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Collaborative Mechatronic Design and Systems Engineering: an Educational Experiment with KARREN

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Abstract—Designing mechatronic systems implies collaborative work with shared parameters between contributors from different domains. Moreover, each domain needs to capitalize knowledge (e.g. design rules) in order not to reinvent specific calculation or simulation processes. In this paper, it is explained how students have been implied in a collaborative design project dealing with an aeronautic actuator, namely an EMA (Electro-Mechanical Actuator) for aileron actuation. Comparing three candidate kinematic architectures regarding the initial set of requirements, the project articulates modeling and simulation with Modelica language, the selection of relevant COTS components and their integration into a 3D mock-up within a wing and aileron assembly. In order to share relevant system and components parameters between design activities, KARREN tool is evaluated and configured for this project thanks to a preliminary systems engineering study to minimize the number of needed iterations to eventually converge on appropriate architectural solutions and their evaluation and comparison.

I. INTRODUCTION

The fast-pace technological development enabled man-made systems to be smarter, more powerful and integrate more functionality for the end user. This led to multi-disciplinary systems integrating components from different domains such as sensors, electro-mechanical actuators, control and power electronics, in order to satisfy a set of customer requirements. They may be mechatronic systems, Cyber-Physical Systems (CPS) or even Cyber-Physical Systems of Systems (CPSoS) as defined by the CPSoS European project ¹.

For such complex highly integrated or/and distributed systems, systems engineering approach supports design teams to elaborate a consistent set of requirements and synthesize functional and components candidate architectures that must then be evaluated and compared with respect to a set of requirements (such as performance, cost, mass, efficiency, etc.). The evaluation of the different architectures requires various competencies and thus involves different teams and domain-specific models (such as mechanics, electronics, computer sciences, safety, etc.) with specific objectives (optimize the performance, reduce costs, reduce safety risks, etc.). In order to

organize the system design, systems engineers provide a global system view that enables to identify the different engineering domains required and their interactions.

For highly integrated systems, the collaborators from different domains cannot work separately as they are interdependent and deal with some common parameters. The interdependencies come from “shared resource (e.g. weight, cost) limits, geometric fit, spatial separation requirements, I/O interface conventions, timing constraints etc” [1].

This requires an efficient sharing and synchronization of the common parameters between the different teams. Moreover, there is a need to provide each collaborator with a personalized framework by giving him access to the appropriate set of requirements and parameters regarding his area of expertise.

To cope with this problem, two approaches can be considered. The first one is to use a fully integrated unique tool that covers (supports) the whole design process from requirements definition to the final solution. However, no such universal tool exists yet that integrates all involved domains. Moreover, it is not strategically wise for industrialists to depend from a unique tool editor. In addition, this approach is constraining for industrialists that have their preferred and own developed domain specific tools.

The second approach is to rely on different domain specific tools. The challenge for this approach is to enable the different teams to collaborate efficiently and to compare and synchronize the design parameters. The work presented in this paper relies on a KBE (Knowledge-Based Engineering) tool, in order to share requirements and parameters between different domains designers and to perform trade-offs. Systems engineering is used to distinguish domain-specific data (knowledge and parameters) and the inter-domain data that should be shared in order to have an effective data sharing and to ensure the consistency between domains.

Three student teams are involved in an educational project to design an Electromechanical actuator (EMA). Each team is considered as a domain specific team and is in charge of a particular task. Parameter exchanges among the teams, that used to be done via e-mail or direct conversations in the

¹<http://www.cpsos.eu>

previous sessions of this teaching module, are now performed via the collaborative KBE tool used. Prior to students work, teacher play the role of systems engineering team and provide the students with the global system view as well as the requirements that are shared via the collaboration platform.

This paper is organized as follows. First, an overview of the related work is given in section II. In section III, Knowledge-Based Engineering tool KARREN is presented. Section IV explains how to organize the collaborative work with KARREN, having a Systems Engineering approach. The proposed approach is then applied to a case study in section V with an educational experiment. The paper is finally concluded in section VI.

II. RELATED WORKS

Today's systems are of increasing complexity with shorter time-to-market and increasing distance between industrial partners [2]. The traditional sequential design where the system is split into different domains, each domain performing independently from the others is no longer suitable. Indeed, it is time consuming and very costly as it requires many iterations implying a lot of work to be performed several times when domains do not agree on the values of shared parameters. Instead, collaborative design allows to reduce both cost and time provided that there is a good management of shared parameters to perform trade-offs in order to synchronize their values.

The data exchange between domains can be performed with traditional means such as e-mails, but more reliable techniques are compulsory for efficient collaborative design. For this purpose, many attempts to support collaboration between different design teams have been achieved.

Collaborative work can rely on PLM (Product Life-cycle Management) including a PDM (Product Data Management). PLM is a specific information system that gathers the various data and processes related to the product to be designed and its life cycle, allowing the various involved professionals to share this information within collaborative environments [3]. However, PLM does not allow an easy access to parameters and rules that are embedded in models.

In [4], a web-based CSCW (Computer Supported Collaborative Work) tool is used on a remote and multi-site educational design project of a mechatronic system, for the management of the project and data sharing, with mixed results. As a conclusion of the experiment, it is pointed out that the availability of initial information to be shared by all design teams is important. The possibility to have face-to-face meeting is also mentioned as being necessary.

PIDO (Process Integration and Design Optimization) tools, such as Model Center and Isight, also enable the integration of different domains tools, with the automation of an optimization cycle that allows tools to share parameters. For a better management of the optimization process, an agent-based approach for partitioning and coordinating the collaborative design optimization of complex systems is proposed [5]. However, these tools are not relevant for complex design processes

implying many domains and diverse collaborating companies with their specific knowledge and design processes and tools, with some modeling that must not be shared for intellectual property reasons or that are not available at the same time. Moreover, these tools are dedicated to the optimization of a single given architecture for a system to be designed, but not to share parameters in order to facilitate trade-offs to choose the best architecture among several ones.

KBE (Knowledge-Based Engineering) tools [6] are preferred for collaborative design, especially in the early steps of a project, since they deal with knowledge, namely design rules and system parameters rather than modeling files. Beyond collaborative design and the necessity of sharing parameters, they allow capitalization and re-use of knowledge, which is of great value for industrialists.

KARREN (Knowledge Acquisition and Reuse for Robust Engineering) from DPS (Digital Product Simulation) French company, is one of these tools and is used in the present educational work, in relation with a French research project (MIME). This tool will be presented in the next section.

III. INTRODUCTION TO KARREN

KARREN (Knowledge Acquisition and Reuse for Robust Engineering) is a KBE (Knowledge-Based Engineering) and Model-Based software framework that enables collaborative engineering across all product development cycles bridging multiple disciplines and organizations. KARREN lets users mutually share and reuse best-practice knowledge and provides consistent parameters for their processes, tools and models. Employing KARREN enables real-time collaboration for making better and timelier design decisions even in a multi-business, multi-disciplinary and multi-actors environment.

KARREN functionalities rely on its ability to capture physical related product behavior data, information and context for efficient and effective reuse of knowledge. This tool does not focus on the CAD models or simulation results, but rather targets common parameters and rules across multiple behavior simulation and design stages from concept to completion in a centralized database of knowledges.

KARREN is based on a set of concepts as showed in Fig.1. The main concept is ICE (Information Core Entities): a structured and generic entity of engineering knowledge. An ICE is the smallest entity to be manipulated. Users decide the most appropriate ICE granularity level. Two crucial types of data can be saved: parameters (may be geometric, physical, material, directory shared) and rules (may be business, logical, boundary conditions, mathematical relations, tables of discrete values, etc.).

A system can be described through different viewpoints at various abstraction levels (models) all along its complete life-cycle. A relevant interaction between these models will enable system complexity management and optimization. Viewpoints are captured in KARREN as User Configurations (UCs) and are composed of ICEs. Whereas needed interfaces between views within a collaboration are stored and managed as Knowledge Configurations (KCs) (Fig. 1).

To enable the parameters exchange/synchronization between KARREN and existing tools (such Excel, Dymola, Catia, etc.), some connectors are available.

KARREN concepts are initially based on the PhD research work of Julien Badin [7] and former French research project ADN [6], [7]. KARREN is now being enhanced within the French research project MIME.

For this, several collaborative case studies are performed within the project to provide appropriate feedback. In addition, the tool is tested in an educational framework in a design project teaching module at SUPMECA.

IV. PROPOSED APPROACH FOR COLLABORATIVE WORK WITH SE AND KARREN

This section presents the proposed approach to enhance the collaborative work with KARREN. The first step is to capture the system requirements. We assume that the requirements have already been defined by the systems engineering team with an appropriate methodology [8]. The system requirements (captured in the system SysML model or any other requirements modeling tool) are translated into requirements ICES (ReqICE) in KARREN.

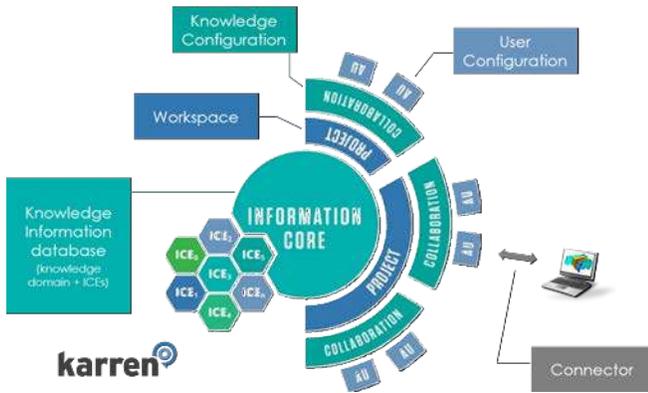


Fig. 1. Conceptual architecture of KARREN. Source DPS

The second step deals with functional and candidate components architectures definition. This part is also performed by the SE team using SysML or any other SE modeling language.

On this basis, ICES can be defined in order to identify shared parameters of the system by different design teams. The choice of the way how ICES are built (partitioned) is up to the SE team and depends on the partition of the domain teams that will perform the different simulations.

The most obvious way is to create an ICE for each component, especially when we are at a high level of detail and the number of shared parameters is not excessively important. If the number of parameters is important or if for the same component different teams enter into play, then, several ICES can be created for the same component, for instance with separated multiphysical domains. In the specific case of a DC motor, a unique ICE may be defined, encompassing electro-mechanical, electrical and 3D parameters. But a more accurate cutting may lead to a more efficient collaborative work, by

providing each team with exactly the needed parameters. In this case, for the DC motor, there may be different ICES for the electrical, electromechanical, 3D aspects respectively. These ICES may be created in the project Workspace or imported from the Knowledge Information Database that is used to store the enterprise knowledge (Fig.1) if they already exist. In the first case, they are also automatically stored in the database of the Knowledge Information Database and may be used in different other projects.

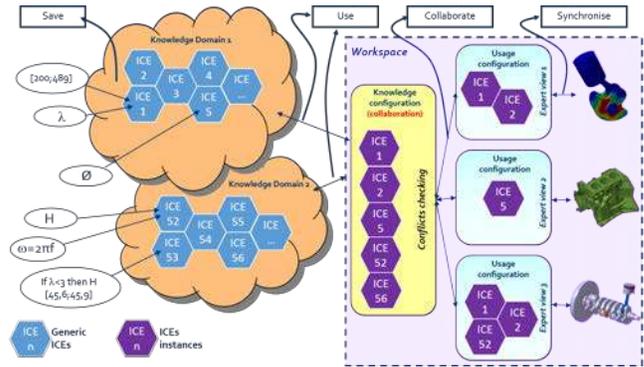


Fig. 2. Configurations in KARREN. Source DPS

Then, the project manager creates Knowledge Configurations allowing the different domain teams to collaborate and the different User Configurations for the different domain teams (Fig2). In each User Configuration, only the ICES needed by the authorized domain team are instantiated.

Each domain team performs the required simulations in their domain specific tools and have to synchronize the shared parameters via KARREN. To facilitate this tasks, some connectors exist to automatically perform the parameters synchronization (for instance there is a connector for Dymola and Catia). Once the teams have final results of their simulations that satisfy the requirements, they publish their ICES so that they become visible to all the other users to perform trade-offs.

V. CASE STUDY

A. Case Study Presentation

The case-study considered in this work is an Electro-Mechanical Actuator (EMA) for a general aviation small aircraft. The EMA is intended to actuate the aileron of the aircraft, replacing the existing rod, cables and lever mechanism (Fig.3), while minimizing changes that may be done to the wing and the aileron structures.

The academic project is then presented as follows: 36 master students of SUPMECA (France), organized into 12 design teams (four teams A, four teams B and four teams C), are provided with a set of system requirements, a description of three candidate architectures to be compared with regards to the requirements and a 3D mock-up of the wing and aileron. They are asked to fulfill three tasks. The first task is to model and simulate a kinematic architectures with Modelica language [9] (using Dymola or OMEdit tools) to dimension the different

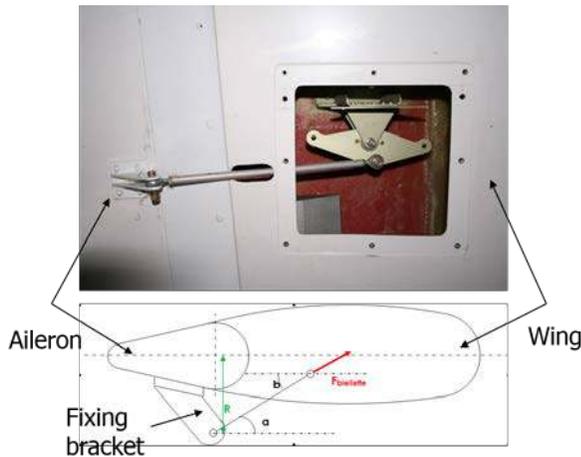


Fig. 3. The existing lever, rod and cables control mechanism

components in order to satisfy the requirements. The second task consists in finding COTS components with the properties determined by the simulation. Finally, the last task consists in building the 3D-mock-up of the components and insert them into the provided mock-up to check whether they fit into the allocated space in the mock-up.

The students here are considered as domain teams and the teachers play the role of the SE team. Prior to the intervention of the different domain teams, the SE team has followed a SE approach (c.f. [8]) to define and analyze the system requirements, identify a functional architecture and propose three candidate component architectures.

The initial requirements for this case study are given in Fig.4

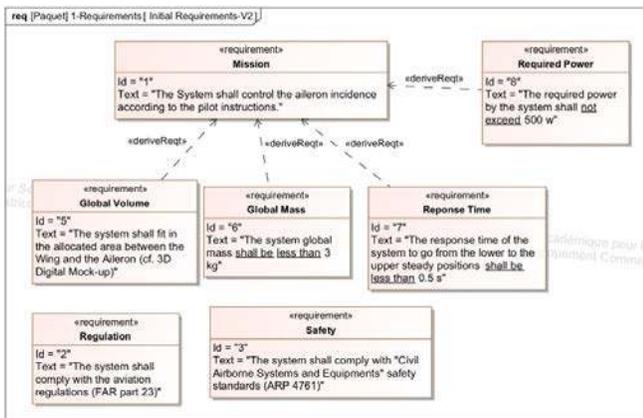


Fig. 4. The Initial Requirements

The three candidate architectures to be compared have respectively a direct drive, a 3 bars and a 4 bars kinematic structures (Fig 5). They are described as follows:

- Direct drive architecture, with a motor and a gearbox that are inserted on the rotating axis of the aileron and directly

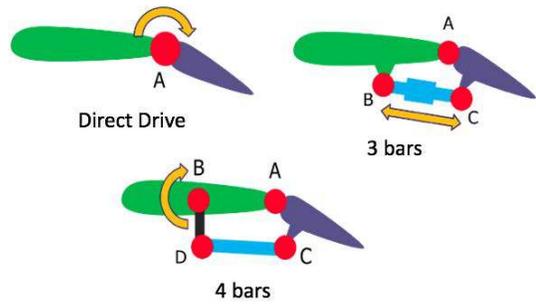


Fig. 5. The three different architectures to be compared

actuate it. The SysML Internal Block Diagram (IBD) for this solution is given in Fig.6.

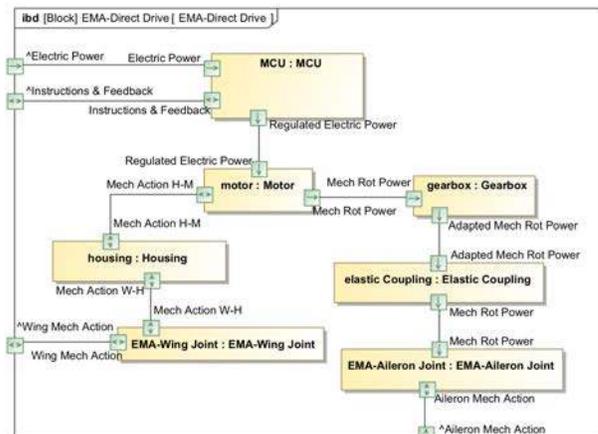


Fig. 6. Component architecture for direct drive solution

- 3 bars architecture, with an electric cylinder fitted between the wing and the aileron, relying on a ball screw and nut assembly. The SysML Internal Block Diagram (IBD) for this solution is given in Fig.7.
- 4 bars architecture, with a rod and crank mechanism actuated with a motorization fitted in the wing. The SysML Internal Block Diagram (IBD) for this solution is given in Fig.8.

To study the different architectures, the students are divided into three teams each having a specific task:

- Team A has in charge to build a Modelica model and to simulate it in order to quantify the required parameters of the different components, while complying with the performance requirements;
- Team B has in charge to find existing off-the-shelf components (COTS components) conforming with the simulation results among available supplier components, or to give the definition of new specific components to be designed for the system (e.g. rod and crank);
- Team C has in charge the 3D integration of the whole mechanism in the wing and aileron assembly, while

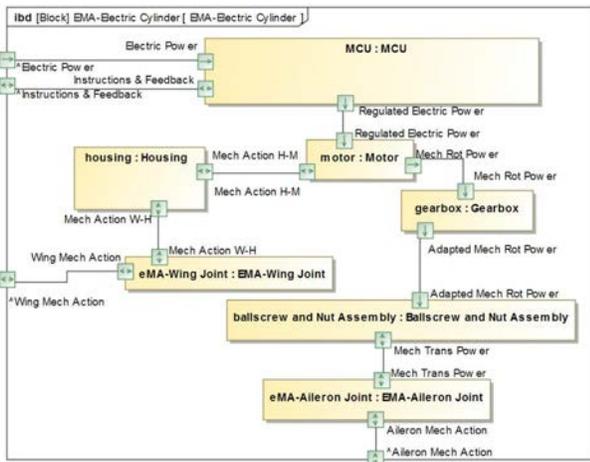


Fig. 7. Component architecture for 3 bars kinematic solution

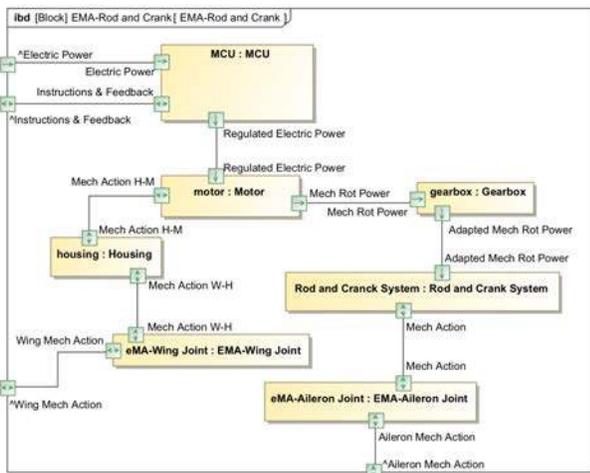


Fig. 8. Component architecture for 4 bars kinematic solution

minimizing structural changes and aerodynamic effects due to added devices;

An iterative collaborative design process (Fig 9) implying all three teams has to be performed in order to simultaneously take into account performance, 3D integration and “COTS mostly” requirements, thus allowing necessary trade-offs to cope with all these constraints for the three candidate architectures.

The use of KARREN helps in sharing parameters and minimizing the number of iterations with more effective trade-offs. These iterations and trade-offs are mainly due to the following situations:

- When team B chooses a set of actual components (COTS and custom ones) in conformance with the given calculated parameters from team A, team A has to check whether the actual components (COTS and custom ones) parameters values still fulfill performances requirements by taking them into account in the simulation models. If not, a new iteration has to be performed, with potential

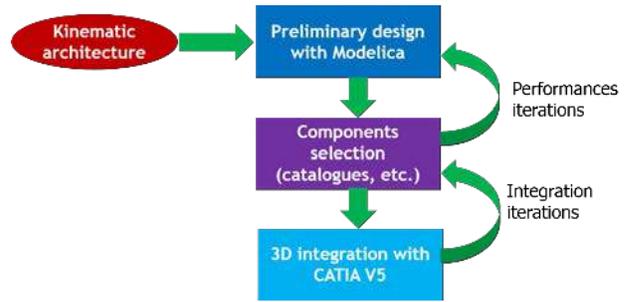


Fig. 9. The iterative design process

trade-offs, for instance related to the type of motor (DC, brushless or stepper motor) or related to the expected performances;

- When team C integrates the actual chosen components provided by team B in the wing and aileron assembly, a fitting problem may occur, due to 3D constraints such as collision, protuberance that may not be appropriate for some aerodynamic reasons, or unacceptable major requested modifications to the wing or the aileron structures. If so, team B is asked to choose new actual COTS or custom components, and as a consequence, to ask to team A whether expected performances are still achieved;
- Obviously, some iterations and trade-offs are also needed. When the initial requirements are modified during the project, even slightly, whatever the reason;

The project manager (the teachers together with DPS team for this project) has to create the different configurations in KARREN as well as the different ICEs if they have not been created yet and give access rights to the appropriate teams. In this project, we have considered to create one ICE per component (as given in the IBDs above excluding the kinematic joints and the housing) for each architecture. Each component ICE is composed of a list of parameters that are shared among the different teams in the collaborative design process and may also include one or more rules on these parameters. For instance for a motor, nominal torque, speed, current and voltage as well as torque constant, resistance and inductance. Based on this set of ICEs, some User configuration have been created for each domain (Dymola modeling and simulation, components selection, 3D integration), this for each students' team. The Project Workspace with the knowledge configuration containing all the ICEs and the different User configurations for each architecture are given in Fig 10.

B. Results and Discussion

In this sections, some results of the students work will be presented.

The modelica model for the 3-bars architecture is given in Fig.11. This model contains a motor, a gearbox, a set of components to model the ball screw nut, the wing, the aileron together with some kinematic joints, sensors etc. Fig.12 shows some simulation results and we can see for instance (see the blue curve) that the EMA reached the upper position

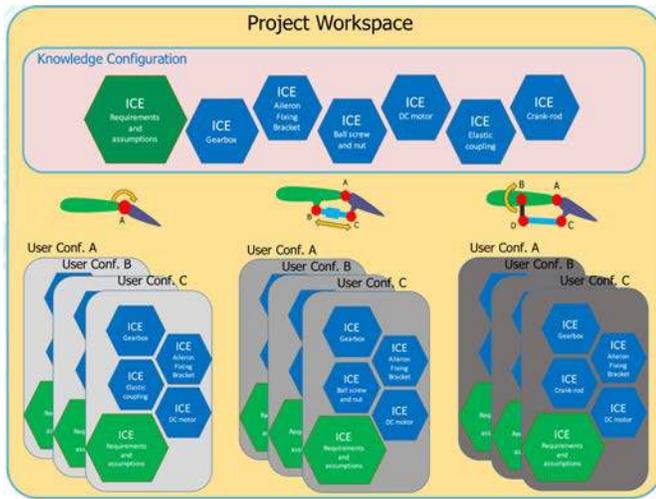


Fig. 10. KARREN Workspace

(+30) from the lower position (-30) within less than 0.5 sec which satisfies the requirement “Response Time” in Fig.4. The green and purple curves represent the current and voltage respectively.

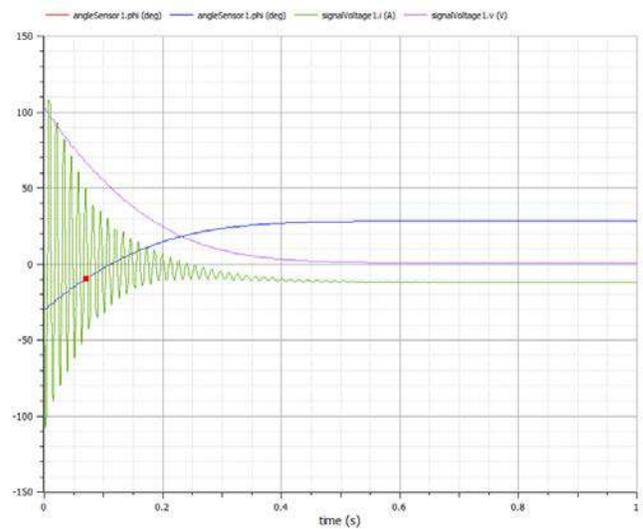


Fig. 12. Dymola results for -30 to + 30 angular displacement

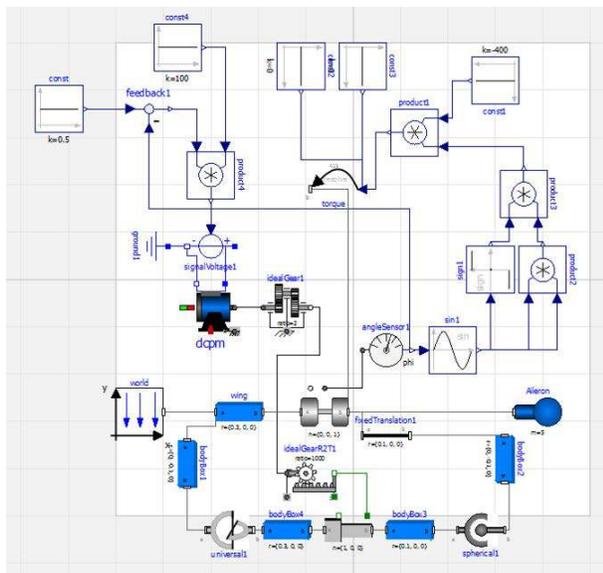


Fig. 11. Dymola modeling of the 3 bars architecture

The ICEs parameters being mapped with the corresponding Modelica model ones thanks to the connector, after each simulation, parameters in KARREN are synchronized with those of Modelica. Once the simulation results are satisfactory (i.e. the chosen components parameters satisfy the system requirements), Team A must publish their ICEs so that they become visible to other teams.

Based on Dymola results, Team B has to choose COTS from existing suppliers. For instance, for the 3 bars architecture, the brushless motor and gearbox in Fig.13 are chosen.

Motor Data		293872
Values at nominal voltage		
1	Nominal voltage	V 48
2	No load speed	rpm 4720
3	No load current	mA 104
4	Nominal speed	rpm 3770
5	Nominal torque (max. continuous torque)	mNm 203
6	Nominal current (max. continuous current)	A 2.19
7	Stall torque	mNm 1050
8	Stall current	A 10.9
9	Max. efficiency	% 82
Characteristics		
10	Terminal resistance phase to phase	Ω 4.4
11	Terminal inductance phase to phase	mH 0.937
12	Torque constant	mNm/A 96.1
13	Speed constant	rpm/V 99.4
14	Speed/torque gradient	rpm/mNm -4.55
15	Mechanical time constant	ms 4.81
16	Rotor inertia	gcm ² 101

Fig. 13. COTS components: motor and gearbox

Once the COTS are validated by Teams A and B, Team C builds a 3D-model of the chosen components and tries to fit it into the provided Catia mock-up like shown in Fig.14 and Fig.15.

During this work, some feedbacks about this collaborative design experiment have been given by the students and professors, such as:

- The set of available parameters in ICEs should have been strictly restricted to shared parameters. Indeed, the preliminary work to define ICEs is based on the SysML system modeling and has to be more precise;
- An Excel COTS components database would have been valuable since a KARREN-Excel connector is also available. If this database contains components costs, it is then

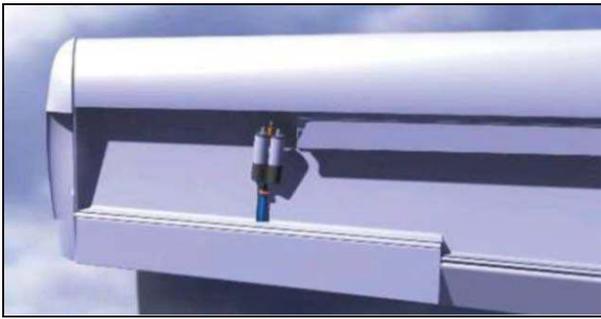


Fig. 14. 3D integration with CATIA, upper surface view



Fig. 15. 3D integration with CATIA, lower surface view

possible to take into account the global cost of the system to compare candidate architectures;

- As stated in [4], face-to-face meetings were needed to help organizing the collaboration and for important project reviews. Obviously, KARREN (and collaborative tools in general) is not intended to replace some important project coordination meetings.

This experiment provided KARREN developers and engineers with users' feedback in order to enhance this collaborative design tool, while also giving means to better implement the collaborative design methodology within MIMe research project.

VI. CONCLUSION

This educational experiment deals with different tools such as Dymola (Modelica) and CATIA, in order to design an Electro-Mechanical Actuator in a collaborative work context. KARREN tool and specific connectors are used to allow sharing parameters between design teams and to perform trade-offs to fulfill performances and integration requirements. Three candidate architectures for this small aircraft aileron actuation system are designed at the same time to be compared. KARREN proves to be helpful to support collaborative work as it shortens design iterations and allows trade-offs on components parameters to converge towards acceptable solutions with respect to the given requirements. This experiment is also valuable since it provides the students with the opportunity to become familiar with collaborative design in a context that tries to imitate industrial design projects in mechatronics.

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