Towards the integration of thermal physics and geometrical constraints for a 3D-multiphysical sketcher

S. Papa, S. Patalano, A. Lanzotti, S. Gerbino, J.Y. Choley

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S. Papa, S. Patalano, A. Lanzotti
Dept. of Industrial Engineering
University of Naples Federico II
Naples (NA), Italy
{stefpapa, stanislao.patalano, antonio.lanzotti}@unina.it

S. Gerbino
DiBT Dept.
University of Molise
Termoli (CB), Italy
salvatore.gerbino@unimol.it

J.Y. Choley
LISMMA laboratory
Supméca - Institut Supérieur de Mécanique de Paris
Saint-Ouen Cedex, France
jean-yves.choley@supmeca.fr

***Abstract*— The paper deals with the relationship between geometrical or topological entities of complex systems and the physics in which the systems are involved. In particular, the paper deepens the integration of thermal physics with geometrical constraints. Therefore, the results of the work could be used within the development of a 3D-multiphysical sketcher viz., a tool for the preliminary design of complex systems, characterized by the presence of one or more overlapping physics. Firstly, the model of Topologically & Technologically Related Surfaces (TTRS) is used and related Minimal Reference Geometrical Elements (MRGEs) and constraint conditions are implemented by means of Modelica language. Then, the implementation of new objects for MRGEs and constraint conditions are applied to a mechanical assembly. Finally, the integration of TTRS model within thermal physics is applied to the case of the layout designing for electronic boards.**

Keywords—Multiphysics, TTRS, Modelica language, preliminary design

I. INTRODUCTION

The design of a complex system nowadays deals with the interaction of many components involving different physics. The designer uses a typical procedure, passing from the preliminary design to the final configuration, validated through several simulations. In general, the multidisciplinary aspect of a complex system, such as a mechatronic system [1], requires an environment suited to all steps of the design, which allows to model mechanics, electronics, automation, and also the interaction between the different physics involved [2].

A methodology for the conceptual design of complex systems, developed at SUPMECA in Paris, proposes the combined use of various instruments widely applied during the different phases of the design process [3], [4].

Nowadays, many studies have been accomplished, but they focus just on each level of the V-Cycle and do not allow a continuity of modeling from the definition of requirements to virtual prototyping [5]. On the opposite, the approach in [6] introduces a hybrid methodology based on different tools, languages and methodologies, such as SysML [7], [8], Modelica [9] and CATIA [10], [11]. In particular, the analysis of a complex system starts from its breakdown into several devices, sub-assemblies or components that could be considered homogeneous and consistent from the topological, functional and multi-physical point of view, respectively. Such goal is accomplished by means of dedicated tools [12]. Each device has a behavior related to one or more physics and contributes, therefore, to the overall multiphysical field that characterizes the complex system. Once identified the functional requirements and the physical parameters of the complex system, the next step deals with the definition of the logical architecture, the connection of different components characterized by their dynamic behaviors and, finally, the simulation of whole system performances. The language used for this step is Modelica [13], [14]. In fact, the libraries developed using Modelica already contain objects and models aimed to simulate different physics, including related equations, and the existing connectors could be used to connect devices by means of compatible parameters [15], [16].

The simulation of multiphysical behavior of a complex system could be very useful during preliminary design. By creating a tool i.e. a 3D multiphysical sketcher for preliminary design of complex systems, in fact, it is possible to reduce the successive use of Finite Element (FE) simulations. Such simulations represent the most expensive task in terms of time consumption for solving the dynamic behavior of multi-physical systems [17]. To accomplish the simulation of different and overlapping physics, it is necessary to determine the relationship existing between geometrical or topological entities of the system and the physics in which the system is involved. A method to establish this relationship is to use Topologically & Technologically Related Surfaces (TTRS) [18], together with the related Minimal Reference Geometrical Elements (MRGEs) and constraint conditions. The present paper deepens the relationship between geometrical or topological entities of complex systems and the thermal physics in which the systems is involved. The paper is arranged as follows. Section 2 presents the implementation of the set of MRGEs within Modelica environment and the application of such MRGEs to a mechanical assembly. Section 3 summarizes the logical scheme supporting the action of a 3D multiphysical sketcher. Section 4 illustrates the application of the integration of TTRS model within thermal physics to the case of the designing for electronic boards. Finally, Section 5 draws the conclusions.

II. Modelling TTRS within Modelica language

The coupling of information related to the position and orientation of different objects in a three-dimensional space could be accomplished using Topologically & Technologically Related Surfaces (TTRS) and Modelica language. According the TTRS model [18], any surface or association of real surfaces of an object can be associated to a kinematic invariance class named TTRS. There are 7 classes of TTRS, classified according to increasing Degrees of Freedom (DOF): Identity equals to 0, Revolute, Prismatic and Helical equal to 1, Cylindrical equals to 2, Spherical and Planar equal to 3. Kinematic joints can be expressed by TTRS. Each TTRS is characterized by a MRGE. Each MRGE is made up of a combination of one point and/or one line and/or one plane, but it does not take into account the intrinsic dimensional aspect of the object (Table I).

In order to assembly two geometrical objects, i.e. to define geometrical constraints between two TTRS, 44 associations were identified depending on the relative orientations and positions. They correspond to the most elementary formulation of a kinematic connection between objects.

TABLE I. A cone associated to TTRS "Revolute Surface" whose MRGEs are a point and a line

Surface	***Class***	***MRGE***	
	Revolute Surface 		Point-Line

Finally, the study of related MRGEs enables to have only 13 possible cases of constraints. These constraints between MRGEs, numbered from C1 to C13, use algebraic expressions and parameters (Fig. 1) [18]. Firstly, each MRGE (point, line and plane) was implemented in Modelica environment as an object. The primary object is the point, defined as a vector with three variable coordinates. The coordinates of the point can be assigned as a datum or evaluated during a simulation (*point* or *point_u* in Fig. 2, respectively). The line block is created using a class containing both two vectors for the coordinates of two points, and two matrices for parametric and Cartesian coordinates. When simulation starts, the environment evaluates both Cartesian and parametric coordinates of the objects. A line could be defined by means of two points, or obtained using geometric conditions, as the intersection of two planes. A plane could be defined by means of three points. For this reason, the line object contains both parametric and Cartesian coordinates. In Fig. 3 the coordinates of the line, defined through two datum points or the intersection of two planes, are shown. The equations of the planes are $ax+by+cz+d=0$ and $a'x+b'y+c'z+d'=0$ respectively. In particular, Fig.3 depicts the condition related to the planes represented by equations $y=0$ and $z=0$. The 13 constraints were generated in Modelica environment by using MRGEs. Each block was created by using vectors and parameters, in order to calculate the coordinates of the involved MRGE. The constraint C2, for example, related to the distance between two points, uses the parametrical Equation in (1):

$$point2 = point1 + vector \cdot d \qquad (1)$$

In particular, *vector* is the unitary vector between the two

Constraints:
C1: point-point, coincidence
C2: point-point, distance
C3: point-plane, distance
C4: point-line, coincidence
C5: point-line, distance
C6: plane-plane, parallel, distance
C7: plane-plane, angle
C8: plane-line, perpendicularity
C9: plane-line, parallel, distance
C10: plane-line, angle
C11: line-line, coincidence
C12: line-line, parallel, distance
C13: line-line, angle and distance

	point ●	line	plane
point ●	$C1 : O_1 = O_2 \rightarrow \{S_{O_1}\}$	$C4 : O_1 \in D_2 \rightarrow \{R_{D_2}\}$	$C3 : \{R_D\}$
	$C2 : O_1 \neq O_2 \rightarrow \{R_{O_1O_2}\}$	$C5 : O_1 \notin D_2 \rightarrow \{E\}$	
line		$C11: D_1 = D_2 \rightarrow \{C_{D_1}\}$	$C8: D_1 \perp P_2 \rightarrow \{R_{D_1}\}$
		$C12: \begin{Bmatrix} D_1 \parallel D_2 \\ D_1 \neq D_2 \end{Bmatrix} \rightarrow \{T_{D_1}\}$	$C9: D_1 \parallel P_2 \rightarrow \{T_{D_1}\}$
		$C13: \begin{Bmatrix} D_1 \nparallel D_2 \\ D_1 \neq D_2 \end{Bmatrix} \rightarrow \{E\}$	$C10: D_1 \angle P_2 \rightarrow \{E\}$
plane			$C6: P_1 \parallel P_2 \rightarrow \{G_{P_1}\}$
			$C7: P_1 \nparallel P_2 \rightarrow \{T_{P_1 \cap P_2}\}$

Fig. 1. The 13 constraints within TTRS model [18]

points and d is the parameter that defines the position of *point2* respect to *point1*.

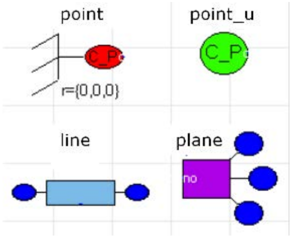

Fig. 2. Objects of MRGEs in Modelica environment

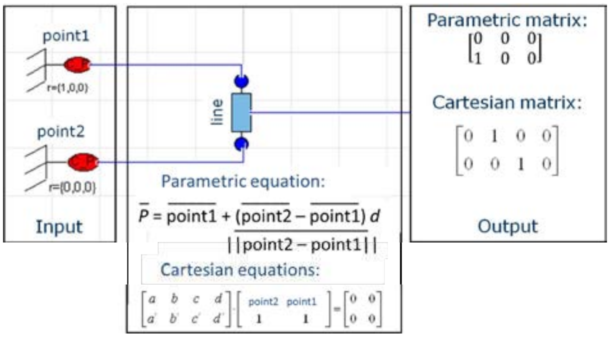

Fig. 3. Example of "line" object expressed by parametric and Cartesian equations

The components of *vector* are evaluated by initial conditions related to the two points or by means of geometrical constraints coming from other blocks. In fact, an additional connector located on the top right of the block was added: when this connector is used, the direction of vector is evaluated from other blocks of the model. Similar procedures were used to implement the whole set of 13 constraints. Fig. 4 depicts the 13 constraints and the implementation related to C2 constraint. In particular, a counter "_x" was added to the label of each constraint to univocally identify the instance used in the system context. In order to verify the implemented objects for MRGEs and the 13 constraints, a lifting valve assembly was preliminarily modelled within Modelica environment.

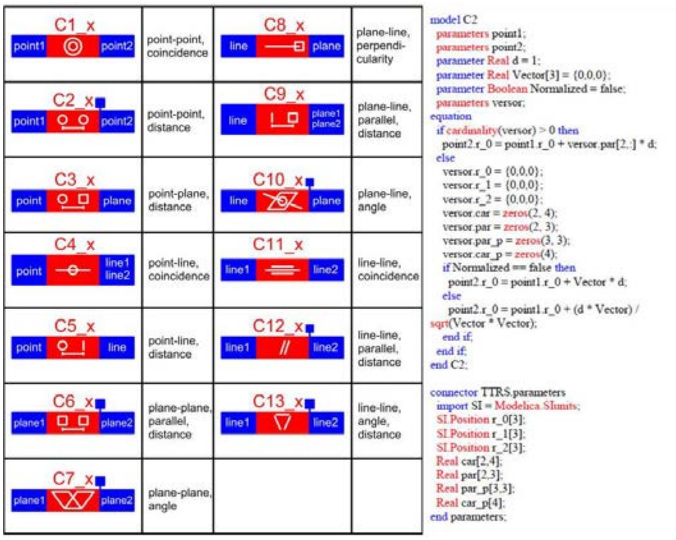

Fig. 4. Blocks related to 13 constraints and the code related to C2 constraint, within Modelica environment

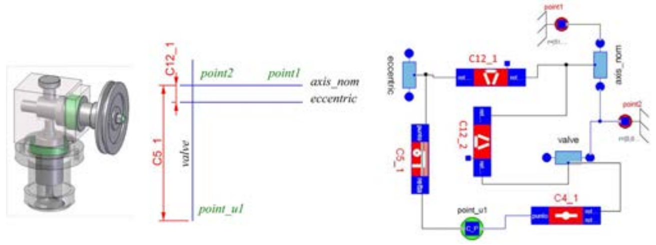

Fig. 5. Lifting valve assembly (left), MRGEs (middle) and Modelica model (right)

The assembly consists in a vertical valve moved by an eccentric shaft rotating around the horizontal axis. The nominal axis (*axis_nom*) is aligned to x axis and defined by two datum points (*point1* and *point2*), while the eccentric axis (*eccentric*) is parallel to the nominal one and translated along y direction by the constraint C12_1. The valve, according to TTRS model, is a revolute surface, so it is associated to the MRGEs line and point. The line is the axis of revolution (*valve*) and it is defined perpendicular to *axis_nom* by the constraint C12_2 and passing through *point2*. The point (*point_u1*) is the center of the valve head and it belongs to the axis of revolution by means of C4_1 constraint; the distance for *point_u1* position is given through the C5_1 constraint (Fig. 5).

III. The Role of TTRS Model Constraints in a 3D Multiphysical Sketcher

The strong integration and the geometrical compactness among the different components of modern complex systems carry as a consequence the proximity between different multiphysical domains and the inevitable physics interactions. In particular, the devices that compose the system are immersed in media with known physical characteristics, which determine the values of the multiphysical interactions. The connectors implemented for each device enable the multiphysical interactions (Fig. 6). The simulation of a complex system works both in terms of time, thanks to the solution of equations by means of Modelica solvers and in terms of variational changes of geometries. The role of geometrical constraints from TTRS model, here implemented in Modelica environment, is to accomplish the updating of geometrical conditions between devices, in a 3D space, during multiphysical simulations.

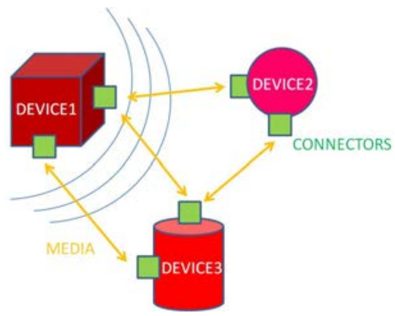

Fig. 6. Logical scheme for the interaction between devices to be modelled in a 3D multiphysical sketcher

At this step, this goal is accomplished by using the same parameters and objects related both to 13 constraints and the simulation of physical interactions.

IV. Case Study: Layout of Components in Presence of Heat Transfer

The case study consists of 2 masses in a 3D space, 1 thermic relation for heat transfer, and 1 metal media for conduction. The two-masses system refers to the case of electronic boards as in [19], or to the case of the evaluation board depicted in Fig. 7 [20]. In the board, a 10 watts power Field-Programmable Gate Array (FPGA) transmits thermal energy to a set of DDR3 memory modules. Therefore, a limit working temperature for the DDR3 modules should not be exceeded. At this stage, a preliminary model for conductive-convective thermal exchange has been implemented. In particular the model uses the classes belonging to Modelica libraries together with the *ad hoc* models implemented for the 13 constraints and related to TTRS. In fact, by considering the TTRS model for the C2 constraint i.e. the distance between two geometrical points, the final displacement of the mass, representing the DDR3 modules, was accomplished (Fig. 8).

The distance between the two lumped masses was associated to the balance distance in the conduction equation, by using Modelica environment (Eq. 2).

```
......
Real e;
equation
G = k*A/e;
Q_flow = G*dt;                                        (2)
e=e0+alfa]dT;
TTRS.C2 c2_1(Vector={1,2,3});
c2_1.d=thermalConductor2_1.e;
......
```

The result was the displacement of the second mass to the allowed distance, evaluated according to thermal parameters in terms of power, heat capacity, thermal conductivity and initial temperatures (Fig. 9).

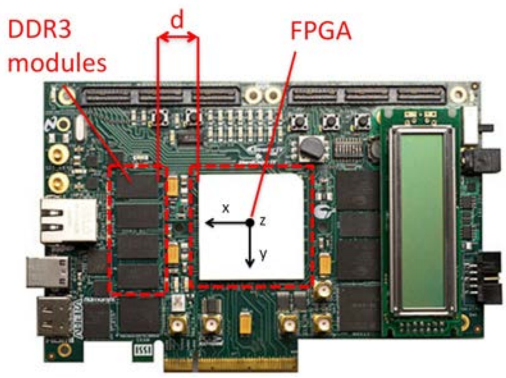

Fig. 7. Relative positioning of DDR3 modules and FPGA related to the electronic board in [20]

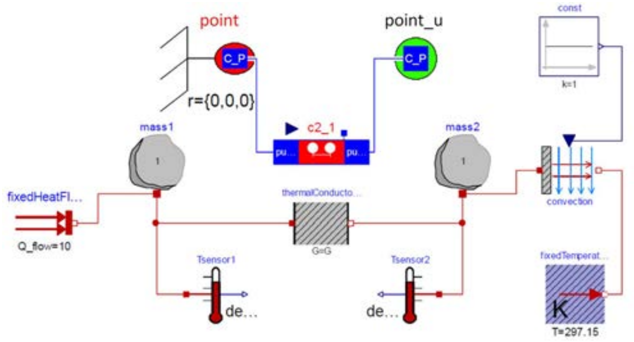

Fig. 8. Object models of the two masses system

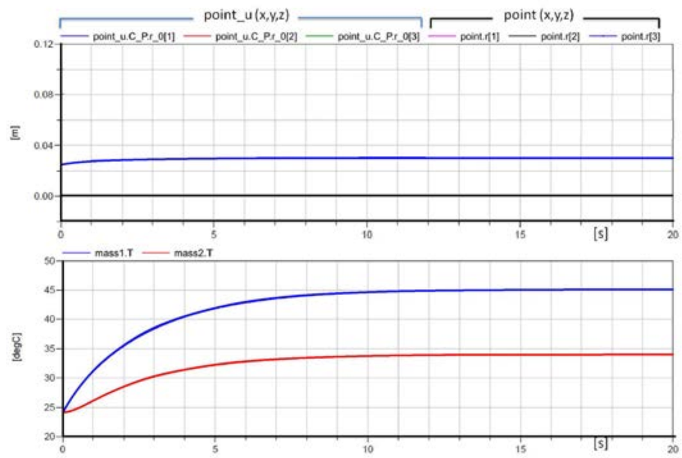

Fig. 9. Results of Modelica simulation in terms of position of masses and related temperatures

The automatic displacement of the two lumped masses is actually accomplished using the 3D animation window related to the Modelica library for multi-body systems.

V. Conclusions

The paper summarizes the preliminary results related to the integration of thermal physics with geometrical constraints, i.e. the possibility to use a thermal exchange to impose a variational change to a set of assigned MGREs (point, line, plane) that represent the complex system. Therefore, such results could be used within the development of a 3D-multiphysical sketcher aimed to preliminary designing of complex systems.

The objects developed within Modelica environment assure the possibility to model every complex system, including all possible constraints conditions between components, thanks to the completeness of TTRS approach that is used as a basis. Furthermore, the approach to simulation, used in the work, operates in terms of time thanks to the solution of equations through Modelica solvers but also in terms of variational changes related to geometrical elements. Therefore, different design solutions could be explored by means of simulation. A first possibility deals with the evaluation of transitory events related to parameters, as in case of working temperatures for critical components. Otherwise, final displacements, such as relative positioning of components, could be simulated providing a significant support to designers.

The developed case study related to a two-mass system showed the potentiality of the approach and the data coming from such simulation. Further works have to be developed to test the whole set of constraints as well as the presence of coexisting and overlapping physics.

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