

### AUTOMATED GENERATION, SELECTION AND EVALUATION OF ARCHITECTURES FOR ELECTROMECHANICAL ACTUATORS

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#### Abstract

This paper describes a fully automated methodology for generating, selecting and evaluating architectures for electromechanical actuators with special consideration for safety and mass.

It also presents the software tool developed on this methodology and discusses results obtained from its use for the preliminary design of a nose gear steering system.

#### Notation

EMA	electromechanical actuator
RRR	rotary-rotary-rotary
RLR	rotary-linear-rotary

#### **1** Introduction

The study presented in this paper has been conducted in the frame of the European project DRESS (Distributed and Redundant Electromechanical nose gear Steering System). The aim of this project is to develop and test an electrically powered nose gear steering system allowing automatic on-ground guidance. Giving the aircraft a true all-weather (true zero visibility) capability, it will hence offer significant aircraft operation gains and increase the Air Transport System efficiency. The reported work focuses on the design of the EMA replacing the current servohydraulic one, scaled to single aisle commercial aircrafts (see Figure 1).

Towards the more electric aircraft, this challenging project must provide a technology step change, improving the system safety and reliability to allow automatic guidance by limiting the weight impact. Such a critical embedded electro-mechanical actuation system is very complex to design and to optimise, especially because of its multidisciplinary characteristic. The design of the power transmission, modulation and transformation must cope with multiple and antagonist constraints when considering mass, reliability, safety, shimmy damping, controllability, operability (towing) and so on.



Fig. 1. Replacing hydraulic nose gear steering system

#### 2 Proposed Methodology

Up to now, the traditional approach for the system design phase activity as defined in the V model for the development of mechatronic systems [1] was based on an iterative bottom-up methodology. This traditional methodology starts with the identification of the possible technological solutions. Then, the identified technological solutions are intuitively combined

into candidate architectures. Finally, the generated architectures are optimized and evaluated before being compared.

Starting with a limited number of parameters and design criteria, the design process involves an increasing number of issues to be taken into account for each iteration loop. If finally a selected set of parameters does not lead to a feasible solution regarding the different involved engineering domains, then another design loop for the concerned architecture is necessary. On the one hand, this traditional methodology allows a re-use of proven solutions by combining them in an innovative to obtain new functionalities way and minimizing the development risk. On the other hand, it is cumbersome and does not ensure the identification of neither the most optimal set of parameters for a given architecture nor the best architecture for the given application. To improve the results and fasten the design process, a more systematic and automated methodology is required, especially in the presence of technology step changes and very demanding new functional requirements.

The proposed methodology is based on an automated and systematic process. A hybrid top-down and bottom-up approach has been developed to generate systematically concept solutions. Scaling laws are used for the presizing of each defined concept solutions. They allow an investigation of the impact at global system level of design parameter variations. Thus, it is possible to optimize the different solution concepts at global system level early in development process. An automated the reliability analysis process based on general fault trees allows the verification of the consistency of the defined architecture solutions with the reliability objectives.

Hence the developed methodology can lead to the best solution concept(s) and provides a reduced optimized framework for the specific design phase while decreasing significantly the development time and effort.

#### **3 The Nose Gear Steering System**

The work presented here focuses on the design of the electromechanical power transmission from the power electronics to the mechanical interface with the nose gear turning tube (see Figure 1).

The mission cycle of the nose gear steering system depends on the different aircraft operation phases: towing, taxiing, take-off, flying gear-down, flying gear-up, and landing. It is assumed that a mission cycle is repeated a given number of times per day for the entire aircraft life. This allows the calculation of the required system lifetime for e.g. fatigue sizing.

In towing mode, the steering system must be passive. Indeed, there shall be no resistant torque from the actuator while the aircraft is steered by an operator on ground. During taxiing, take-off and landing the steering system is operative and the steering angle is limited as a function of the aircraft velocity. Figure 2 illustrates the power need for the steering system in the normalized torque-speed plan.



Fig. 2. Mission cycle – Torque vs. speed (norm.)

#### 4 Generating Systematically Solution Concepts

illustrates This section the proposed methodology for generating systematically solution concepts with a special consideration to mass and safety. The process starts from the results of a detailed functional analysis of the studied steering system. Once the actuator major sub-functions and constraints are identified, a functional architecture frame can be proposed. The next step consists in embodying this frame conceptual particular level with a at consideration to safety requirements. The same operation is repeated at technological level. This systematic architecture generating and filtering process allows the generation of a limited number of actuator architectures that comply with the system requirements in general, and the safety requirements in particular.

# **4.1 Actuator Major Sub-functions and Constraints**

A detailed functional analysis of the actuator allows the identification of the actuator subfunctions and constraints driving the design. These sub-functions and constraints are described in Table A below.

Actuator sub-functions	
Modulate electric power	
Transform electric power into mechanical power	
Transform mechanical power	
Allow free castoring during towing	
Divide or combine power flow(s) to ensure redundancy	
Fail operative	
Actuator constraints	
Be highly reliable	
Fit into specified geometrical envelope	
Henry a limited total musicht	
Have a limited total weight	
Allow operating in harsh conditions (e.g. extreme	
Allow operating in harsh conditions (e.g. extreme temperatures)	

Tab. A. Actuator sub-functions and constraints

#### 4.2 Functional Architecture Frame

Based on the identified actuator sub-functions and constraints, it is possible to develop the corresponding functional architecture frame.

For many reasons, as integration or safety, an actuator can consist of multiple power paths. In order to simplify the development of the functional architecture frame and to cope with the weight constraint, it is first assumed that the number of power paths is limited to two. This allows redundancy by limiting the weight impact. In the same way, active-active power path configurations is preferred to stand-by, i.e. in case of two independent power paths both are acting during actuator operation. In order to minimize the number of unique parts and improve maintainability of the system, it is that parallel power paths assumed are symmetrical.

At least, one functional stage must correspond to each actuator sub-function. However, the function *transform mechanical power* can involve more stages. Indeed, mechanical power can be either rotary or linear. Transforming a rotary motion into a linear motion would require only two functional stages. Yet it can be interesting to consider a rotary-linear-rotary (RLR) mechanical power transformation with a rotary-rotary modulation, especially because of the high reduction ratio and compactness that this solution might offer. At technological level, this last transformation could be realized combining a roller-screw, rack and pinion with a reducer. Therefore, three functional stages will correspond to the function *transform mechanical power*.

The resulting functional architecture frame is illustrated in Figure 3.



#### Fig. 3. Actuator functional architecture frame

From a combinatorial calculation, it results 15,360 different possible solutions for the given architecture frame. In order to reduce this number before embodying at conceptual level, it is interesting to study the impact of the safety constraints.

The two major undesired failure events that can be caused by the electromechanical part of the actuator are a jamming (classified as catastrophic) and a loss of torque control (classified as hazardous) at the turning tube. Based on fail-safe principle, no single failure of the actuator shall lead to these events.

Starting with an actuator consisting of a single power path, a corresponding failure inhibiting element has to be mounted downstream the last component that may fail to

ensure that no single failure will lead to the aforementioned undesired events.

In case of a single power path, jamming of the landing gear turning tube and loss of torque control are antagonistic failure events. Indeed, inhibiting a jamming by declutching causes a loss of torque control of the turning tube, and inhibiting a loss of torque control failure by holding position causes a jamming of the turning tube. This indicates that it is necessary to use at least two independent power paths. In this way, a single failure occurring in one path could be inhibited by the corresponding element located downstream the failed component, while the remaining healthy path would take over the actuator functions.

To sum up, safety consideration reduces the actuator functional architecture frame to two independent power paths. The power is combined at the turning tube only. A failure inhibiting element is installed as downstream as possible in each path (at F6 or F7 levels of Figure 3). These statements reduce the number of different possible solutions from 15,360 to 48.

#### **4.4 Conceptual Architecture Frame**

At conceptual level the function *modulate electric power* is realized by a power electronic unit. *Transform electric power into mechanical power* can either be performed by a rotary or linear electric motor. The mass requirement would lead to the selection of a linear motor with a long stroke (some meters at least), which is not compatible with the integration constraints.

At mechanical transmission level, four candidate types of power transformers (rotaryrotary, rotary-linear, linear-rotary, linear-linear) can be associated in three stages, the first stage being driven by a rotary electric motor. This makes eight different possible combinations. The use of a rotary electric motor and the rotary nature of the actuator output (landing gear turning tube) reduces the problem to four possible combinations which can be resumed in two main concepts, the RRR and RLR.

The function *allow free castoring* ensures the towing capability of the aircraft on ground. This can be realized in two different ways: making a completely reversible actuator or disconnecting from the turning tube during towing operations.

Mechanical power flows can be combined in a speed or torque summation scheme. On the one hand, a speed summation offers the capacity to drive the turning tube even in case of jamming of one upstream power path, while a torque summation would jam the turning tube. On the other hand, a torque summation offers the capacity to drive the turning tube even in case of loss of torque control of one upstream power path, while a speed summation would lead to the loss of torque control of the turning tube. Thus, inhibiting a single failure requires braking and declutching elements in a speed summation and torque summation configuration, respectively. At technological level, the speed summation can be realized with a planetary gear train directly mounted on the turning tube. Because of the number of rotating elements in such a component, it is not acceptable with respect to jam resistance. Additionally, this component would have a mass out of the acceptable range. Therefore, only torque summation is considered with the corresponding declutching elements. Additionally, the declutching element can be used to ensure the function allow free castoring if it can be declutched and re-armed during operation.

Before discarding linear motors and speed summation with respect to technological constraints, there were 160 different possible solution concepts. These decisions and their impacts on the other actuator functions reduce this number to 40.

#### **4.5 Technological Architectures**

Usually, rotary electric motors used in EMAs are DC, synchronous (brushless) or induction motors. Among these different technologies, electric motors can be conceived either to favour torque or speed.

The induction motor consists of a simple assembly, is robust and cheap. However it has a low power density compared to the DC and synchronous motors. For this reason, its use is generally limited to industrial applications. The DC motor is easy to command and minimizes the cost of the associated controller. It also ensures a smooth torque. However, this advantage is balanced by the presence of brushes which require to be protected from a harsh environment as it is the case here. Moreover, due to their fast wear out, these brushes imply frequent replacements.

The synchronous motor has a high efficiency and power factor. It requires a quite more complicated and expensive controller than a DC motor. It does not offer the same torque smoothness. The absence of brushes allows a significant reduction of maintenance needs and an inhibition of critical behaviour in a harsh environment. Its mass and reliability advantages make of this motor the current standard for aeronautical applications. In the present project, two main kinds of synchronous motors have been selected: the *speed* and the *torque* motors. Speed motors refer to constant pole number motors with a cylindrical shape. Torque motors refer to variable pole number motors with an annular shape.

Rotary-rotary mechanical power transmission can be realized by cycloidal reducers, harmonic drives, gear boxes (e.g. planetary trains), worm gears, spur gears etc. For integration purposes, worm gears and spur gears offer interesting means to interface with the turning tube. Cycloidal and harmonic reducers have a higher power density than planetary trains but are dedicated to rather high transmission ratio ranges while planetary trains can reach much lower transmission ratios. Therefore, it is interesting to consider planetary trains for small transmission ratio and cycloidal and harmonic reducers for high transmission ratio.

The roller-screw technology has been identified as the most suitable solution to realize RLR mechanical power transformations interfacing with the turning tube, especially for integration purposes and because of its high load capacity and transmission ratio.

Disconnecting the complete actuator from the turning tube during towing operation or one power path in case of failure can be realized by an electromechanical clutch. This clutch can be mounted only upstream the component interfacing with the turning tube. Therefore this interfacing component is located in a single path from a safety point of view, and shall be jam resistant. The failure behaviours of roller-screws and worm gears are well-known and not subject to jamming in *useful life* conditions. In the same way, spur gears are simple components that can be adequately oversized to guarantee a jam free behaviour.

An ultimate solution against jamming could be to develop an in-house declutching system that would be installed in parallel to the interface between the actuator and the turning tube. Basically, it would isolate the failed power path by pushing out its interfacing element (e.g. rack, pinion, worm screw) from the turning tube gear. On the one hand, such a device would raise re-arming issues to ensure its necessary testability and would have a significant impact on the system's mass, maintainability and reliability. On the other hand, it is not proven that it will be sufficient for ensuring the jam resistance of the actuator. Therefore, it will not be considered further here.

Figure 4 illustrates the resulting solution concepts at technological level in the form of a morphological diagram.



## Fig. 4. Power transmission technological candidate architectures

It must be noticed that filtering the architecture frame with respect to technological constraints has allowed a reduction of the number of different possible solutions from 72 to 24. Such a limited number of candidate architectures is acceptable for preliminary sizing an comparison studies.

#### **5 Reliability Analysis**

The evaluation of the candidate architectures regarding reliability is based on a probabilistic approach. General fault trees covering all the candidate architectures are developed for the three considered failure modes that can be caused by the electromechanical part of the actuator: jamming of the nose landing gear, loss of torque control and reversionary mode. The reversionary mode refers to fail operative condition, when one power path fails and is disconnected while the remaining healthy power path carries alone the actuator functions for a each limited duration. For candidate architecture, the failure rates of the different components and their effects are propagated through the trees to obtain the occurrence rates of the failure modes. This process can either check the validity of a candidate architecture or provide target failure rates of given components.

In order to support the design, this study will focus on the failure rates assessment for two main groups of components. The first group consists of those located in the single power path, i.e. downstream the clutches. Indeed, because of their safety criticality, their design will strongly depend on their required reliability level. The second group of interest consists of the system parts located upstream the power electronics. They will be called *system upper parts* for practical reasons. A consistent design at global system level is performed assessing their global failure rates from the power transmission performance.

#### **5.1 Reliability Calculations**

In order to reduce the problem complexity, the different architecture components are assumed to operate in their *useful life*, i.e. their failure rates are invariant with time [2]. Their failure probabilities can therefore be described with the simple exponential distribution function:

$$F(t) = 1 - e^{-\lambda t} \tag{1}$$

with *F* the probability of failure as function of the time *t* (hour) and the failure rate  $\lambda$  (hour<sup>1</sup>).

Reliability calculation requires failure rate data for all the components involved in the

candidate architectures. Most of the values used in this study are adapted from published summaries [3].

Reliability calculation also requires to take the system parts operating time into account. Indeed, if a system is not working continuously during a mission it is less exposed to failure and thus can reach a higher reliability. It has been assumed that the critical components and the clutches are always exposed to failure except during in-flight phases. The system upper parts have been assumed to be exposed during taxiing, take-off, landing and gear-down phases. Thus, for a typical mission, the operating times of the critical components and system upper parts correspond to 35% and 30% of a flight hour, respectively.

#### **5.3 Probability of Jamming**

The jamming of the turning tube is classified as catastrophic implying a failure rate of 10<sup>-9</sup> per flight hour from the aviation authorities [4]. This failure is inhibited in case of jamming of a component upstream the electromechanical clutches. This implies a proper operating clutch. The jamming of any components downstream the electromechanical clutches (included clutch output shafts) would cause the jamming of the tube. Therefore, these turning critical components shall be designed with special consideration to jam resistance.

The other major variable of the problem is the global reliability of the system upper parts. The jamming of a component must be combined with a clutch blocked in engaged position to cause the jamming of the landing gear leg turning tube. Due to the very low probability of this event, power electronics reliability is not restricted by the jamming reliability target. Thus, from the jamming reliability target of  $10^{-9}$ per flight hour it is possible to asses a target jamming failure rate of 2  $10^{-9}$  per operating hour and per path for the critical components.

#### **5.4 Probability of Loss of Torque Control**

The lost of torque control is classified as hazardous implying a failure rate of  $10^{-7}$  per flight hour from the aviation authorities [4]. However, in order to allow automatic guidance

on ground, a failure rate of  $10^{-9}$  per flight hour shall be achieved. The control of the torque is lost if the two power paths simultaneously either declutch to prevent failure propagation or loose torque control at any point of their architecture.

In order to assess the reliabilities of the critical components and system upper parts, it is interesting to draw their interdependency for a global system failure rate for loss of torque control of  $10^{-9}$  per flight hour. Figure 5 illustrates this interdependency.



Fig. 5. Interdependency between system upper parts and critical components failure rates.

As shown, in case of ideal failure behaviour (no failure) of the system parts upstream the power electronics, the maximum acceptable loss of torque control failure rate for the critical components is about  $10^{-4}$  per flight hour and per path. On the other hand in case of ideal failure behaviour (no failure) of the critical components, the parts upstream the power electronics have a maximum acceptable general failure rate of 1.2  $10^{-4}$  per operating hour and per path. Between these two points, the interdependency of the acceptable failure rates is linear. Reliability levels of  $10^{-4}$  per operating hour are not design constraining.

#### **5.5 Probability of Reversionary Mode**

The reversionary mode characterizes the case of an active failing actuator, i.e. a power path has been disconnected to isolate a failure occurring in one of its elements and the remaining healthy path is taking over the actuator functions. Being in reversionary mode reduces dramatically the reliability of the actuator with respect to the loss of torque control. Indeed, in this case a general failure of the system parts upstream the power electronics or a loss of torque control failure of the critical components leads automatically to declutch the last power path, i.e. to a total loss of torque control.

Calculation shows that the target probability of reversionary mode can significantly constrain the reliabilities of the critical components and system upper parts. Additionally, it shows that it is not possible to reach a reliability better than  $10^{-5}$  per flight hour for this event. Based on this reliability target, the maximum acceptable loss of torque control of the critical components and the maximum general failure rates become  $5.10^{-7}$  and  $6.10^{-7}$ per flight hour and per path, respectively. As for the probability of loss of torque control, this interdependency varies linearly between these two points (see Figure 5).

Based on this information, it is possible to assess failure rates for the critical components and the system upper parts taking into account their interdependency.

#### 5.6 Conclusions of the Reliability Analysis

The reliability analysis allows an assessment of the jamming failure rate of 2  $10^{-9}$  per operating hour for the critical components independently of the actuator architecture. It also supports the assessment of the general and loss of torque failure rates for the critical components and system upper parts, respectively. It results that these failure rates shall be of an order of magnitude of  $10^{-7}$  per operating hour. Based on this information, it is possible to take corresponding measures to ensure the global reliability of the actuator.

The high reliability of a component can be ensured by an adequate sizing [5], internal redundancy, scheduled maintenance or monitoring [6].

#### **6** Power Sizing

In [7] the authors develop a fully automated power sizing methodology based on scaling laws. For the presented work, this methodology has been implemented into an in-house software tool for the preliminary integrated design of EMAs. Basically, assuming ideal operating conditions (nominal environmental conditions, etc.), the different components of a given architecture are sized using an inverse method that consists of propagating the power demand from the load up to the electric power supply.

This activity requires physical relationships between the main characteristics of the architecture components. In the proposed methodology, these relationships are established using scaling laws. A main advantage of the scaling laws as those described in [7] is their simplicity, which minimizes the number of parameters required to estimate the component characteristics. Another advantage is that they are representative of a given technology and very adaptive to its evolution. Finally, they are well suited to support a fully automated sizing process.

#### 7 Developed Software Tool for the Preliminary Design of EMAs

The solution concepts generation, reliability analysis and power sizing methodologies described previously have all been implemented into a single software tool. This tool has been developed in a Matlab<sup>®</sup> environment and is based on the following main modules: *Architecture Generating, Reliability Analysis, Power Sizing, Design Exploration, Analysis.* The modular scheme of the developed software tool is illustrated on Figure 6.





The architecture generating module uses generating and filtering algorithms based on the

principles of systematic combination and technological and design compatibility matrices [8]. It delivers a series of architectures consisting each of a set of components in a given order. The components are represented by blocks containing the necessary information for the reliability analysis and power sizing activities (e.g. reference design parameters, failure rates).

The reliability analysis module computes the failure rates for the different architectures and undesired events by propagating the reliability data stored in the component blocks through the general fault trees. Depending on the results, this allows the designer to quickly discard unsatisfactory architectures or assess new reliability targets.

The *power sizing* module propagates the required performance and lifetime in a reverse way, from the interface with the load to the power electronics unit, and sizes each component one by one. It returns the main characteristics of each component depending of its technology (e.g. geometry, mass, electrical characteristics, thermal characteristics).

The *design exploration* module includes an algorithm that allows serial power sizing loops, varying given design parameters of the candidate architectures. For the moment, this algorithm consists in varying linearly the transmission ratio. However, it could be extended to more sophisticated optimization approaches (e.g. genetic algorithm), and thus exploring more design parameters.

The *analysis* module stores and computes the data coming from the reliability analysis and power sizing modules. Storing the data for all the defined and sized architectures allows the designers to perform detailed analysis. The module can compute the actuator total mass, geometrical envelope, power and energy consumption, etc., depending on the main constraints of the application. The obtained results can then be plotted to support the designers in the tradeoffs.

#### 8 Results

It is interesting to use the automated sizing to investigate the impact of the transmission ratio

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on the global actuator characteristics. Thus, it is possible to identify an optimum for each architecture which can then be compared.

The nose gear steering system is operating during limited times compared to the other airborne systems. Thus its energy consumption does not have a significant impact on the overall aircraft performance. On the other hand, its weight can be significant and thus impact the overall aircraft performance. Therefore, the comparison study focuses on the mass of each candidate architecture.

The automated power sizing of all the different solutions shows that the global mass of the actuator tends to decrease when the transmission ratio increases. E.g. the minimum actuator mass obtained with an architecture based on a speed motor, cycloidal reducer, electromechanical clutch and worm-gear is about 1.7 times lighter than for the same architecture without reducer. A more accurate look to the results shows that this difference is mainly due to the motor mass. Thus mass consideration favorizes architectures with a high transmission ratio capacity and discards direct drive solutions. In the same way, the single stage planetary train that is dedicated to low transmission ratios is discarded in benefit to the cvcloidal and harmonic reducers.

Power sizing also shows that due to their low efficiency at very low temperatures, the harmonic drives impact significantly the sizing of the architecture and thus are less advantageous than cycloidal reducers with respect to mass.

Manufacturing constraints limit the diameter of the spur-gear interface with the turning tube. Thus the architectures based on this solution are limited in their transmission ratio range at the interface between the landing gear leg and the actuator. This impacts the sizing of all the components located between the interface and the reducer including the reducer itself (e.g. electromechanical clutch and cycloidal reducer). For example, an architecture based on a spur-gear, clutch, cycloidal reducer and torque motor is about ten times heavier than the same architecture with a worm-gear and a speed motor. It has to be noticed that the worm gear allows a transmission ratio about three

times higher than the spur-gear. Thus mass consideration also discards spur-gear solutions.

The two outstanding solutions are illustrated schematically (top and 3D views) in Figure 7. During the sizing process, the variation of the global transmission ratio has been obtained by increasing the reducer reduction ratio and decreasing the lead of the roller screw for the RRR and RLR solutions, respectively.



Fig. 7. Outstanding architectures – RRR (left) & RLR (right). CAD views thanks to Messier-Dowty.

As shown on Figure 8, both solutions reach nearly the same minimum total mass. A more detailed analysis of the automatically sized architectures indicates that the transmission ratio range is limited by the maximum allowed speed at the input shaft of the cycloidal reducer for the RRR solution, and by the maximum allowed speed of the motor for the RLR solution.

The roller screw can reach higher transmission ratio than the worm gear. Therefore the components upstream the roller screw, as the reducer, are smaller than those upstream the worm gear and thus can reach higher speed. However, high transmission ratio at the roller screw decreases its efficiency and thus increases the required torque at its entry for a given ratio. It also implies higher speed at its input shaft, which impacts its fatigue sizing. These effects tend to limit the interest in high transmission ratio for this component.

It has to be noticed that the dynamic aspect of the considered use case is rather low. For other applications, where this dynamic aspect

Servo drive n s Speed motor 🔲 Cycloidal reducer 0.8 Clutch Worm screw 0.7 (; 0.6 (uou) 0.5 Sep 0.4 0.3 0.2 ٦Ľ C 1000 1200 1400 1600 1800 2000 2200 2400 2600 600 800 Overall Transmission Ratio (1) Servo drive 0.9 Speed motor Cycloidal reducer 0.8 Clutch Roller-screw 0.7 Rack () 0.6 () 0.5 0.5 Sept. 0.4 0.3 0.2 0.1 ſ 1500 3000 3500 2000 2500 Overall Transmission Ratio (1)

would be significant, the analysis of the design may lead to different conclusions.

Fig. 8. Mass vs transmission ratio – RRR (top) & RLR (bottom) solutions

#### **9** Conclusion

The presented innovative approach has opened the discussion and the applied design methodology that were firstly only driven by bottom-up reasoning and experience feedback. The very demanding requirements including severe operational aspects (e.g. free mode for towing, free mode in ultimate response to failure) did not allow an efficient application of a conventional methodology. Instead, a mixed top-down (from needs) and bottom-up (from technological constraints) approach has been used that generates, optimizes and evaluates all the acceptable architectures in a single and automated process. Starting from a countless number of possible solutions, two best

architectures were identified with respect to mass and safety aspects. Moreover, the preliminary optimization of these architectures provided a limited framework for the specific design of these solutions reducing significantly the remaining development time and effort.

In order to take advantage of this methodology for even more complex multidomain system designs, it would be interesting to extend the developed software tool to the exploration and optimization of numerous design parameters (e.g. based on genetic algorithm) while enriching its component library.

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