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Sizing a Drone Battery by coupling MBSE and MDAO

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Abstract

Drones have increasingly been used to assist Humans for rescue and surveillance missions. To do so, their design turns out to be a challenging issue, in particular when their autonomy is expected by sizing of batteries. Thus, solutions are to be sought to engineer a drone rigorously while specifying its main features. This paper introduces a work in progress aiming to bridge the gap between two engineering disciplines that have so far been developed separately: Model Based Systems Engineering (MBSE) and Multidisciplinary Design Analysis and Optimization (MDAO). Coupling of MBSE and MDAO is addressed in terms of language, tools, and methods.

1 Introduction

Over the past decades, drones have increasingly been used to assist Humans in hostile environments. Examples include high voltage electric line inspection in mountains, where hostility of the nature and the climate make missions life-critical. Of prime importance for these drones is to accomplish their inspection missions without power outage. Clearly, autonomy is a key issue for inspection drones.

Autonomy is a challenging issue for drones in general, and sizing of batteries raise complex design problems. Solutions may be sought in well-established engineering disciplines and associations of these disciplines.

This paper addresses the problem of drone batteries sizing by associating two families of engineering disciplines: Model Based Systems Engineering, or MBSE for short, and Multidisciplinary Design Analysis and Optimization, or MDAO for short. The benefits of using MBSE approaches for drone design have been acknowledged [ASV20]. By contrast, little work has been published [CS21] on joint use of MBSE and MDAO for revisiting the way drones are designed.

An early work [Aïe+21] by the authors of this paper has indicated that joint use of MBSE and MDAO opens promising avenues for sizing drone batteries and

for drones design in general. Even if this work is still in progress, this paper goes beyond the concept proof presented in [Aïe+21], and formalizes the coupling of MBSE and MDAO in terms of language, tools and method.

The paper is organized as follows. Section 2 introduces MBSE and MDAO, and discusses the rationale behind the coupling of MBSE and MDAO. Section 3 surveys related work. Section 4 details the main contributions of the paper. Section 5 discusses a case study. Section 6 concludes the paper and outlines future work.

2 Rationale

2.1 MBSE

One of the current challenge is to develop innovative systems faster than ever, meeting ever higher expectations in terms of performance and safety. To take up this challenge, new methodologies are studied. One of the widely studied and promising approach to manage the complexity of systems is Model-Based Systems Engineering (MBSE) [Zha+21].

MBSE aims to facilitate the understanding of a system made up of parts interacting together. MBSE replaces document-centric approaches by model-centric ones. It improves communications between people involved in systems development. It also improves the understanding of the system under design, and reinforces testing and verification of the system throughout its life cycle [ZMT18].

The main asset of MBSE is its power of abstraction and its graphical representation. MBSE models may be classified into physical, geometric and mathematical models depending on their degree of abstraction [CS21]. These three different levels of abstraction ease the management of systems complexity, and make them understandable [CS21]. MBSE is increasingly used for the development of complex systems, for instance in [PF13] MBSE approach is used to design submarine subsystems. The authors of [PF13] propose to start modelling from the mission of the submarine to its components specifications. The interest of using

MBSE to design a submarine is that it contains more than 40 subsystems and a large number of functions. The subsystems of a submarine are highly integrated and cover a wide range of functionalities such as the navigation ones and the combat ones [PF13]. Another example in [Rim+] is to use MBSE approach to design a rover autonomous guidance, navigation, and control (GNC) and its collaborative drone. The authors of [Rim+] justify the choice of using MBSE because it allows to understand the general behavior of a complex system. According to [PF13], MBSE is commonly used in various industries such as aerospace and defence.

However some limitations are highlighted in the literature. In [CS21] the authors point out that MBSE still suffers from a lack of acceptance in terms of scientific and technical fields. Further, [Zha+21] highlights that it remains difficult to examine the design of the system under development from the conceptual design phase using domain-specific simulation. In addition models abstract the reality and address a simplified representation of the system. It becomes therefore almost impossible to include all the characteristics of the system into one model and a set of models may be needed. Moreover, existing MBSE methodologies are criticized for being too focused on high-level modeling which leads to a lack of precision in the design of the system [Zha+21]. On top of that, to achieve their objectives, each domain involved into the system development prefers to use its own methodology which does not allow to ensure consistency between models [Zha+21].

To ensure the consistency between domain-specific models, the authors of [Zha+21] propose to build an integrative system model which is linked to other domain-specific models. In this way, it is possible to describe the system with the accurate level expected. With regard to the methodology proposed in this paper, MBSE approach is also used to act as a guideline for the development of the system to which the MDAO will be integrated. The MBSE language used in this paper as well as in [Zha+21] is the Systems Modeling Language (SysML). SysML is a standard of the Object Management Group (OMG). It is also a multi-purpose language that allows to analyze, design, verify and validate a wide range of systems. Another benefits of using SysML is that it is not tool dependent and can therefore be supported by a wide range of MBSE tools.

[Par+21] reports that MBSE tools are currently used to describe the system baseline. [Par+21] mentioned also that only few papers use MBSE tools to look for design alternatives and to explore decision tradespace which forced engineers to evaluate the different alternatives at each life cycle stage. On the one hand, in which systems performance models is concerned, [Par+21] emphasizes the fact that MBSE tools would offer a way to include varying fidelity models and multiresolution models. On the other hand, in which definition and description of systems alternatives are concerned, [Par+21] points out that continuous design parameters are required to identify tradespace and perform Set-Based Design. Set-Based Design is a methodology

allowing to take into account numerous design options and that eliminates poorer design choices throughout the development of the system [Sha+21]. The idea developed in this paper is to integrate MDAO approach into the MBSE one to precisely size a drone battery. The MDAO offers the possibility to create low and high fidelity models and to run different kind of analysis. The MDAO approach can also perform design space exploration, as well as trade-off analysis taking into account several design parameters distributed into different disciplines. For this reason, coupling MBSE and MDAO seems to be a good solution to reduce the limitations of MBSE tools above-mentioned.

2.2 MDAO

Unlike MBSE, MDAO is not intended to describe the system but rather to analyze a model in order to demonstrate the properties of the system using dynamical models based on mathematical theories [CS21]. MDAO is commonly used for designing engineering systems, such as airplanes and drones for instance, because their design requires to involve several disciplines [Joa12]. MDAO applies numerical optimization using algorithms that minimize or maximize an objective function. The problem allowing to find the minimum or maximum of the objective function can be constrained or not [Joa12]. For instance, a structural design optimization may consist in varying several parameters such as thickness in order to optimize the weight of the piece while taking the stress constraints into account.

A MDAO model describes in details an aspect of the system in a formal language. In [CS21], several strengths of MDAO are identified. Firstly, MDAO uses high computing performance for simulating and analyzing the models. But MDAO is also able to integrate high fidelity simulation tools, to deal with a large number of design variables and constraints, to have a wide range of efficient optimizers, and finally, to take into account model uncertainties [CS21]. Since its emergence, MDAO has demonstrated its effectiveness. For instance, MDAO can be used to design aircraft with minimum environment impact [Joa12], to design a CubeSat, and to achieve structural topology optimization [Gra+19].

OpenMDAO This paper presents and uses MDAO models built with OpenMDAO. OpenMDAO is an open-source framework that aims to solve design problems involving coupled numerical models [Gra+19]. OpenMDAO simulates complex systems such as satellites, drones, and aircrafts taking into account the interactions between all disciplines involved in the problem. Further, design variables of the problem are optimized simultaneously by paying attention to the interdisciplinary coupling. Several trade-offs are performed while running the analysis.

XDSM One difficulty in using MDAO to solve a problem is to choose the suitable architecture, that is to say, the strategy for organizing the analysis in order

to achieve an optimal design. [LM12] identified a lack of standard representation with respect to multidisciplinary design and optimization architectures. The solution proposed in [LM12] is to create a diagram offering a visual representation of the MDO architecture based on a common set of mathematical notations. This diagram is called an extended design structure matrix (XDSM) and its strength is to enhance the links between the elements of the diagram and the underlying mathematics.

WhatsOpt In this paper, we use the application WhatsOpt [LDL19] developed by French laboratory ONERA to create the XDSM of the MDAO models built. Its environment facilitates collaborative work providing a shared vision of the model under construction. In addition, WhatsOpt interfaces tools to conduct studies and generates skeleton code to facilitate analysis implementation [LDL19].

2.3 Why coupling MBSE with MDAO?

According to [CS21] MDAO model is restricted to a single aspect of the system. That is to say, all the components contained in the system are not identified by MDAO as well as their interconnection in terms of functions and data flow. Therefore, it is interesting to associate MDAO with MBSE given that designing system’s models is a strength of MBSE. Moreover, it takes time to engineers to write and validate MDAO models because of the formal languages that support MDAO, whereas all these information are available into MBSE description. Conversely, the MBSE sometimes lacks precision in terms of analytical values. This is the reason why, this paper proposes coupling MBSE and MDAO in order to compensate the lack of one with the assets of the other. The following section of this paper focuses on the desire to improve requirements. To do so, we propose to start writing requirements with data provided by the stakeholders and the limitations of current technologies for sizing batteries. Then, to use this first set of data as input parameters of MDAO models. At the end of the MDAO analysis we expect to be able to improve several requirements thanks to MDAO results. Using more precise requirements from the conceptual phase will allow one to design the system in a safer and faster way since the design space to explore will already be reduced.

2.4 MBSE-MDAO coupling proposal

Figure 1 illustrates the main points covered by the MBSE-MDAO coupling method proposed in this paper. The coupling is split up into three distinct branches: Approach, Type and Tool. The *Approach* branch provides the two approaches concerned by the coupling and conveys the idea that MDAO results are used to populate MBSE description. The relation “Triggers” shows that it is the MBSE that initiate the request of using MDAO. Thanks to the coupling with MDAO, data contained in the MBSE description, and

more precisely into the SysML diagrams modelling the system under development, are more accurate. The green arrow illustrates that point through the connection named “Refines” which associates MDAO to MBSE. The second branch entitled Type expresses that the coupling occurs at two different level: firstly there is a methodological coupling and secondly, there is a language coupling. A future goal of the coupling is to automate the communication and the data transmission between the two approaches. Finally, the third branch presents the main tools used to realize the coupling describe in this paper.

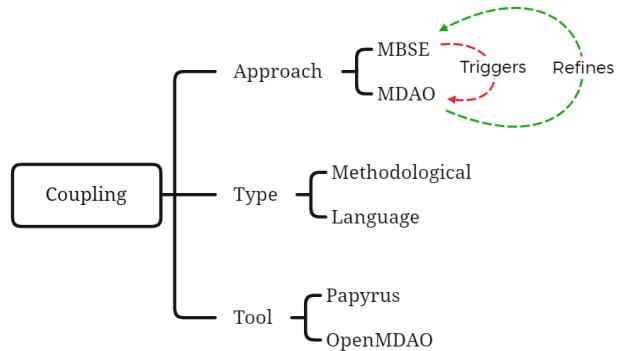


Figure 1: MBSE - MDAO coupling mind map

3 Related work

As mentioned in section 1, it is sometimes required to complete the MBSE approach by another one such as MDAO [CN21]. Or, by another tool, such as Matlab/Simulink (for instance, [Zha+21] which enables simulation of models developed through an MBSE approach [ZMT18]). According to [Nik+16], simulation is one of the preferred method to explore the performance of SysML. In the literature [Nik+15], several approaches aim to use simulation results to verify SysML models, that is to say, to ensure that requirements specified are satisfied by the system. Simulations are used to make trade-off analysis and take design decision.

In order to optimize the development of drones, it is indeed required to make decisions from the conceptual design phases. Modeling and simulations can help designers in making trade-off to select the most appropriate design solutions before building the drones [ZMT18]. According to [ZMT18] modeling and simulation are two different things: modeling helps understanding phenomena whereas simulation allows one to experience a model in different environments. One of the advantages of simulation is to better understand the behavior of a system simulating its associated model in different situations. In this paper, the SysML language is selected as the main modeling language. Simulating SysML models is a major step to validate models in terms of performance. Numerous researches are currently ongoing on the subject of generating simulation code from SysML models. For instance, [Nik+15] presents several approaches for automating

SysML models simulation process. The general process consists in exporting SysML models in XMI format and to transform them into another model readable by the simulation platform. Additional information such as constraints are transmitted to the simulation platform through profiles introduced in the SysML model. Thanks to the variety of diagrams offered by SysML, for instance use case diagrams and block definition diagrams, structure and behavior of the system can be defined. However, the behavior of the system is still described directly into the simulation platform using their libraries. The solution proposed by [Nik+15] to carry out the transformation from SysML models to simulation models is to define a meta-model describing simulation entities. Model transformation languages such as ATL and QVT are presented as good candidates to perform SysML to simulation models transformation.

In [Ker+13] the authors agree with the idea to develop models in SysML and to simulate these models with domain-specific tools. The approach developed in [Ker+13] consists in creating an integrated SysML model containing relevant data. From this integrated model, it is proposed to generate domain specific models. In this way, all domain-specific models are not developed from scratch and they depend on the same model (the integrated one). Such a method contributes to achieve consistency between all models. The low cost required to implement such a method, and the ease to set up simulation and test that allow one to obtain quick results, are its major advantages [Ker+13]. In terms of coupling, the SysML physical architecture of the system is directly simulated in tools such as Modelica where a code is generated from the logical architecture and tested on a real Programmable Logic Controller (PLC) [Ker+13].

The approach proposed in this paper is different from the ones presented above. Even if any model transformation is performed in the method proposed in this paper, two different approaches working on different tools are coupled. To be efficient, the coupling between MBSE and MDAO requires to set up communication between both of them. Using XML to exchange the data contained into SysML diagrams as it is done in [Nik+16] can be a solution for the MBSE-MDAO information sharing.

The objective of our work is, in the first instance, to refine the requirements in order to give as much details as possible about the expected features of the system. Writing good requirements is a crucial step of the systems engineering approach, it allows the definition of the system under development [BCN21].

The project Agile 4.0 also addresses MBSE-MDAO coupling and considers it as an enabler to accelerate the development of innovative products. The authors of [CN21] identified in the literature that deploying an MDAO collaborative design process could help in reducing the system development time [CN21]. The methodology proposed in [CN21] covers the entire life cycle of the system, starting from the stakeholders identification to the validation process as it is done

in a systems engineering approach. The conceptual framework in [CN21] use systems engineering for upstream architecting phases such as system identification and system specification whereas they use MDAO processes for downstream product design phases. In our work, we propose to initiate the coupling between MBSE and MDAO from the requirement writing in order to add as details and accurate values characterizing the system as early as possible in the life cycle.

To write good requirements, that is to say requirements that are complete, consistent, understandable, unambiguous and traceable, [BCN21] proposes to judge their quality using measurable indicators. The authors of [BCN21] further present several viewpoints as modeling guidelines with stakeholders, needs, and requirements in mind. As far as requirements writing is concerned, 5 fields to be filled in are expected : Text, ID, Type, Author, and Version. The Text field is supposed to be filled in by following a requirement pattern corresponding to a standard sentence, according to the type of requirement to be defined. For example performance requirement, design constraints requirement or even environmental requirements.

Finally, certification of the drone developed is also part of the research spectrum of the Agile 4.0 project. A certification-driven process is presented in [Tor+21]. Since drones are embedding an ever increasing number of functionalities and become more complex, integrating the issue of certification as early as possible in the development of such system will facilitate its final certification.

4 Contributions

The work presented in this paper aims to size a drone battery in order to complete a given mission. To do this, an MBSE model and an MDAO analysis are done. The expected result is to have precise value of drone and battery characteristics that are required to go further in the design of both of them. Obtaining reliable values from the conceptual design of the system is an asset to ensure a good development of the battery and it reduces the design space to explore from the beginning of the project.

4.1 Process proposed

The process proposed in this paper is made up of 5 steps, as depicted by Figure 2.

The first step consists in writing requirements in a SysML requirement diagram using existing SysML stereotypes and the 3 additional stereotypes proposed in this paper (Figure 3). In this step the scalar that needs to be sized with the MDAO is identified with the Boolean identifier named *MDAOObjectiveFunction*. If the Boolean is true, the variable corresponds to the objective function. During the second step, the MDAO model that will optimize the objective function is built: this allows one to identify the design variables and parameters required to complete and run the MDAO model. The third step corresponds to the search for

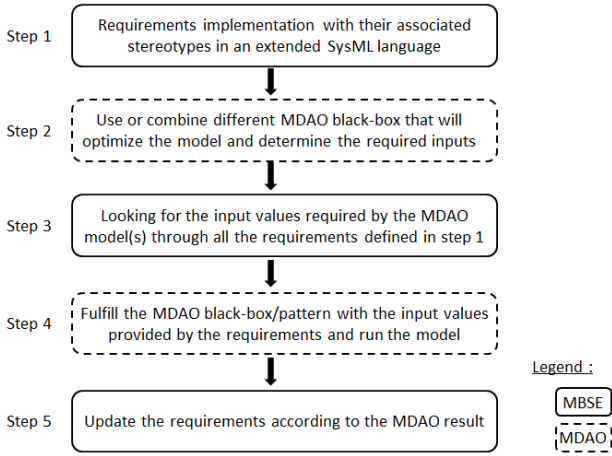


Figure 2: Requirement improvement process

these variables values in the requirements diagram using the stereotypes created in this paper (Figure 3). Then the input values are exchanged from the requirement diagram to the MDAO model. Finally, after running the MDAO analysis and optimization, outputs are added to the requirements diagram, which allows one to update it and improve its accuracy. An example is run in section 5.

4.2 MBSE modeling

To create a strong coupling between MBSE and MDAO, several changes are proposed and presented in the remainder of this paper. First, to highlight the new links between MDAO and MBSE models, new stereotypes were created in the Papyrus tool [DLG09]: MDAOproperties, MDAOinput, and MDAOoutput Figure 3.

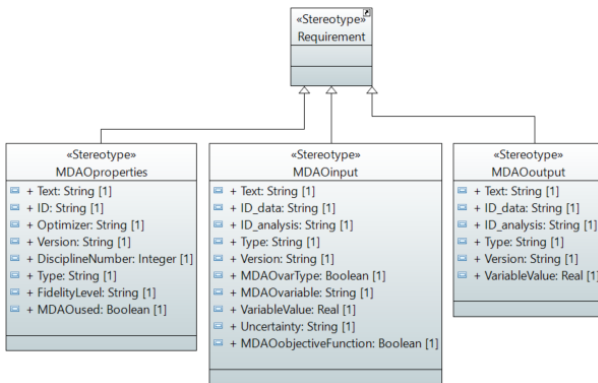


Figure 3: New stereotypes proposed for the requirement diagram

MDAOproperties contains all information related to the MDAO model definition used to improve associated requirements. Requirements with the stereotype \ll MDAOproperties \gg contains for example the solver used for the optimization in the Optimizer attribute, the number of disciplines that are part of the MDAO model, and the fidelity of the model in use. The Boolean MDAOUused indicates if the

MDAO described in the requirement with the stereotype \ll MDAOproperties \gg is used to improve another requirement with another stereotype or not.

MDAOinput contains data that can be used as input values by the MDAO model. These data are classified into 3 categories: "design variable", "parameter", and "objective function". The objective function is characterized by a true value of the Boolean MDAOobjectiveFunction. The difference between design variables and parameters is that a value of a design variable can be modified during the MDAO optimization process when parameters remain fixed values. The Boolean MDAOvarType returns the type of the variable. If the Boolean MDAOvarType is true, the variable is a design parameter; otherwise, it is a parameter. MDAOvariable indicates the name of the corresponding variable used in the MDAO model.

MDAOoutput allows one to integrate the outputs of the MDAO into the SysML requirement diagram. For this reason two relations are created: MDAOupdate and MDAOaddition. MDAOupdate represents the link between the original requirement and the requirement containing the variable value obtained with the MDAO. MDAOaddition represents the link between a new requirement given by the MDAO optimization and a requirement already present in the initial requirement diagram.

Several attributes created in this paper mean the same thing in different stereotypes. They are defined as follows. 'id_data' represents the identifier of the requirement which contained a data used or obtained by the MDAO. 'id_analysis' represents the MDAO solver that modifies or uses the value of the considered requirement. 'version' indicates the version of the requirement. If the requirement is modified, the version number will be incremented. 'type' indicates if the requirement is functional or non-functional. Finally, 'text' is a text field that supports controlled natural language (not addressed in this paper) and defines the variable provided into the requirement.

The 3 stereotypes \ll MDAOproperties \gg , \ll MDAOinput \gg and \ll MDAOoutput \gg cover the needs of the drone battery sizing developed in section 5. Future work will allow one to complete and generalize them so that they can be used for other applications than battery sizing.

4.3 MDAO modeling

At this point, requirements are considered to be written, but they may not be accurate enough to restrict the possibilities of design of the future drone battery. For instance, this applies to the requirement named MaxWeight presented in the example section 5.

Another concern is to ensure that the drone will have enough autonomy to complete its given mission. For this reason, an MDAO model is built and run. It aims to help improving part of the requirements written in a SysML requirements diagram, and to verify if the drone is able to complete its mission with a battery developed that meets these requirements. The objective function

of the MDAO model used in this paper is the state of charge of the battery, deduced from the Bréguet range equation (1) for fully-electric UAV that is optimized by the MDAO.

$$R_{elec} = \frac{c_b C_L}{g C_D} \frac{W_{batt}}{W_{TO}} \eta_{ESC} \eta_m \eta_p \quad (1)$$

Where :

- c_b is the battery specific energy
- g is the gravitational constant
- $\frac{C_L}{C_D}$ is the lift to drag ratio
- W_{batt} , W_{TO} are the drone battery weight and the takeoff weight
- η_{ESC} , η_m , η_p are the Electronic Speed Controller (ESC), motor and propulsive efficiency

The MDAO is used to find a trade-off between all design variables of the problem that provides the maximum range of the drone, which is obtained as an output of the optimization.

In this paper, Bayesian optimization [Moc75] is performed and, the objective function is approximated by a Gaussian Process [Wil+20]. This approach suits to find a global optimum of an objective function expensive to evaluate [Fra18]. The optimizer used is named Super Efficient Global Optimization with Mixture Of Experts (SEGOMOE) [Pri+20]. SEGOMOE optimizer is a good candidate to solve global optimization problems subject to nonlinear constraints and involving numerous design variables [Bar+19].

The MDAO model is presented in Figure 4. The technical vocabulary defining a wing and used in the MDAO model is presented in Figure 5 and Figure 6.

The MDAO model is made up of seven disciplines.

- Atmos, that takes as inputs parameters the flight altitude of the drone and the Mach number. It uses these two parameters to compute several parameters such as temperature, speed of sound, and computes and returns Reynolds number, air density and True Air Speed (TAS) as outputs parameters. These values are available for the other disciplines and thus used in other computations.
- Geometry, this discipline creates the mesh of the wing and the tail of the drone. It takes as inputs data the root chord, the span and the twist of the wing, respectively the tail of the drone. This mesh is required for others disciplines such as Aerodynamics and Structure for instance.
- W0, this discipline adds the mass of the battery with the mass of the fuselage and of the payload. The output corresponding to the mass of the drone without wing and tail is required in the discipline Structure to determine the mass of the two entities wing and tail.

- AeroStructure: this fourth block corresponds to a second MDAO model presented in Figure 7. It is made up of three disciplines (Structure, Aerodynamics, and LoadsTransfer), and another block named DispTransferGroup.

- Structure: discipline that takes as input the dihedral, the sweep, the twist, the taper ratio, the mesh and the thickness of the wing, respectively the tail of the drone, and W0. It outputs some parameters such as the displacement of the wing and the tail, the mass of the wing and the tail, and a new mesh taking into account the real shape of the wing and the tail (dihedral, twist, sweep...). It also verifies if the wing, respectively, the tail resist the forces exerted when the drone makes a turn.
- DispTransferGroup: it is a third MDAO model shown in Figure 8 and made up of two disciplines: ComputeTransformationMatrix and DisplacementTransfer. ComputeTransformationMatrix takes as inputs the displacement of the wing and the tail from the discipline Structure. With this, it builds a matrix used by the discipline DisplacementTransfer to define the deformed mesh of wing and tail of the drone.
- Aerodynamics: this discipline computes lift and drag cruise coefficients as well as forces applied on the wing and the tail. It uses variables previously computed by other disciplines like the Reynolds number, the air density, the TAS, the mesh and the deformed mesh of the wing and the tail. But also design variable found in the requirement diagram like the dihedral (wing and tail), the sweep (wing and tail), the taper ratio (wing and tail), the twist (wing and tail), the angle of attack (AOA) and the Mach.
- LoadsTransfer: this discipline takes as input only variable defined by the other disciplines of the MDAO model. The deformed mesh of the wing and tail are transmitted by the discipline DisplacementTransfer, whereas forces applied on the tail and the wing come from the discipline Aerodynamics. The outputs of LoadsTransfer are the loads of the wing and the tail.

Once the analysis of the AeroStructure MDAO model is completed, outputs values are sent to the first MDAO model Figure 4 and used for the computation of the state of charge of the drone battery.

- Masses, takes as inputs the output of W0 and the mass of the wing and tail computed by the discipline Structure to determine the Take-Off Gross Weight (TOGW) of the drone.
- BreguetElec, contains the equation (1) to optimize. It takes as input parameters such as the

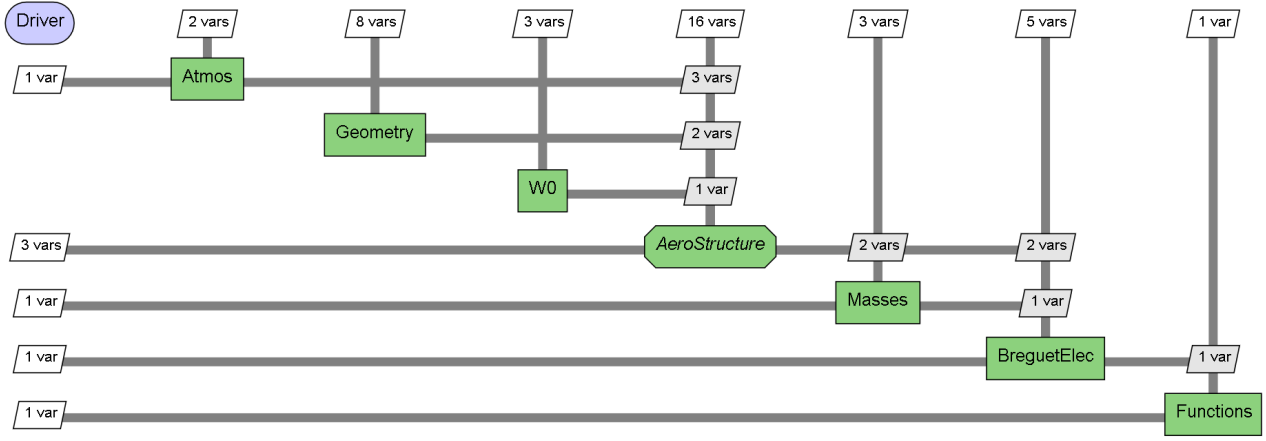


Figure 4: XDSM maximizing the drone range.

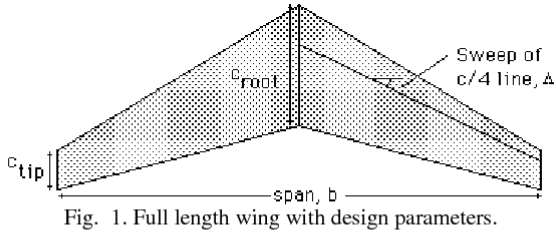


Fig. 1. Full length wing with design parameters.

- S =span
- AR =aspect ratio (b^2/s)
- sweep
- thickness
- Δ =tapper ratio (C_{tip}/C_{root})
- Θ = wing twist angle.

Figure 5: Technical vocabulary of a wing.

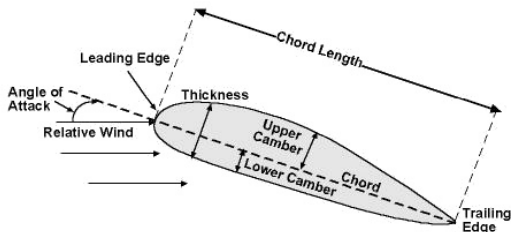


Figure 6: Technical vocabulary of a NACA profile.

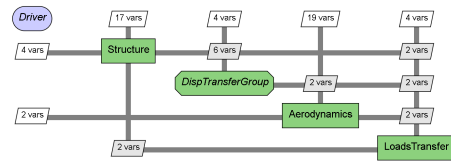


Figure 7: AeroStructure XDSM

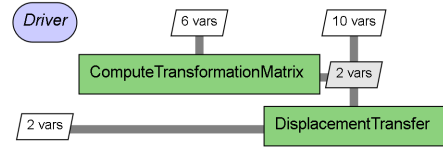


Figure 8: DispTransferGroup XDSM.

mass of the battery, the battery specific energy and the efficiency of the ESC, of the motor and of the propeller. It also uses lift and drag cruise coefficients obtained as output variables of the Aerodynamics discipline, and the TOGW computed by the discipline Masses. This discipline returns as output value the maximum range that the drone can travel.

- Functions, which is the objective function. It provides the optimized state of charge of the drone battery by taking as input variable the maximum range computed by BreguetElec and the target range (corresponding variable: target_range) to travel.

5 Case study

5.1 Mission Description

The mission considered in this paper is a high-voltage power line surveillance mission executed by a drone. In this mission, the drone should fly over a high-voltage power line recording data using embedded sensors.

Traditionally, inspection of high-voltage power lines is achieved by Humans or using an helicopter [Liu+19]. Dangers for human beings along with inspection costs

lead to investigate new inspection solutions. Drones have many advantages in terms of low cost, and easier access to areas that remain difficult for Humans or helicopters. For safety reasons, high-voltage power lines are often located far from housing and crowded areas. They can be located in mountains or in forests for example, which increases difficulty for technicians [Liu+19].

A high-voltage power line mission may present different objectives. The advantage of using a drone for executing such a mission is that a drone can be customized depending on the tasks it will have to perform. For instance, a drone can evaluate the state of the wires using cameras, make repairs on the wires with a robotic arm, and acquire electrical measurements from wires (for instance, the temperature and the value of the current). Drones need to be designed for the equipment they carry, and according to the parameters related to their mission. For instance, one needs to maintain a minimum distance from the power line, and to adapt to weather conditions and relief.

In the power line surveillance mission chosen in this paper, the main criterion to be taken into account is the distance to travel. The drone should take-off, inspect the high-voltage power line, return to its starting point and land. In this paper a fixed wing drone is preferred to a multirotor one because of the former's greater flight autonomy.

In addition to having an impact on the design of the entire drone, the mission objectives, the onboard and the operational environments have an impact on the drone's battery. At the moment, the mission achievement depends on the flight autonomy, and thus, on the battery performances. It should be noted that developing models for battery discharge is a challenge in many ongoing researches [Cha+16].

5.2 Drone battery

Lithium polymer (LiPo) batteries are commonly used to power drones since they present several advantages. For instance, they provide from ten to thirty times the theoretical energy density supplied by lead batteries. Further, they are lighter than Nickel-Cadmium batteries. Other interesting characteristics that justify their use in drones include the low cost, the durability, and the high charge and discharge rates [Cha+16].

In [Cha+16] the idea of categorizing drones and creating a large energy consumption model for each class created is introduced. The objective of these models is to estimate the energy consumption of the battery, once the drone is associated to the mission it has to execute. This way, the mission can be better planned before it is executed. The objective of this paper is similar, that is to say, to find a way to predict the battery discharge based on the mission being performed. The difference in this paper is that a method coupling the MBSE and MDAO approaches is proposed and implemented to predict the battery discharge. This coupling method is detailed in section 4.

5.3 Drone battery modeling

According to the requirement TargetRange (Figure 9) the length of the high voltage power line is 20000 m that corresponds to the value called target_range in the MDAO model. The target value expected as an input value in the MDAO model is provided by the excerpt of the SysML requirement diagram Figure 9. The remaining state of charge of the battery at the end of the mission is computed with this target_range value and other design parameters of the drone and the battery. In the MDAO model used in this paper, the problem is constrained by four parameters that are the lift coefficient of the drone, the wing and the tail failure, and the TOGW. Considering the lift coefficient as a constraint allows one to ensure that the drone is able to fly. Sizing the drone thinking about wing failure and tail failure parameters ensures that neither the wing nor the tail will break during the flight. Finally, the maximum weight of the drone authorized is 8 Kgs (requirement MaxWeight Figure 9). For this reason the parameter max_mass is also used to constrain the problem Figure 10.

The MDAO model built in this paper takes 19 inputs parameters and design variable, as described in section 4. After 250 optimization iterations it returns 31 variables as output, as shown on Figure 11, Figure 13, and Figure 12.

The best result obtained after 250 iterations is the one presented in Figure 12 that corresponds to a drone of 7.87 Kgs (TOGW).

The discipline breguet_elec shows that this drone is able to travel 109,442 m thanks to its battery, Figure 12. Knowing that the high voltage power line surveillance mission required to fly 20,000 m, it is possible to ensure that the drone is able to complete the mission described at the beginning of section 5. After executing this surveillance mission, the discipline functions computes the remaining SOC of the drone that is of 81,7% Figure 12.

In view of the results obtained, particularly in terms of remaining autonomy, it is legitimate to think that the drone is oversized. However this gives us the possibility to rethink and reorganize the mission. For example, it is possible to embed more energy-consuming sensors into the drone that would allow to better inspect the high voltage power line. Another option is to extend the distance of high voltage power line to monitor during the surveillance mission. For instance, it could be interesting to inspect a nearby high voltage power line the same day. However, this drone won't be sufficient to inspect the longest high voltage power line in the world which measures 1700 Km.

In addition, the objective of this example was a proof of concept showing the feasibility of the coupling mechanism proposed in this paper. For this reason, not all variables have been optimized. In particular, the battery mass has been fixed and was not part of the optimized variables. In future works, more variables will be optimized, including the mass of the battery which is a major point in the dimensioning of many systems.

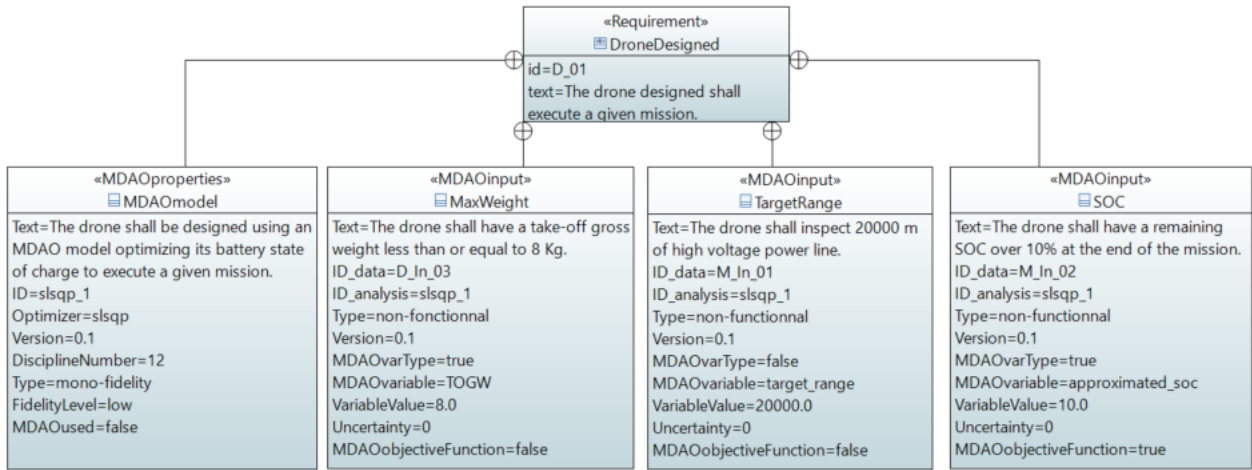


Figure 9: Excerpt of the initial requirements diagram.

```

40 [SEGO] Constraints:
41 CL_cruise (0)
42 wing_failure_cruise (1)
43 tail_failure_cruise (2)
44 max_mass (3)

```

Figure 10: Constraints of the MDAO problem.

```

70044 31 Explicit Output(s) in 'model'
70045
70046 varname val
70047 -----
70048 atmos
70049 Reynolds [1477110.14567701]
70050 rho_air [1.28288361]
70051 TAS [19.94991158]
70052 geometry
70053 mesh_tail [33.441179704071445]
70054 mesh_wing [32.98522988588984]
70055 w0
70056 w0 [6.]

```

Figure 11: Output variables of the disciplines atmos, geometry, and w0.

```

70086 masses
70087 TOGW [7.87133643]
70088 breguet_elec
70089 Range_max [109442.71278247]
70090 functions
70091 approximated_SOC [0.81725599]

```

Figure 12: Output variables of the disciplines masses, breguet_elec, and functions.

The variables that characterize the drone are set in the block AeroStructure Figure 4 by the disciplines Structure, ComputeTransformationMatrix, DisplacementTransfer, Aerodynamics, and LoadsTransfer. The results are presented in Figure 13.

5.4 Results: requirement improvement

Finally, the analytical values obtained with the MDAO analysis (Figures 11, 13, 12) are used to update the initial requirements diagram Figure 9. The new stereotypes proposed in section 4 as well as the relations between requirements are applied in Figure 14, the re-

```

70057 aero_structure
70058 structure
70059   disp_tail [15.099668870632314]
70060   disp_wing [14.696939311846727]
70061   fem_origin_tail [0.35]
70062   fem_origin_wing [0.35]
70063   mesh_tail_twisted [33.450117129830765]
70064   mesh_wing_twisted [32.99824747681123]
70065   nodes_tail [11.333583713997037]
70066   nodes_wing [10.810484330466467]
70067   struct_mass_tail_cruise [0.24886297]
70068   struct_mass_wing_cruise [1.62247346]
70069   tail_failure_cruise [-0.98193365]
70070   wing_failure_cruise [-0.84420774]
70071 disp_transfer_group
70072   compute_transformation_matrix
70073     transformation_matrix_tail [18.493242009045186]
70074     transformation_matrix_wing [18.00000685650097]
70075   displacement_transfer
70076     def_mesh_tail [33.45011746224209]
70077     def_mesh_wing [32.99820984283152]
70078 aerodynamics
70079   CD_cruise [0.03471341]
70080   CL_cruise [0.49999198]
70081   tail_sec_forces [22.535731112734233]
70082   wing_sec_forces [42.976823546451236]
70083 loads_transfer
70084   aero_loads_tail [4.632074287590359]
70085   aero_loads_wing [15.684387141358123]

```

Figure 13: Output variables of the blocks AeroStructure and DispTransferGroup.

quirement diagram obtained after inserting MDAO results inside.

The updated requirement diagram, more accurate than Figure 9, allows one to go to the next step of the drone battery design with a stronger background than if the design method had not used MDAO model.

6 Conclusions

From some years now, drones are even more present in the sky and execute a wide range of missions to ease Humans' work. There exists different kinds of drones. Some of them are employed to travel a long distance whereas others are smaller than a human hand

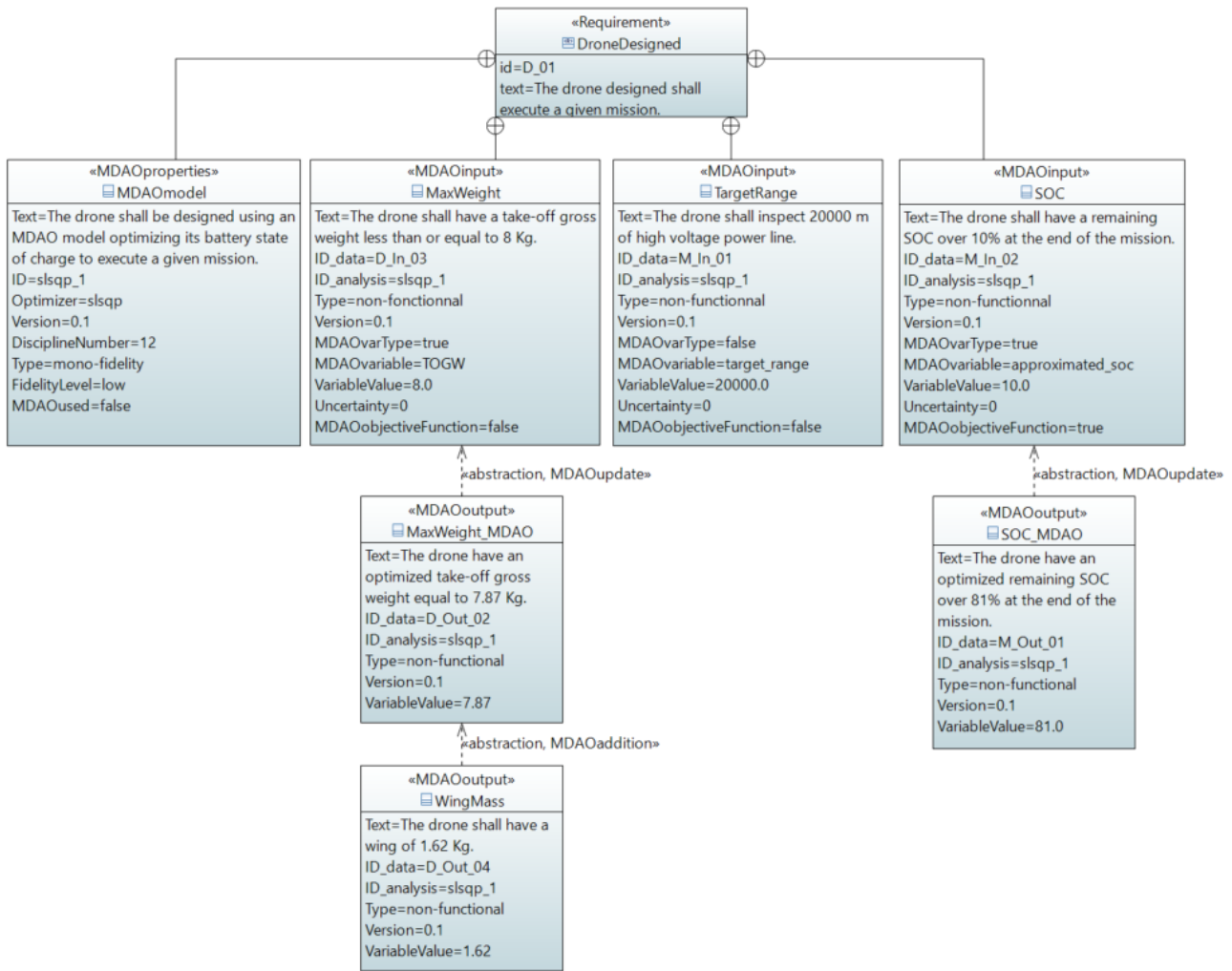


Figure 14: Updated excerpt of the requirement diagram.

[Gro+21]. The design of each drone depends on the mission it will have to execute. MBSE allows one to describe the system from at least a structural and behavioral point of view [CS21] and to manage the requirements that the system should satisfy. However some limitations in the MBSE approach can be pointed out [CS21].

This paper proposes to strengthen the MBSE approach by coupling it with the MDAO approach. The latter advantageously provides precise analytical values after analyzing and optimizing a model composed of several inter-related disciplines. In such a way, MBSE takes advantage of the mathematical computations achieved by the MDAO. On the other hand, the MDAO can use the MBSE as a data base to fill in its models. For instance, requirement diagrams may contain a lot of information expected as inputs by the MDAO. In this paper, different stereotypes are proposed to initiate the communication and exchange of data between MBSE and MDAO approaches. The consistency between all models (MBSE and MDAO) is preserved because the ones are modified according to the others. In other words, they evolve in a synchronous way.

Keeping in mind that the main objective of the

MBSE-MDAO coupling is to accelerate the development process of the drone, future work will consist in automating the exchange of data between the requirement diagram and the MDAO model. A common language understandable by MBSE and MDAO will be proposed.

Formalizing the drone mission will be an important milestone of our project. More precise parameters required by the drone will be taken into account to satisfy the mission. This will contribute to an improved design of the drone.

Creating MDAO model patterns from the SysML requirement diagram is also an avenue to explore.

Finally, the coupling of MBSE and MDAO approaches will be extended beyond the requirement step in order to cover the entire lifecycle of the drone.

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