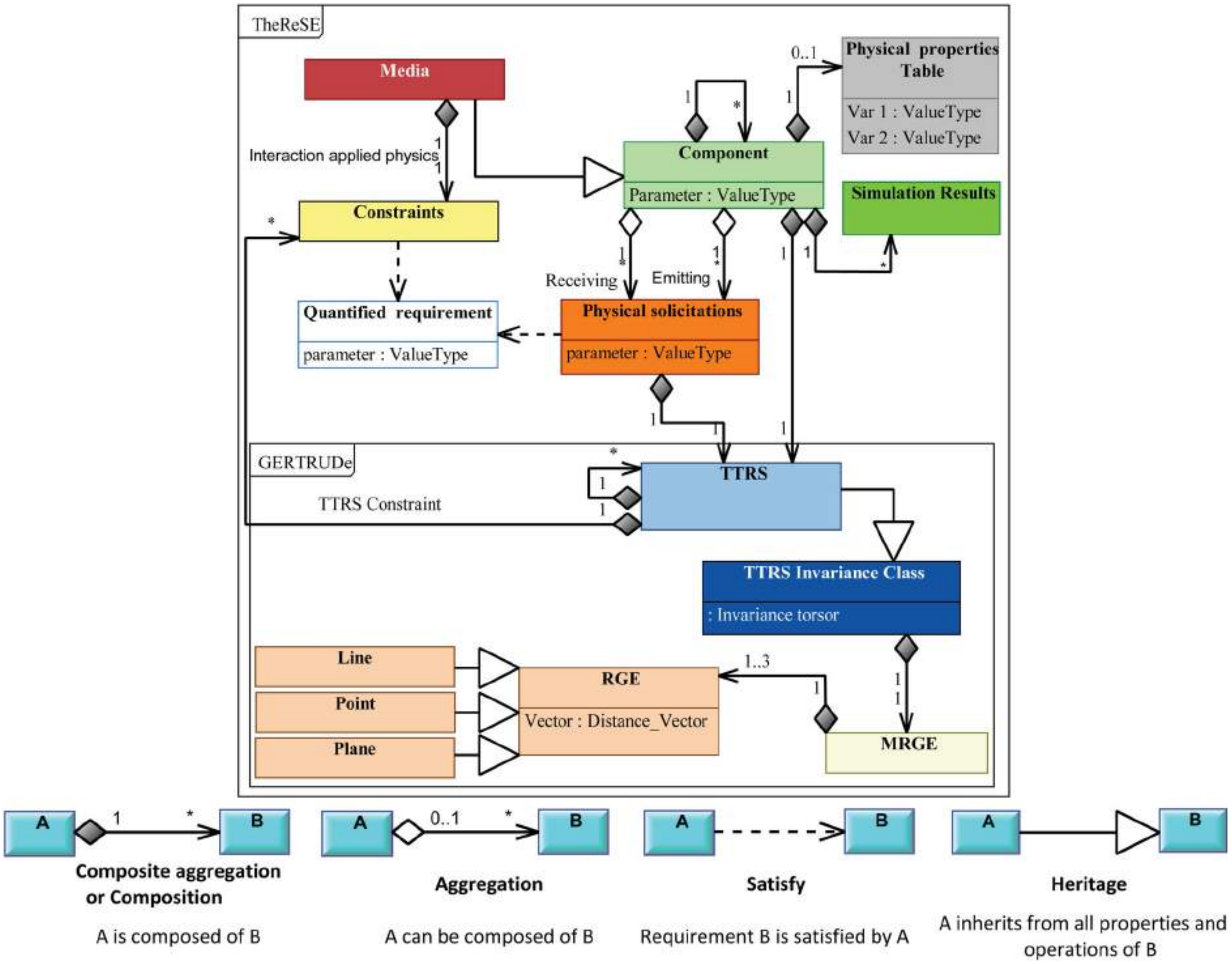


Figure 8. GeRTRUDe and TheReSE data models, based on the developed ontology.

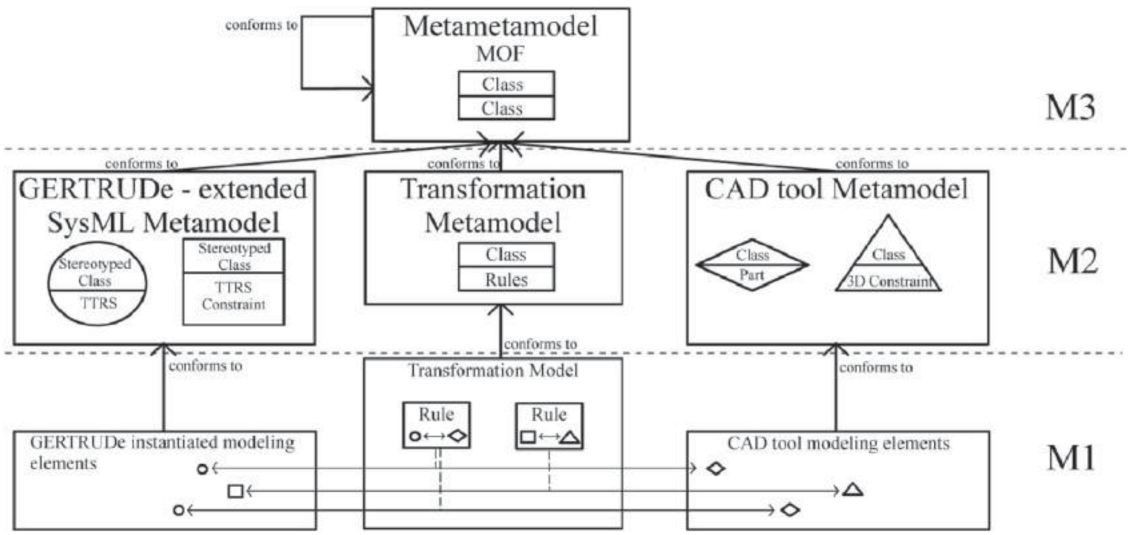


Figure 9. Geometrical Knowledge Model Transformation Approach.

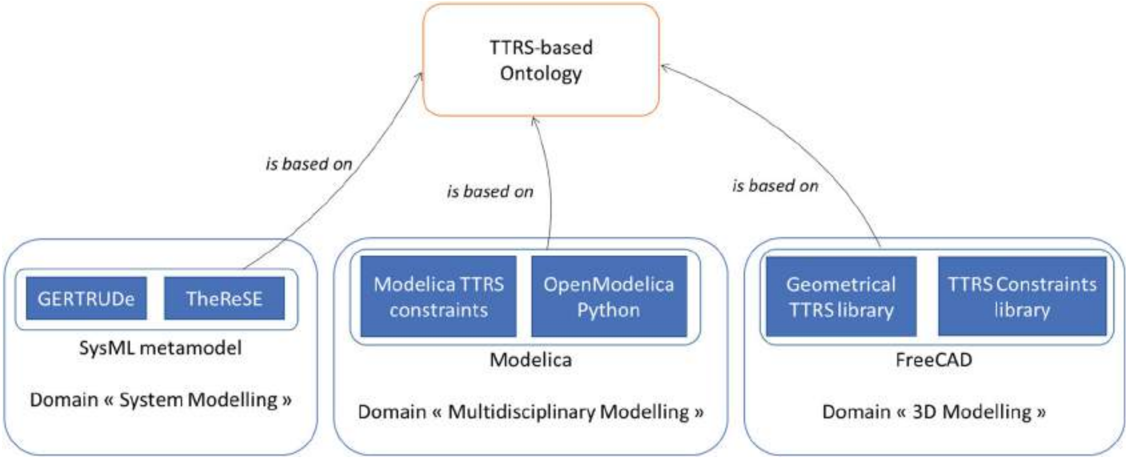


Figure 10. Geometrical knowledge consistency ensured by the TTRS-based ontology.

geometrical properties (concrete geometry, emitting and receiving thermal geometry) and the parameters required to be managed by thermal equations during simulation. Be it geometrical constraints equations or thermal equations, they are managed by Modelica modeling which is also interfaced by Python. Indeed TTRS constraints, based on the TTRS-based ontology have already been implemented in the Modelica language [25][30].

Fig. 10 presents the various modeling types occurring in the conceptual design stage (respectively based on the SysML and Modelica languages and FreeCAD tool) and how the use of the TTRS-based ontology allows to keep the geometry knowledge consistency, notably through successive model transformations. Indeed, from a meta-model viewpoint, the various respective modeling domains are based on the developed ontology as a reference, since this can be considered as an "upper/generic ontology" for the geometrical point of view. This will ensure the meeting of the geometrical specifications and corresponding data traceability, and then facilitate the verification automation.

4. Case study application: Electric Power Train

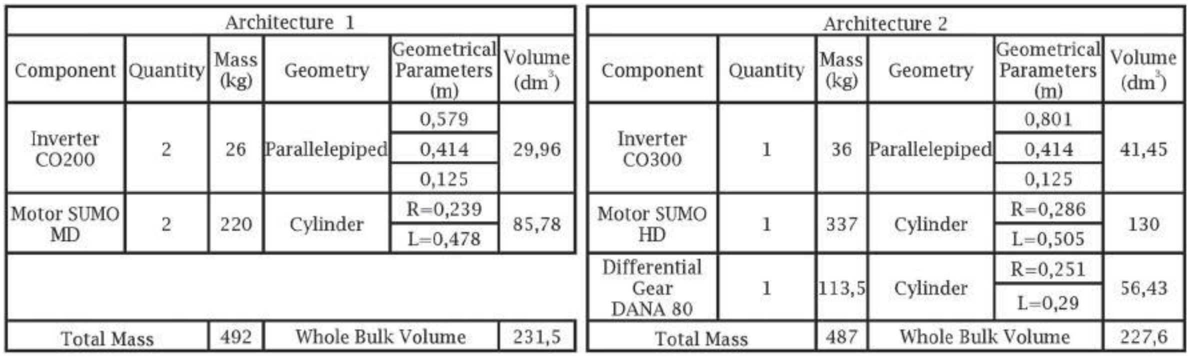
4.1. Case study description

To illustrate this approach, and to see how ontology can help to ensure the geometrical consistency of a mechatronic system design, we choose the scenario of the 3D architecture of an Electric Power Train (EPT) for bus vehicles, mounted on a chassis. Regarding the 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.

For this example, we took dimensions and mass of existing C.O.S.T.S. (as mentioned in Tab. 2). The corresponding dimensions of the simplified geometry have

Table 2. Architecture evaluation results.



Architecture 1					
Component	Quantity	Mass (kg)	Geometry	Geometrical Parameters (m)	Volume (dm^3)
Inverter CO200	2	26	Parallelepiped	0,579	29,96
				0,414	
				0,125	
Motor SUMO MD	2	220	Cylinder	R=0,239	85,78
				L=0,478	
Total Mass		492	Whole Bulk Volume		231,5

Architecture 2					
Component	Quantity	Mass (kg)	Geometry	Geometrical Parameters (m)	Volume (dm^3)
Inverter CO300	1	36	Parallelepiped	0,801	41,45
				0,414	
				0,125	
Motor SUMO HD	1	337	Cylinder	R=0,286	130
				L=0,505	
Differential Gear DANA 80	1	113,5	Cylinder	R=0,251	56,43
				L=0,29	
Total Mass		487	Whole Bulk Volume		227,6

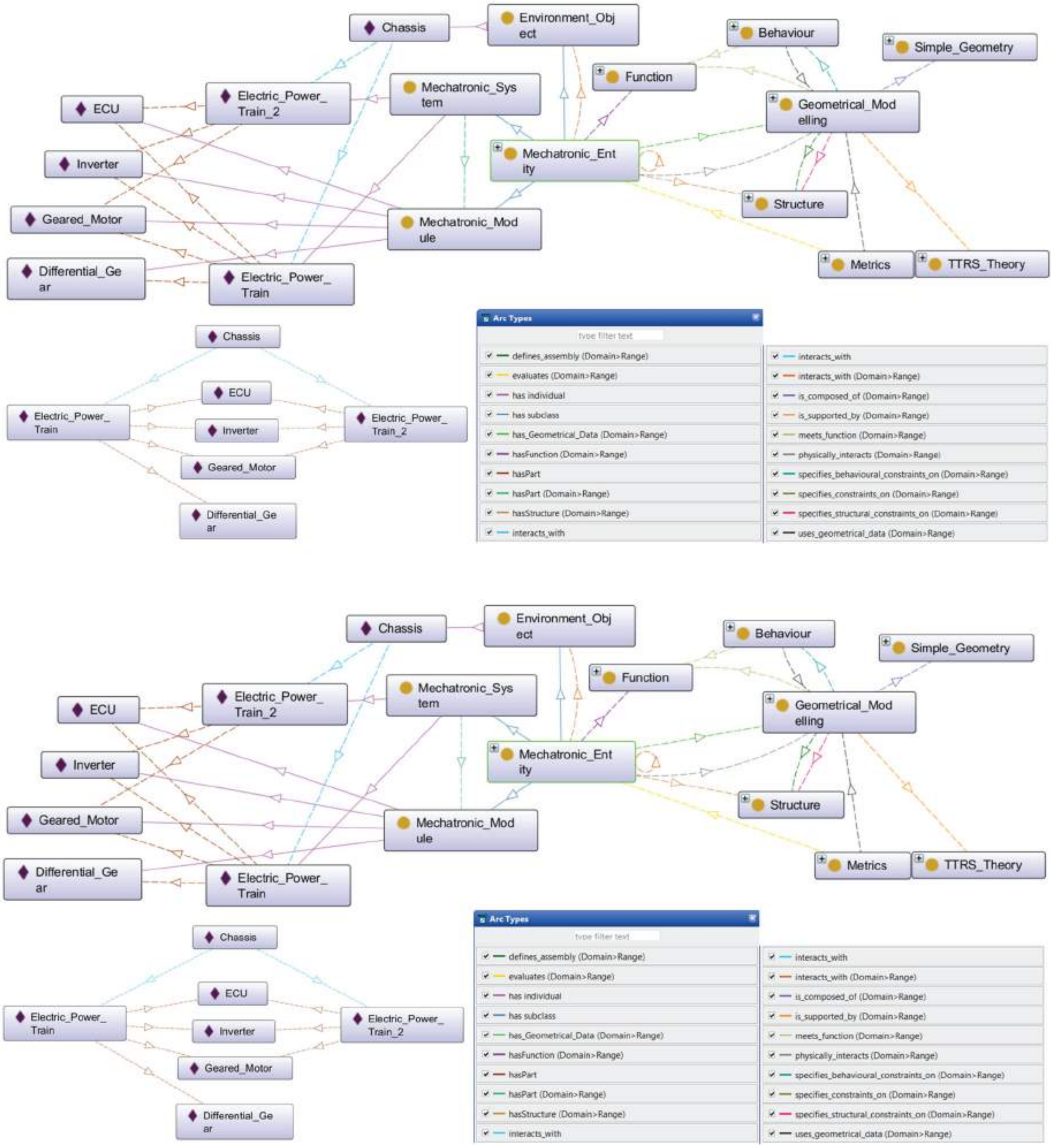


Figure 11. Case study based on the ontology developed with the PROTÉGÉ environment.

been based on the higher dimensions related to the considered spatial directions.

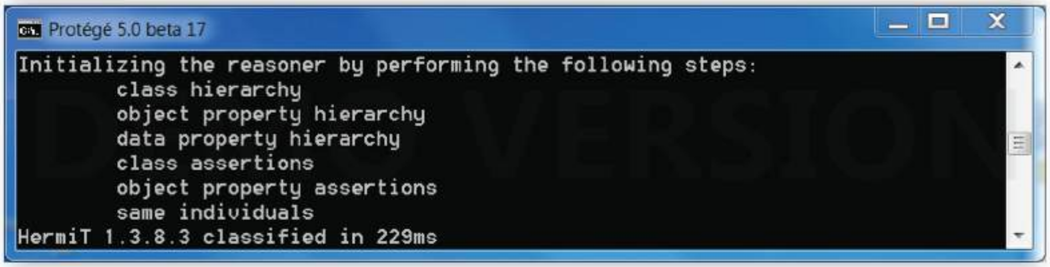
4.2. *Case study ontology modeling*

The developed ontology and its application to the case study have been implemented with the Protégé environment (Fig. 11).

An inference engine embedded in the Protégé software proposes some reasoning processes. The consistency of the developed ontology model has been checked with the HermiT1.3.8.3 reasoner. The reasoner classifies and assesses classes and object properties (Fig. 12).

4.3. *Ontology-based scenario validation*

Geometrical consistency is ensured by the model transformation between these various level modeling, made possible by the implementation of the following developments: TTRS-based ontology in the SysML metamodel through GeRTRUDe and TheReSE developments, the integration of the TTRS constraints in Modelica



```
Initializing the reasoner by performing the following steps:
        class hierarchy
        object property hierarchy
        data property hierarchy
        class assertions
        object property assertions
        same individuals
HermiT 1.3.8.3 classified in 229ms
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Figure 12. Result of consistency checking of the case study within Protégé using HermiT 1.3.8.3.

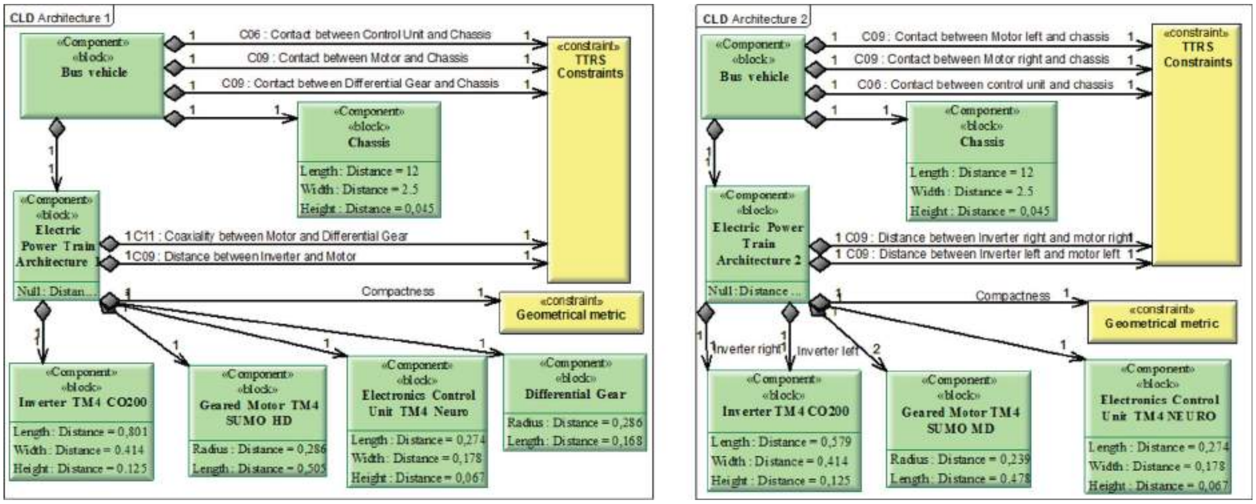

Figure 13. Alternative EPT spatial architectures in SysML with GeRTRUDE.

and the use of OpenModelica Python language to support physical behavior modeling, and the TTRS finite volumes and constraints libraries in FreeCAD for the 3D modeling.

These different modeling steps are presented with the EPT case study example.

On the Fig. 13, both architectures are specified by the System Architect in the SysML modeling, thanks to the developed GERTRUDe SysML extension [6]. 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 geared motors and differential have been approximated by cylinders, and inverters, electronic control unit and chassis have been approximated by rectangle parallelepipeds.

The relative positioning (position and orientation) of components can also be specified by the TTRS constraints, between their respective Minimal Reference Geometrical Element (MRGE). In our example, we specify some contact and coaxiality constraints between the architecture components. Finally, the geometrical metric to calculate the compactcness of the system is also defined by a constraint block.

Then, 3D modeling (Fig. 14) is automatically generated in the FreeCAD environment thanks to the developed SAMOS platform (Fig. 15), based on model transformations [4], which implements the developed ontology.

After performing the geometrical metric defining the compactness of each architecture [33], as the second architecture presents the slighter weighted compactness metric (Tab. 2), we choose it to carry out the thermal modeling.

For this thermal behavior modeling, performed thanks to the developed TheReSE SysML extension [5] (based also on this ontology) and then Modelica, we need four additional components: a fan and three pipes to complete the 3D architecture, in order to simulate the thermal behavior based on the defined 3D geometrical architecture. These components can be added either in FreeCAD by 3D designers and then traced back in the SysML model or they can be directly defined in the SysML environment by System Architects (Fig. 16 on the left). Then the Modelica modeling can be processed and simulated, after having defined thermal requirements, thermal properties of components and thermal simulation conditions, in the SAMOS implemented platform.

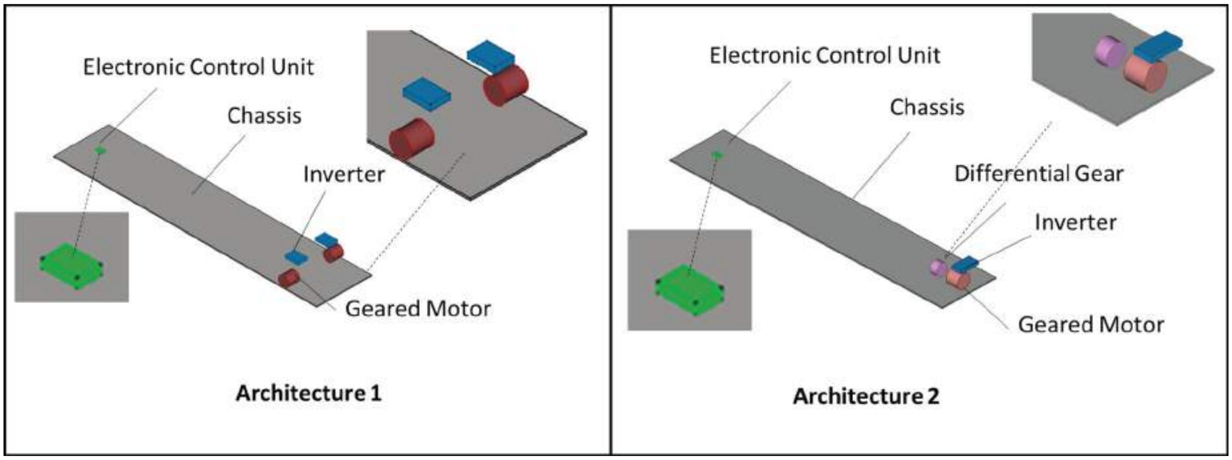

Figure 14. Generated 3D modeling of the different architectures.

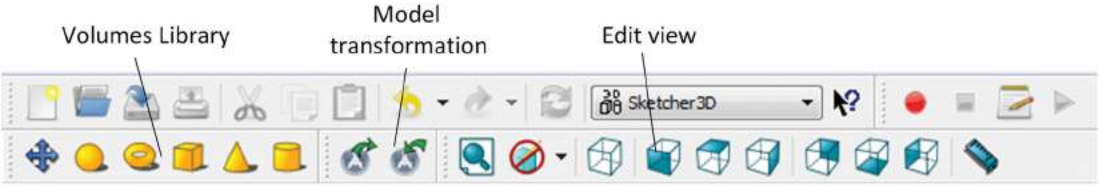

Figure 15. HMI development in FreeCAD for the implementation of the SAMOS approach.

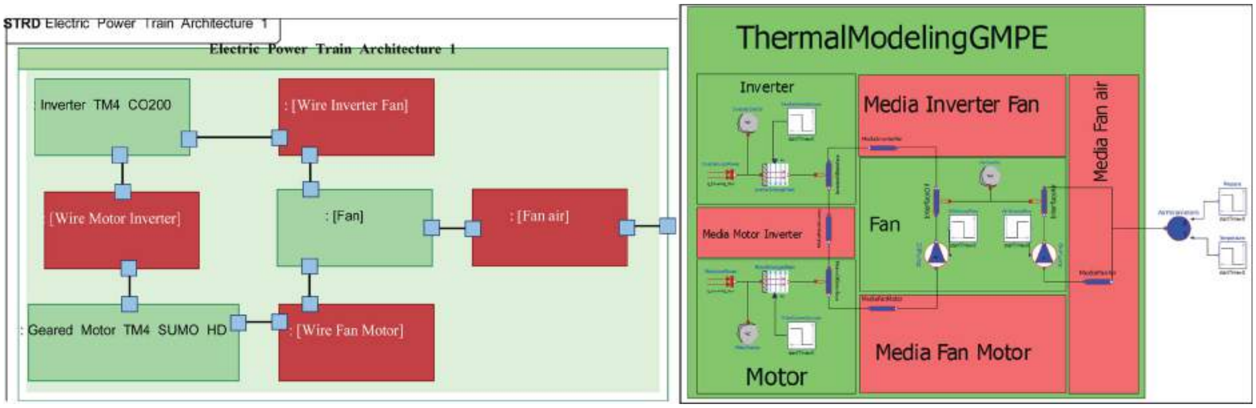

Figure 16. Thermal constraints and modeling of the architecture 1 in SysML (left) and Modelica (right) environments.

The developed geometrical knowledge ontology for mechatronic systems design based on the TTRS theory has been implemented in the data models of the GERTRUDe and TheReSE SysML extensions. It allows 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 design 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.

5. Conclusions

After presenting the TTRS theory and describing mechatronics design complex challenges, we have proposed a geometrical ontology, based on this 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), in accordance with MBSE approaches. This ontology has been validated through the effective development of model transformation processes between the different modeling using geometrical data. Moreover, it has been applied to a scenario of the architecture choice of an

Electric Power Train, including many additional geometrical issues related to mechatronic system design, such as physical integration and its related compactness metric, and thermal modeling for multi-physics.

After taking into account the geometric modeling in the mechatronic design ontology, other complementary modeling parts will be developed through the use of categories associated with infomorphisms suggesting expansion and modularity capacities of this geometry extended ontology.

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