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***Abstract*— For mechatronic design, physical integration of components is both: a challenge for compactness, and also a critical element since it can cause harmful multi-physical couplings. So a SysML profile is proposed to take into account geometrical specifications since the emergence of physical architectures of mechatronic system design. This additional information allows to calculate geometrical metrics on different possible architectures or to specify geometrical constraints for relative positioning of components.**

I. Introduction

A. *Physical Integration in Mechatronic Design*

The design of mechatronic systems is particularly complex due to their high functional integration, multi-domain and multiphysical features and other resulting couplings [1]. Indeed, mechatronics is an approach that integrates usually mechanics, electronics, automation and computer sciences. The complexity of these systems results from the increasing number of components to be integrated in a compact volume, which interacts in different physical, creating multiphysical couplings [2].

In this article, we focus on the physical integration. This integration can sometimes cause problems when multi-physical couplings can damage surrounding components, but it can also lead to additional functions to raise the overall system performance. For example, a rolling bearing generates a useless magnetic field. However, if a sensor is integrated in this bearing [3], this magnetic field enables the sensor protection from external magnetic disturbances. This instrumented bearing has so an additional function due to the physical integration of the sensor (Fig. 1Figure 1.).

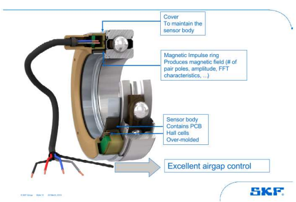

Figure 1. *Illustration of physical integration on a mechatronic system : Instrumented Ball Bearing (SKF™)*

B. *SysML Language*

In this paper, we consider SysML (Systems Modeling Language) [4] as the language for the system's modeling in the pre-design phase.

SysML was developed to support specifications, analysis, design, verification and validation of complex system design, with diagrams, whatever the field is, from the definition of requirements to components architecture. Thus it provides the same set of parameters for all technical teams working in the design [5]. But SysML is method agnostic and it provides so a very general boxology with "low" semantics [6], that facilitates the integration between design processes of different disciplines.

While this language is more and more a leading topic for System Engineering (SE) in any domain [7], there is not yet implementation of geometrical consideration at the early stages of design. However for mechatronic systems, the constraints emerging from components positioning are primordial [8][9] to take into account compactness [10][11] and multiphysical couplings [12][13].

What is finally at stake is to allow system architects to formalize geometrical requirements before preliminary design starts, in order to give to all technical multidisciplinary teams a unique view of these specifications, as inputs of their domain-specific studies, and so to facilitate design trade-offs notably for final architecture choice.

Currently, logical or physical architectures in SysML [14] formalize the system decomposition into technological components, usually represented by a block definition diagram (bdd), or they detail control and physical flows between these components depicted in an internal block diagram (ibd) [6].

Introducing geometrical positioning in a model centric SysML approach, long before the usual detailed design with CAD tools, allows:

- taking geometrical specifications right from the system architect level, and so to reduce time spent on design by limiting iterations number,

- providing graphical means with understandable geometrical information sharing between several different discipline teams,
- ensuring a seamless and inexpensive traceability/consistency between the first (geometrical requirements) and final stages (3D detailed design) of design.

SysML provides many diagrams to choose depending on the use or view modeled. According to MBSE, and related methodologies [6][7], after having defined different physical architectures that allocate physical components to logical elements previously identified, designer needs criteria and metrics to evaluate and compare these architectures. So, to evaluate physical integration of different architecture, geometrical data have to be added in order to build and use corresponding geometrical metrics.

C. *Geometrical Paradigm*

Previous considerations shows how important is it to consider as soon as possible component geometry and positioning to design complex and mechatronic systems.

In the case of geometrical metrics, in relation with mechatronic physical integration and compactness concept, it would be interesting to have access to data volumes, distances, surfaces of the components.

These geometrical data can be multiple and various depending on the modeling view addressed. SysML proposes indeed to model various roles of components and this is particularly interesting to specify geometrical constraints, like kinematic joints. The “composition link” in SysML may integrate the multiplicity of parts when their role is identic, that is a posteriori true for geometrical roles. So when the role of parts is different, we need to split geometric roles to manage this kind of geometrical information. For example a table is composed by four table leg, whose position impacts stability of the table (Fig. 2). So three of them have to generate an isostatic planar joint specification and the fourth needs a hyperstatic role to be adjusted.

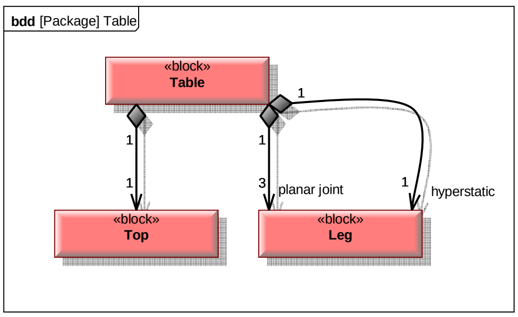

Figure 2. *Composition of a table illustrating roles of components linked to geometrical specifications*

Indeed to identify a valid architecture requires so taking into account the geometry and the relative positioning of each component [8]. In the case of Measures of Effectiveness (MOE) some geometrical relationships may be useful to do some preliminary behavioral simulations of each physical architecture in order to evaluate their performance relating to the considered MOE [15].

So the idea is to investigate physical interactions related to geometry, as soon as possible in the design life cycle (notably during pre-design phase). Indeed even the simplest assessment of any physical behavior needs to know orientation and distance between components.

In [16], we had already proposed a change of paradigm. Common paradigm is geometry in physics where geometric parameters are secondary but we think that paradigm physics in geometry will be efficient. To improve easily a model with a lot of multiphysical couplings, modeling has to be in 3D. Indeed, tools generally propose a 2D object modelling with 3D geometrical parameters hidden in components. The real geometry appears only when simulation. 2D icon representation of the Modelica objects with positions and dimensions has no geometrical meaning and geometrical data is not coupled to these 2D icons as illustrated in Fig. 3.

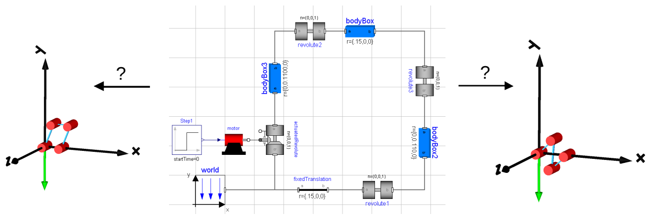

Figure 3. *3D alternative simulation of the 2D iconic 4 bars model [17]*

With 3D paradigm we handle the geometrical objects with their owning behaviour. Dimensions of 3D objects are related to their size (specified or real). The position corresponds to a physical 3D position. We created a TTRS [18] library to manage geometrical constraints and contacts by the 3D modeler [17] to develop this declarative approach.

So for the preliminary design phase (0D simulation), where first summary geometrical information is required: shape, dimension, etc., the consideration of this information in the requirements will help to implement structural constraints to well prepositioning spatially components before physical simulations (see section II.C).

II. OUR PROPOSAL: A SYSML GEOMETRICAL PROFILE

A. *Objective*

We propose to take into account physical interactions related to geometry, as soon as possible in the design life cycle. SysML geometrical Profile added value consists in:

- providing a mean to System Architect to specify geometrical requirements to enrich physical architectures;

- taking into account geometrical constraints (component positioning), to facilitate the work of preliminary design teams, by prepositioning relatively the components, before to evaluate their corresponding physical interactions;
- providing geometrical metrics to assess physical integration (compactness, available volume, physical interaction distances…), specially important for mechatronic system.

Today, very few research studies have focused on the integration and the importance of geometrical specifications in the "System" model. In [19], Baysal et al. propose a method to model the geometry and positioning for tolerance analysis on UML, but the positioning is not relative and doesn't integrate directly the constraints. It's really difficult for designer to calculate general positioning for each part. In [20], Graignic et al. propose a method to take into consideration interfaces between components on Logical Modeling of CATIA V6, but geometrical aspects are not explicit.. However, once the physical components have been selected, often on the shelf, it is easy to imagine that System Architect, from its industrial expertise or because of certain geometric configurations imposed, would specify geometrical requirements like their simplified geometry, maximum bounding box volume (especially if compactness is desired), but also sometimes a few simple constraints relative positioning between two components (in contact, in, on, distance ...) to enrich physical architectures specifications..

Currently, industrials need to bridge the gap between the "System" team and their models, and technical multi-disciplinary teams and their preliminary simulation models. Thus by enriching the "systems view" model with geometrical data and constraints, it enables engineering teams not only to share such data among multidisciplinary services (this is today rarely the case), but it gives them also the means to quickly validate if such architecture with spatial geometric constraints, can meet the performance requirements and physical behavior (thermal, EMC, vibration) expected.

Finally, to tackle physical integration issue of mechatronics systems some geometrical metrics are needed to assess the different physical candidate architecture relating to their compactness, remaining available volume, physical interaction distances…

B. Geometrical SysML Profile

Thus, we focus first our works on a SysML profile for geometry.

A profile is a set of additions, such as stereotypes, constraints and diagrams extensions, which are used to tailor the SysML language for a particular application or domain. So, SysML can be considered to be a profile of UML, tailoring it for the systems engineering domain [21]. A profile is applied to user model. This profile was defined here using Artisan Studio (Atego). This profile supports the modeling of mechatronic systems, because of their high interest for physical integration, and so corresponding geometrical constraints.

This profile defines stereotyped blocks for each simplified geometry: sphere, cylinder, hollow cylinder, rectangular parallelepiped, hollow parallelepiped, undefined parallelepiped, cone, prismatic, hollow prismatic, torus ... We propose also an associated Geometrical Model Library (Fig. 4), in order to facilitate the capitalization of components with geometrical information. Typically, a company could enrich some existing known component blocks with predefined geometrical information, and re-use them as their own "component library" in all their modeling, adding the geometrical dimension to their standard specifications…

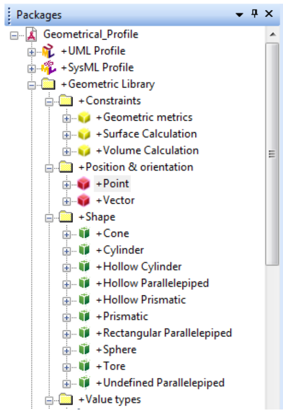

Figure 4. *Simplified Geometric Volume Blocks Library*

It includes for each geometry, elements specific to this geometry: known or desired maximum dimensions, position (a point, which is typically geometrical barycenter), orientation if any (one or two vectors) (Fig. 5).

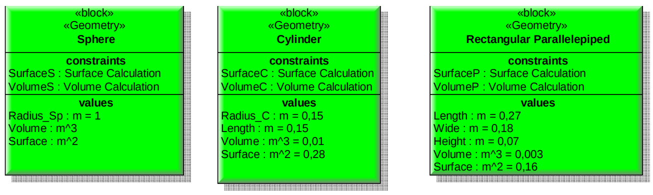

Figure 5. *Specific Geometrical Parameters Regarding to a Given Geometric Volume*

And for any component defined by a block in the physical architecture, it is very easy to apply the stereotype "geometry" and assign it the corresponding simplified geometry (Fig. 6 & Fig. 7).

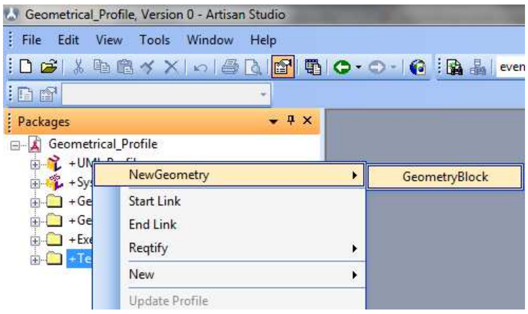

Figure 6. *Geometric Block Creation*

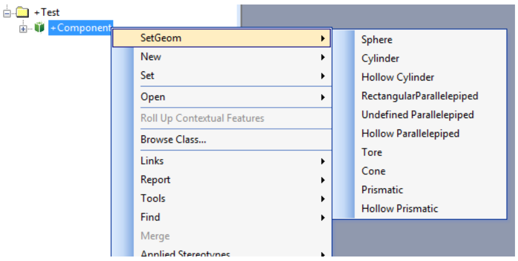

Figure 7. *Application of a Specific Geometry Stereotype on a Physical Component (Block)*

C. *Implementation of Geometrical Constraints (TTRS)*

In future work, this geometric profile will be used to integrate the modeling of the Topologically and Technologically Related Surfaces (TTRS) on SysML, and so promote the transfer of geometrical data specifications modeling in SysML physical architectures into a multi-physical simulation language, like Modelica. TTRS theory is introduced here as a unified framework for geometric objects representation and geometric constraints solving for components relative positioning [22]. According to TTRS, three-dimensional surfaces or features are classified according to their respective degree of invariance under the action of rigid motions. Basically, seven main features equivalent to kinematic lower pairs are identified (Fig. 8): planar feature, cylindrical feature, revolution feature, spherical feature, prismatic feature, helical feature and complex feature. Each main feature is then described by a unique Minimum Geometric Reference Element (MGRE) that allows positioning in Euclidean space without using a lot of ressources. An MGRE is set as a combination of elementary geometrical objects: point, line and plane. TTRS Theory has been adopted by international standards [23][24] and successfully implemented in the CATIA V5 CAD system. To obtain the relative position of the technological surfaces, it becomes possible to extract one or several vectors to represent the relative positions of two surfaces, parts or components. Moreover, during the early stages of the design of a product, there often exists a simple geometrical representation of the product such as a skeleton from which positioning vector parameters should be extracted. To prepare the future work, that will integrate TTRS on SysML, we adapted the MRGE modeling to the finite volume, for exemple a Finite cylinder will have a MGRE formed with a point for position an vector for orientation.

TTRS classes[1]	Complex	Prismatic	Revolute	Helicoid	Cylinder	Plan	Spherical
Invariance degree	0 (identity)	1 translation	1 rotation	1 rotation & 1 translation combined	1 rotation & 1 translation	1 rotation & 2 translations	3 rotations
MGRE[2]	Point		Point	Helix			Point
	Line	Line	Line		Line		
	Plan	Plan				Plan	

[1] Technologically and Topologically Related Surfaces
[2] Minimal Geometric Reference Element

Figure 8. *TTRS Model Elements* [18]

Then TTRS constraints (Fig. 9) can be applied between geometric elements, dependently on their class, to position them relatively.

Reclassing case of MRGE and induced constraints	Line (cylindric) (C_C)	Plan (Plan) (C_P)	Point (Spherical) (C_S)
Line (cylindric) (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
Plan (Plan) (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

Figure 9. *13 TTRS Constraints* [18]

This modeling was already implemented on Modelica [17] (Fig. 10), where the icons became parallelepipeds or cylinders bounding boxes. Connections had not only a topological meaning but also a geometrical direction, or even a physical one when required (for instance for EMC or thermal problems). This framework was already dynamic before the global simulation of physics.

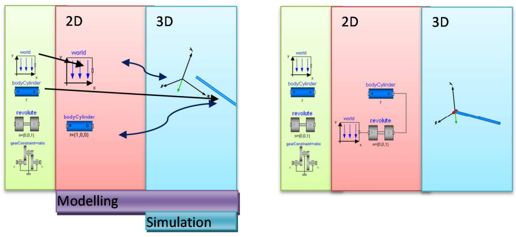

Figure 10. *3D Modelica framework where 2D and 3D zones are equivalent to model (double arrow) [16]*

The future works will consist in implementing this approach in SysML language, so that geometrical volumes will be dissociated in TTRS (Fig. 8), and geometrical constraints (Fig. 9) will be implemented with SysML constraints on a parametric Diagram (see future works of R. Barbedienne (Fig. 11)).

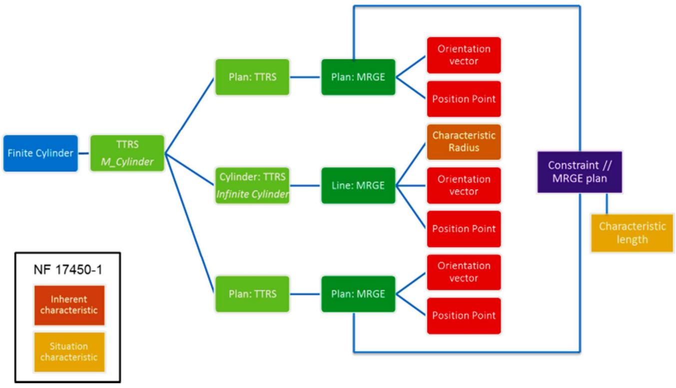

Figure 11. *Illustration of TTRS approach implemented for finite volume*

D. Geometrical Metrics for Physical Integration

During pre-design stage, designers must make the best choices to meet customer requirements and also technical requirements. Metrics are a way to help the designer to make these choices, and to ensure an objective traceability. In fact, they can help to evaluate different candidate architectures generated during the pre-design phase. Our research focus concerns so metrics for assessing the integration in the design of mechatronic systems [25]. Today this article deals specifically with the physical integration and therefore will rather address geometrical metrics for integration.

For this, we have developed several metrics that allow at the top-level consideration to evaluate the compactness of a system.

For example, one of these metrics allows to compare the available space within the system or within a hollow component, in order to evaluate their residual capacity to incorporate other components in the component assembly (Fig. 12).

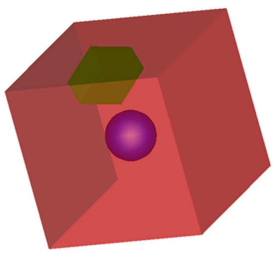

Figure 12. *Compactness Assessment (avalaible volume Metric)*

Another metric of "accessibility" allows to know if there is a passage volume to access a component (solid) (e.g. routed cable) inside of another component (solid) (Fig. 13).

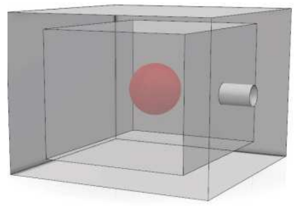

Figure 13. *Geometrical Illustration for “Accessibility” Metric.*

A third example concerns the assembly optimization: the assembly metric used to analyze architectures to find the one with the smallest bounding box possible (Fig. 14).

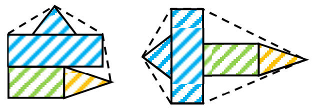

Figure 14. *Illustration of use of metric to evaluate assembly optimization*

These different geometrical metrics will be detailed in a future paper.

Finally, simplified modeling of geometry, implemented in SysML with this profile will allow the designer to build these different metrics and so to be able to calculate them to facilitate his choice between several candidate architectures, in accordance with a physical integration objective.

III. Illustration and Discussion

A. Illustrative Example

To illustrate the approach, we choose the scenario of an electric power train, composed of the main following components:

- A motor : modeled by a cylinder
- An inverter for power electronics : modeled by rectangular parallelepiped

- A reducer: modeled by a cylinder
- A control electronics unit: modeled by rectangular parallelepiped

On Fig.15, architecture of the electric powertrain is detailed, with four components represented by four blocks stereotyped with “Geometry”: each block is associated with a simplified geometry, its dimensions can be specified in “values” compartment, in the unit predefined, its position and orientation are given by their Minimal Relative Geometrical Element (MGRE) mentioned in “parts” compartment, finally associated constraints (calculation and metric), which can be calculated are represented in “constraints” compartment. Geometrical Metrics associated to the whole system are declared as a constraint “block” composing the system.

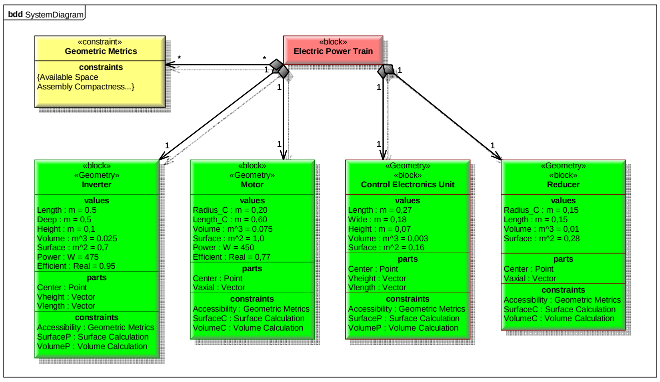

Figure 15. Illustration of the Geometrical Profile on an Electric Power Train Architecture

B. Discussion and Future Developments

This geometry-enriched physical architecture allows to calculated geometrical metrics for each possible architecture, and then to compare these different architectures related to geometrical consideration like component accessibility, system compactness or also assembly compactness. Even if the error made with this geometrical simplified approach is still high, it gives some trends. As to this point, the aim is to compare different architectures, the relative errors between architectures become still relevant.

Moreover, the possibility to enrich physical architectures in SysML with geometrical specifications (simplified associated volumes, with dimensions and position), allow designers to precise to specific domain teams, some useful constraints: bounding boxes, distances, inclusions…, to begin their pre-sizing work. This common information shared between all multi-disciplinary teams is very helpful to ensure global consistency, and geometrical optimization of the system. Thus, the relative positioning of the different components has to be added in our future works to address the whole physical integration challenge: compactness but also multiphysical couplings management.

IV. CONCLUSIONS

The proposed geometrical SysML profile involve geometrical paradigm in the early stages of design, by integrating some summary geometrical specifications to allow designer to compare different architectures relating to their physical integration/compactness, by means of geometrical metrics. This profile will also help, with our future developments about relative component positioning, some technical disciplinary teams to begin their behavior simulation with some spatially-constrained architectures.

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