Topological Approach for the Modeling of Complex and Mechatronic Systems

Mariem Miladi Chaabane, Régis Plateaux, Jean-Yves Choley, Chafik Karra, Alain Riviere and Mohamed Haddar

Abstract The main objective of this chapter is to show the advantage of the application of a topological approach for the modeling of complex and mechatronic systems. This approach is based on the notions of topological collections and transformations and it is applied by using the MGS language (Modeling of General Systems). The various applications studied by applying this approach such as bars and beams structures and elementary mechatronic components (piezoelectric structures and motor reducer) are presented.

Keywords Mechatronic systems · Topological approach · Topological collections · Transformations · KBR graph · MGS language

1 Introduction

Thanks to technological development and because of consumers requirements, new systems called mechatronic systems, appeared. Among these systems we can quote as examples the SEGWAY which is a single-seat electric vehicle with two wheels, the Electronic Wedge Brake (EWB) which replaces a whole hydraulic brake system and the Nao robot which is an intelligent humanoïde robot. These systems have

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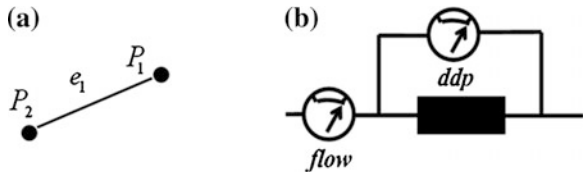


Fig. 1 **a** Topological structure. **b** Physical component

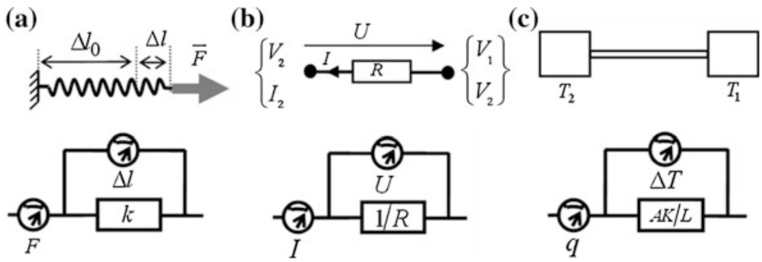


Fig. 2 **a** Spring. **b** Electric resistance. **c** Metal bar

a high level of integration of electronics, mechanics, automatic and data processing and then present complex behaviors also these mechatronic systems present new constraints of precision and size as well as new environmental constraints. From where the need for a new modeling approach allowing to guarantee the continuity and the coherence of the modeling of mechatronic systems (Plateaux 2011; Plateaux et al. 2007). Therefore, in this work we are interested to adopt a topological approach for the modeling of mechatronic systems. In fact, each field of mechatronic can be characterized by its topological structure and its behavior law.

2 Contribution of Topology for the Modeling

Considering the topological structure presented by the Fig. 1a which is a linear graph composed of an arc noted e_1 and two nodes noted P_1 and P_2. By associating variables of type flow and potential difference to this topological structure, it can present various physical components (Fig. 1b). For example, basing on the inverse analogy which retains the topology (Firestone 1933), this topological structure can present a spring in traction compression in the mechanical field (Fig. 2a), an electric resistance in the electrical field (Fig. 2b) or a metal bar in the thermal field (Fig. 2c).

In order to apply this approach, we are based on the topological graph named KBR, in the honor of their creators Kron, Branin and Roth (Fig. 3) (Kron 1963; Branin 1966; Roth 1955). The KBR graph enables the distinguishing between the topological structure of the system and the associated physics and then can be used as a unification basis for the modeling of complex or mechatronic systems.

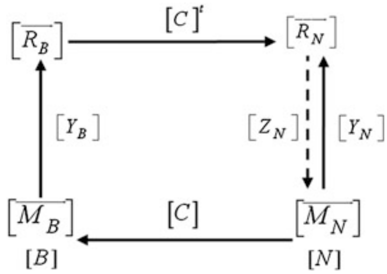


Fig. 3 The KBR topological graph

As a language for the application of the KBR graph, we initially applied MODELICA language. Indeed, MODELICA is an object-oriented language that uses the concept of flow and potential thus respecting the Kirchhoff laws. Also, it offers a great number of free libraries and it has the advantage of being interfaced with other software such as CATIA V6 and MATLAB/Simulink…. On the other hand its topological nature is limited to 0 and 1complexes and the access to higher dimensions can be done only via transformations. For example a variable magnetic field adding a stray current in a control circuit could be taken into account in MODELICA only if the model describes with its connectors (0-simplexes) is created. Also, it associates the topology and the behavior in the same model that limits the generalisation of the studied model. Therefore, the limitations of MODELICA language impose another language for the KBR graph (Plateaux 2011).

In our study, we resorted to use the MGS language which is an abreviation of General Modeling System. This language is a research project in the IBISC (Laboratory for Computer Science, Integrative Biology and Complex Systems) of the University of Evry (France) (Spicher 2006; Cohen 2004). This project study the contribution of topological concepts in the programming languages and apply these concepts to the design of new data structures and control for the modeling and simulation of dynamic systems with dynamic structures. In addition to its basic elements, MGS integrates a new kind of values called topological collections which consist of a set of cells organized with a neighbourhood relationship and decorated by values. To manipulate its data structure, MGS uses the transformations which are defined by a set of rewriting rules of the following form $m \Rightarrow e$. The left-hand part of the rule is called pattern and the right-hand part is the expression that replaces the instances of m. We mainly distinguish functions defined by case, paths transformations which allow the update of values associated with cells and patches which are intended to modify the structure of the cells. Then, we are interested to use the topological collections to present the topology of the studied system which means the interconnection laws between its components and the transformations to specify the local behavior law of these components.

The general modeling approach using topological collections and transformations consists in presenting the studied system by a cellular complex to which we associate the variables of interest. Then, we specify the local behavior law and

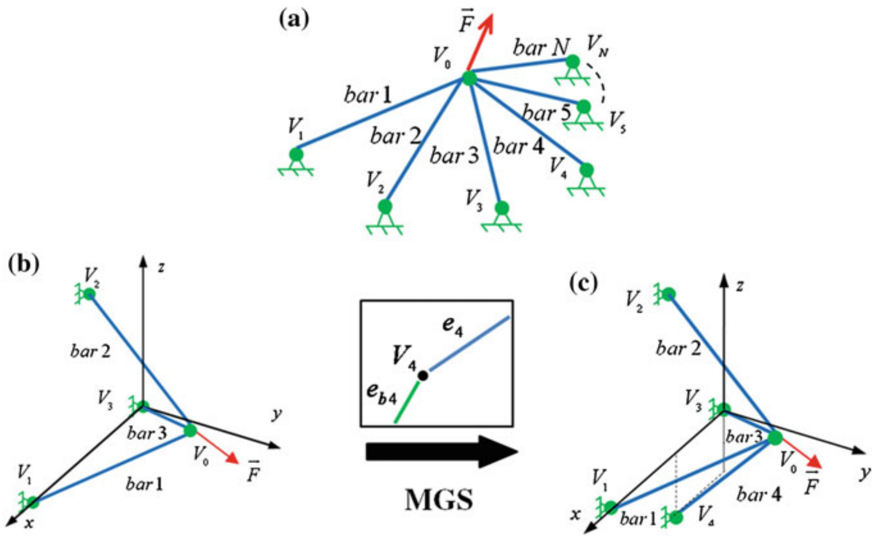


Fig. 4 **a** N bar truss structure with pyramidal structure **b** three bar truss structure **c** four bar truss structure

equilibrium equations of the different components of the studied systems. Finally, the generation of the system of equations is done by sweeping all the cells representing the system. This system is written in MODELICA format and we use DYMOLA as a solver.

3 Applications

In order to validate the topological approach presented in this chapter, we applied it in a first part to the modeling of mechanical structures of bars and beams. Then in a second part, we applied it to the modeling of mechatronic components (Miladi Chaabane 2014).

First of all, we applied this topological approach in the particular case of an N bar truss structure with pyramidal structure (Fig. 4a). Two particular cases are studied which are an isostatic case for a three bar truss structure (Fig. 4b) and a hyperstatic case for a four bar truss structure (Fig. 4c) (Miladi Chaabane et al. 2013a). Using topological collections, the passage from a three bar truss structure to a four bar truss structure is done only by adding the cells related to the addition of the fourth bar and the parameters which are associated to these cells (Fig. 4).

Then, we apply this topological approach to the modeling of plane and space bar structures by studying the particular case of a two-bar plane truss structure (Fig. 5) (Miladi Chaabane et al. 2012) and finally, we generalized this approach to the modeling of plane and space beam structures by studying the case of a plane

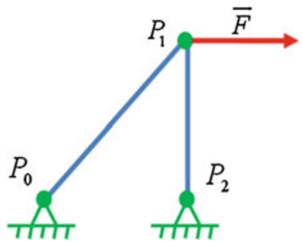


Fig. 5 Application for bar structures: two-bar plane truss structure

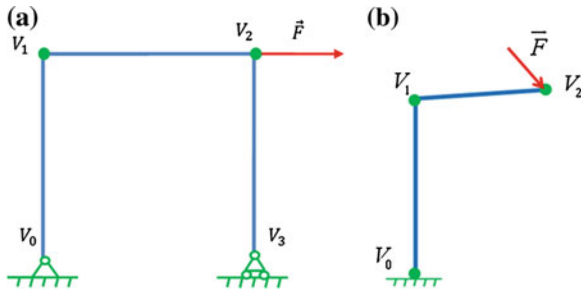


Fig. 6 Application for beam structures **a** plane portal and **b** spatial structure made up of two beams and non-coplanar force acting on it

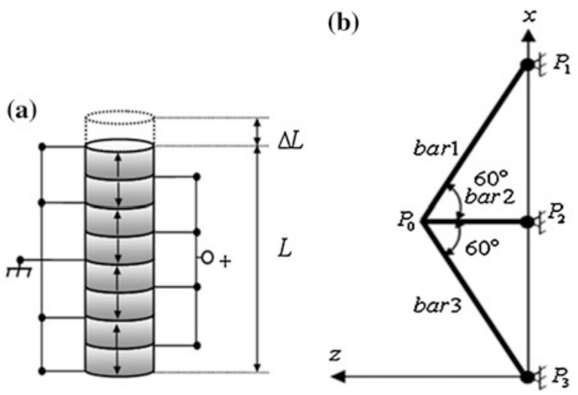


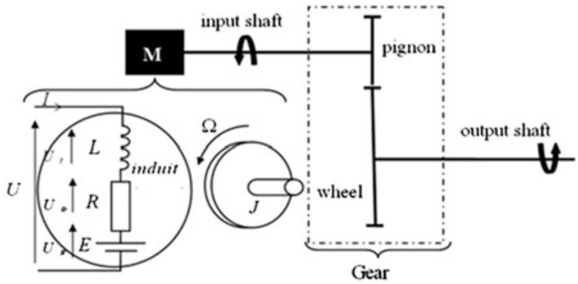
Fig. 7 Application for piezoelectric structures **a** multi layer piezoelectric stack and **b** piezoelectric truss structure

portal (Fig. 6a) and the case of a spatial structure made up of two beams and non-coplanar force acting on it (Fig. 6b).

The advantage of the application of the topological collections and their transformations for the modeling of bar and beam structures compared to the other approaches is that we declare the local behavior law of the bars or the beams independently of their numbers and the way in which they are connected i.e. of their topology. Indeed, we consider a bar or a beam as a local element.

In the second part, the application of the topological collections and their transformations is extended to the modeling of more complex mechanical systems. First of all we applied this approach to the modeling of piezoelectric structures by

Fig. 8 Motor reducer



studying the case of a multi layer piezoelectric stack (Fig. 7a) and the case of a piezoelectric truss structure (Fig. 7b) (Miladi Chaabane et al. 2013a, b). Finally we applied the topological collections and their transformations for the modeling of a motor reducer (Fig. 8).

For the various cases presented by Figs. 7 and 8, the studied systems are described by a set of local interactions between elementary entities. For example, using the topological collections, the motor reducer is modeled by taking into account all its elements (resistor, inductor, EMF, inertia, gear (pinion/wheel), input and output shafts) and then the motor reducer is considered as a set of local elements linked by neighborhood relationships.

Indeed in this example, the topological collections are used to present the topological structure of the motor reducer i.e. the interconnection law between its elements and the transformations are used to specify the local behavior law as well as the equilibrium equations of each component of the motor reducer. The generation of the system equation is done by sweeping all the cells representing the motor reducer.

4 Conclusion

In this chapter, we presented a brief overview of the application of a topological approach for the modeling of complex and mechatronic systems on the basis of topological collections and transformations. This topological approach allows the consideration of topological relations. Indeed the topological structure of a system is independent of its behavior. Also, this topological approach allows the simplification of the modeling of complex systems and then a complex system is described by a set of local interactions between elementary entities. Finally, this approach allows taking into account of the multi-scale aspect and then the model associated with the component can be more or less important from a functional or physical point of view.

On the other hand, in the different studied examples, we are limited to the case of mechanical structures and elementary mechatronic systems. However, it is necessary to extend this topological approach for the modeling of systems which integrate all the fields of mechatronic by integrating data processing and the automatic. Also, it would be interesting to apply the topological transformations of type patchs which allow the automatic refinement. Finally, we can create a MGS library by the determination of the local behaviors laws of the various fields of mechatronic systems.

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