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Research Article

A Novel Re-Engineering Method Utilizing Model Based Systems Engineering[1]

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Abstract

This paper provides a novel re-engineering method utilizing Model Based Systems Engineering (MBSE). It takes knowledge and experience accumulated over many years to develop an engineering product of good performance and quality. For those who lack that pool of knowledge and experience but aims to develop the product, this novel method could reduce the time required to accumulate the knowledge, to gain the experience and moreover to come up with a more enhanced product. The method also provides a way to build an infrastructure consisting of digital models validated by experimental data that would boost the pace of the product development cycle. The infrastructure not only preserves the knowledge but also it makes the knowledge easily accessible to developers for immediate use.

Keywords: Requirements, Modeling, Simulation, Prototyping, Verification and Validation.

Model Tabanlı Sistem Mühendisliği Yardımıyla Özgün Bir Yeniden Mühendislik Yöntemi

Öz

Bu makale Model Tabanlı Sistem Mühendisliğini (MTSM) kullanan özgün bir yeniden mühendislik yöntemi sunmaktadır. İyi performans ve kalitede bir mühendislik ürünü geliştirmek uzun yıllar boyunca biriken bilgi ve deneyimi gerektirir. Bu bilgi ve deneyim havuzundan yoksun, ancak ürünü geliştirmeyi amaçlayanlar için, bu özgün yöntem bilgiyi biriktirmek, deneyim kazanmak ve daha gelişmiş bir ürün bulmak için gereken zamanı azaltabilir. Yöntem ayrıca, ürün geliştirme döngüsünün hızını artıracak deneysel verilerle onaylanmış dijital modellerden oluşan bir altyapı oluşturmak için bir yol sağlar. Altyapı sadece bilgiyi korumakla kalmaz, aynı zamanda bilgiyi anında kullanım için geliştiriciler tarafından kolayca erişilebilir hale getirir.

Anahtar Kelimeler: İsterler, Modelleme, Simülasyon, Prototipleme, Doğrulama, Geçerleme.

1. Introduction

Per the Oxford dictionary the Re-engineering is defined as "redesigning a device or machine." The term re-engineering is usually mixed with the term reverse engineering meaning "the reproduction of another manufacturer's product following detailed examination of its construction or composition." There is a significant difference between the two. While the first approach, the re-engineering, targets a superior product; the latter approach, the reverse engineering, merely tries to copy the original, aiming to get close to its performance at best. The presented novel re-engineering method in this article integrates the basic principles and methods of Systems engineering in a model-based fashion into the re-Engineering process to insure the performance and efficiency of the redesigned product are up to the mission level operational requirements.

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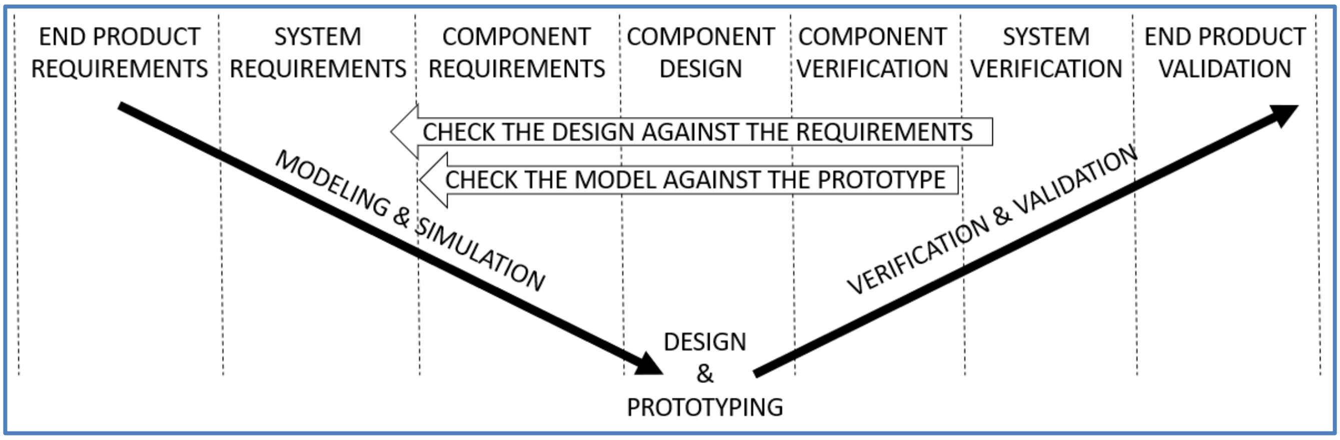

Figure 1- An MBSE product development process

Systems engineering is defined as "an interdisciplinary approach and means to enable the realization of successful systems" (Walden et al, 2015). Systems engineering is also defined as "an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in near optimal manner, the full range of requirements for the system" (Eisner, 2008). There is almost a century long history to the evolution of Systems engineering originating from Bell Labs in late 1930's. With the rise of the digital technology, Systems Engineering discipline has recently been transforming itself to adapt to this new era by incorporating modeling and simulation into its design cycle for verification and validation early in concept and development phase. MBSE is defined as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (Walden et al, 2015).

In a typical development life cycle, a concept is laid out and functions to serve this concept are developed. Components are designed to satisfy the desired functions. Development of components and the way they interact with each other paves the way for the system architecture. Through the implementation, the designs are brought to life. After the implementation, the product is ready to be tested to see if the product functions as planned. Using the test data, the desired functions can be validated. At each development step, it is critical to check back with the functions that the planned design is going to be satisfactory.

The cost of design changes after the implementation are very prohibitive in terms of both budget and time. That is why a more systematic approach has been introduced in the form of a V cycle in Systems Engineering (SAE ARP 4754-1996) (Figure 1). The cycle starts with the End Product Requirements on the top left and finishes with the End Product Validation on the top right. The sharp edge of the Vee is where the design is developed, and implementation starts. The left side of the Vee is the development of requirements broken down from the End Product to component's level; while the right side is the verification and validation carried out on the prototype from component to the End Product against the requirements. In the conceptual design stage since there is no prototype yet to test, modeling and simulation is the most effective and advantageous to quantitatively test the mission level requirements. After the verification of all the requirements through modeling and simulation, the design is carried out and a prototype per the design is built. As the component and system verification and validation tests are carried on the prototype, the models used on the left-hand side of the Vee are enhanced to better represent the components and hence the system behavior. Execution of the tests on the prototype also provide means to validate the design.

The Computer Aided Design (CAD) and Engineering (CAE) tools started to gain acceptance following the digital transformation. About a decade later Systems Engineering practices were revolutionized with Model Based methods (see Figure 2).

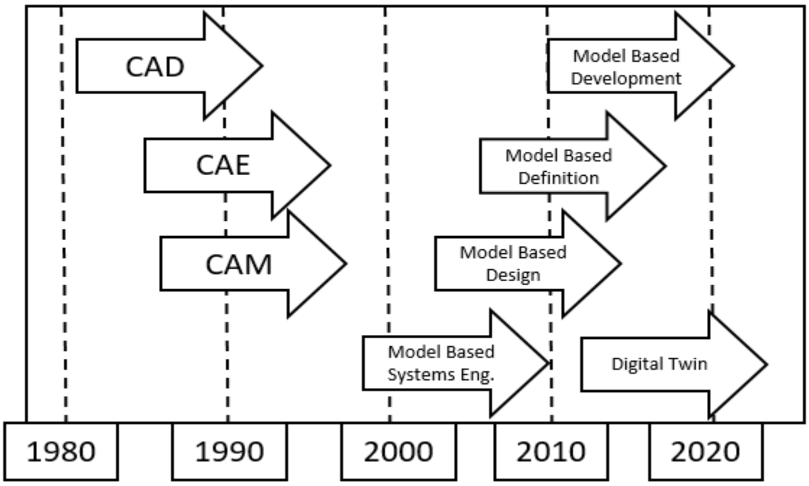

Figure 2-The propagation of model-based methods following the digital revolution (Oral, 2019)

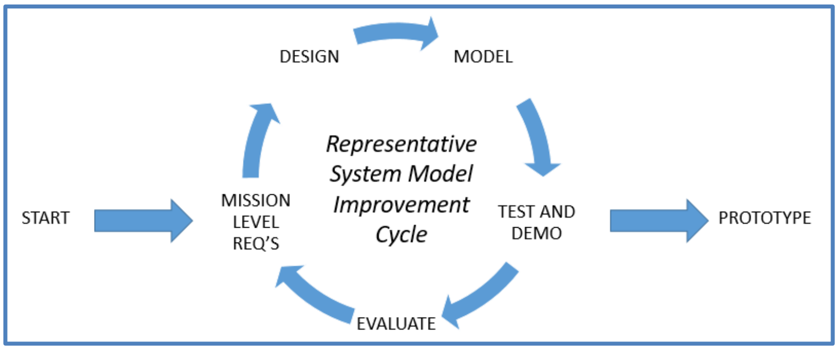

Figure 3- Incremental development through mission level testing before prototyping

The MBSE methods enable the verification and validation at the conceptual and preliminary design stage by means of simulation therefore reducing the risk of running into prohibitive design changes on the right side of the Vee cycle. Transferring the component and system dynamic behavior into digital domain in the form of models and using the verification and validation data from the real tests enhancing model accuracy and fidelity enables the transfer of the knowledge and know-how from document-based environment into model-based environment.

A model-based environment is executable with capability to provide automated reports eliminating the documentation workload that many companies still undertake. Keeping the know-how in an executable form in digital environment makes it accessible for learning and leveraging it for other projects on-demand instead of documentation form which is a lot harder to utilize. A large project can produce as many as 50 thousand documents and principally at every design change these documents must be reviewed and reprocessed, however in a model-based systems engineering setting this task including verification and validation tests can be done in a matter of hours using limited resources.

Probably one of the most challenging parts of the Systems Engineering is the development of the requirements. A model-based environment allows the tests to be carried out much earlier against the requirements. The defined functional requirements at unit level are usually satisfied. However, as the system hierarchy level increases from unit level to system level, and later to system of systems level (SoS), it becomes harder to maintain the initial design solution without any changes to meet the requirements. Especially in the case of SoS, emerging behaviors, that is behaviors that are unexpected, surface leading to design changes (Walden et al, 2015). When emerging behaviors are faced, it is usually the case that more requirements are added to account for the unexpected since it is impossible to foresee those emerging behaviors in advance. The best solution to face this problem is building representative models for the systems and simulate the test cases to help identify the potential problems as early as possible in conceptual design phase. It is therefore very critical to have representative models to carry out SoS level tests to ensure that functional requirements are satisfied. It is recommended to run the tests in simulation environment against the mission level requirements, since the requirements broken down to systems and unit level might be insufficiently defined (Coppola, 2019). The model improvement cycle shown (Figure 3) utilizes mission level requirements with capability to execute the simulations based on representative models.

2. Material and Method

2.1. A Novel Re-Engineering Method

The schematic of a novel Re-Engineering method utilizing Model Based Systems Engineering is shown in Figure 4. Unlike a typical development life cycle, this process starts with an already existing product that is available to be studied and tested.

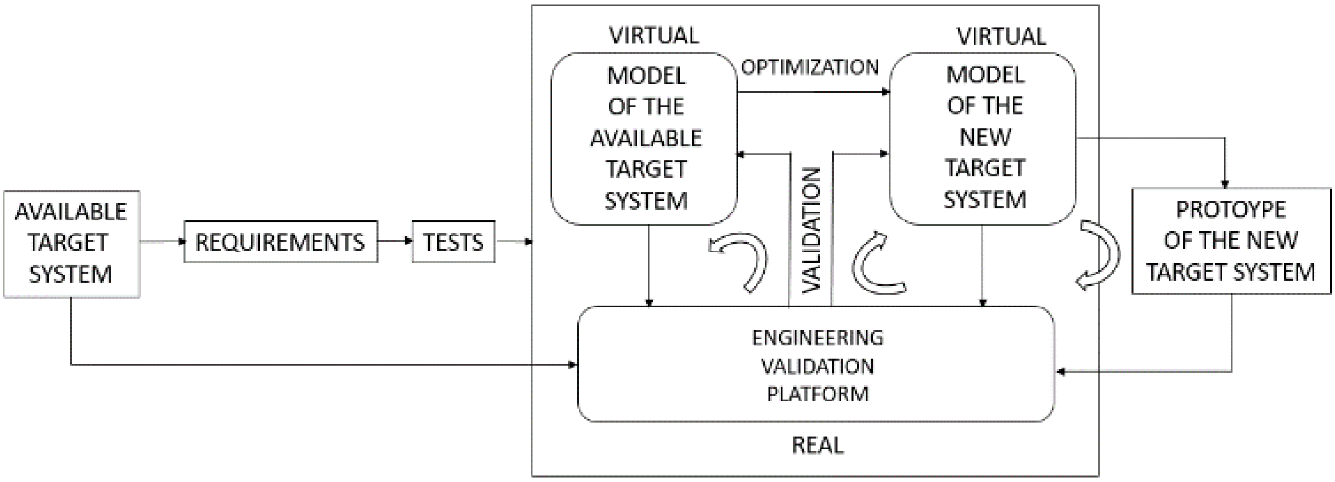

Figure 4- A novel re-engineering method utilizing model-based systems engineering

2.1.1. Defining requirements/Designing Test Cases

The first step is identification of the mission level requirements and development of the associated test cases to verify and validate these requirements according to the end customer’s demand. Using the existing engineering validation platforms and the test capabilities, the requirements can be derived for systems as well as low level components.

2.1.2. Modeling the available target system

The development cycle shown on the left side of the figure represents the effort of transferring the available target system into a model form in digital environment. The reference data and desired dynamic behavior of the available target system are generated in the engineering validation platforms and then they are used to validate the models built to represent the system in digital form. The cycle continues until the digital model provides the same behavioral characteristics of the actual target system in model simulation environment compared to the available target system test measurements obtained from the engineering validation platforms.

2.1.3. Optimizing the available target system

Once the target prototype functions and behavior are represented in virtual environment in digital form, the next step is to enhance the requirements and optimize the design for an even better product than the available target prototype leading to the Re-Engineered product. Optimization work could be in variety of forms such as weight reduction, performance improvement, enhanced durability etc. Following the completion of the optimization process, the developed requirements on the left side of the Vee cycle and associated test cases for verification and validation must be executed over the models to ensure that the re-engineered product successfully satisfies the requirements.

2.1.4. Prototyping the new target system

The prototyping the new re-engineered system is the next step in the development process. This stage of development consists of two cycles, one of which involves the prototyping step which is costly but represents the transformation of the optimized/re-engineered design from virtual environment in model form into the real environment in hardware form. Once built, the prototype is tested over the engineering platforms according to the specified test cases to verify and validate the requirements. The already developed digital model enables the developers to further understand the physics and debug the issues faced during testing. However, there might be cases that would call for changes in the models and even worse in the prototype. When a design change is introduced that requires a prototype modification or replacement, it would be costly both in terms of budget and time. The cycles can only be terminated successfully if the re-engineered design provides the same performance both in digital environment and engineering test platforms per the developed verification and validation tests.

2.2. Implementation Requirements

To execute the presented re-engineering method there are several requirements which are briefly described in this section.

2.2.1. Model development and simulation infrastructure

This is where representative models could be used to make sure that the modeled design satisfy the mission requirements and how parameter of each component affects the mission performance could be demonstrated. Later the models are computationally optimized to run in real time in SIL environment. Model development environments are also ideal to develop controls algorithms and test them against the requirements. Control algorithms can be taken through model in the loop (MIL), software in the loop (SwIL) and hardware in the loop (HIL) stages to ensure successful implementation (Figure 5).

2.2.2. A Systems Integration Lab (SIL)

This is where actual systems work together with virtual systems both functioning as in the aircraft during normal operation. In a SIL environment all the systems could be virtual, or all could be real except those that might not add any value. That is why most sensor inputs are dynamically simulated to keep the controller units running as in the vehicle. Actuators are also part of the loop, simulated or real with reactive loads. Since the set up might contain real systems, the simulations must execute in real time in SIL environment.

Figure 5- Model development and simulation infrastructure (left) and a systems integration lab (right)

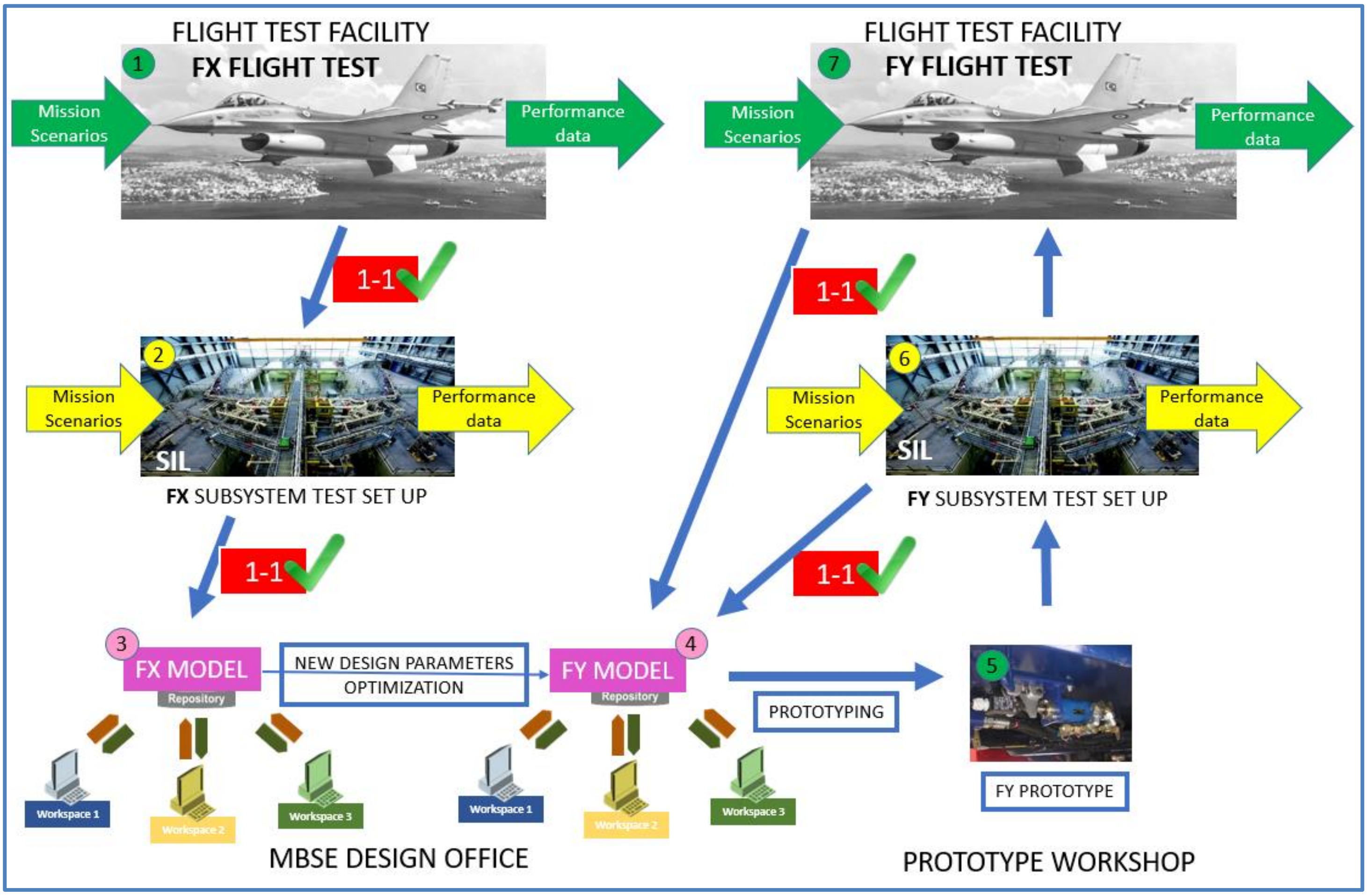

Figure 6- The implementation steps

2.2.3. An instrumented test vehicle

This is the ultimate testing environment but if there is any way to execute a test on a bench, that should be preferred. The instrumentation without interference with the systems operation in a mobile vehicle is a challenging task. The data collected during vehicular missions help to run equivalent scenarios on the test bench set ups and the model simulation environments as well as characterization of vehicle dynamics for controls purposes. The amount, the frequency and the quality of data collected is also critical to characterize the target system across its operation range.

2.3. Implementation Steps

In this section the implementation of the re-engineering method is explained step by step for a specific example of an aircraft system. Assuming a certain aircraft system would like to be re-engineered. In figure 6, all 7 implementation steps are shown. The implementations carried out in real life environment are steps 1, 5 and 7; which are colored green. The implementations that are carried out in digital modeling environment are steps 3 and 4; which are colored pink. The engineering test platforms are steps 2 and 6; which are colored yellow. Following sections are numbered the same as the implementation steps.

2.3.1. Understanding the system behavior

The implementation of the re-engineering method starts with understanding the target system behavior through testing. To be able to test the target system as if it is in an airplane running a mission, the flight test data is required. For several mission scenarios, the signals are measured during flight tests in relation to the target system. An instrumented aircraft running the mission scenarios provides the required data. Identified key performance values are calculated using the flight data both at aircraft level and at subsystems level including the target subsystem. Hence as the first step of the implementation, the input signals and output signals of the available target system are obtained for all mission scenarios obtained from flight data.

2.3.2. Building the SIL for the available target system and verifying it with flight data

Setting the testing environment on the ground rather than using the actual airplane provides a much more accessible and observable environment. The SIL environment is instrumented to allow collection of the data at target system component level both at inputs and at outputs. Executing the mission scenarios on the ground test set up allows the validation of the individual component models in the target system. At the same time, the mission level requirements are broken down to target system and further down to the component levels. In addition, the tests cost considerably less and more importantly they are safer than flying an aircraft. Using the flight data obtained during the previous step, a system integration lab set up can be verified running the hardware in the loop simulation of the same missions. Once the performance data obtained from the flight tests per specified missions compare to the ones simulated in the SIL environment within acceptable tolerances, it can be said that the model built and simulation conditions realized within the SIL environment reasonably represents the target system during the flight tests. Once this is achieved, the task of setting up the SIL test environment for the available target system is complete.

2.3.3. Developing the representative target system models and verifying them with SIL data

As the next step, the objective is setting up models to represent the target system and validate the model performance by comparing mission level simulation results between the model development environments and the SIL. Using the aircraft mission scenarios and executing them on the newly developed behavioral and physical models producing the comparable results to the ones obtained on the SIL should prove that modeling environment could be used to check the system performance against the requirements; the model development work is continued until this is achieved.

2.3.4. Customizing the target system design and enhancing it through optimization

The re-engineering method aims to deliver a better system than the one at hand. This is achieved at this step; as soon as the available target system model is successfully created in the virtual world, the models are optimized to achieve better performance at comparable cost. Considering that the design parameters are changed in the process of optimization, all the tests are repeated to insure that the new optimized design satisfies the requirements. In addition to the design parameters, some requirements may change and new requirements may be added. Therefore, the process starts with the optimized target system model to be verified and validated as if it is a new conceptual design and treated according to the MBSE development process previously shown in Figure 1. Tests are redesigned for all the requirements and executed in the virtual world from mission level down to system level and further down to component level until all the requirements are successfully satisfied that can be evaluated using simulation and analysis methods. Having successfully passed all the requirements, then the design for the prototype is readied for production.

2.3.5. Building the optimized target system prototype

This step requires building the new re-engineered target system prototype per design specifications obtained in the previous steps.

2.3.6. Developing the optimized target system prototype

A new SIL environment for the optimized system has to be built unless the previous set up can be re-used with some reversible changes. It is critical to maintain tightly controlled test environments the same as the model environments which can be re-utilized at a desired development stage.

The prototyped system is tested in a SIL environment using the same test scenarios carried out in the simulation environment from component level to system level and to mission scenarios; this approach makes it possible to easily compare the results and identify the issues that should be taken into account on the prototype. In case of any failure in regards to satisfaction of a requirement, necessary actions are taken either by improving the models or the prototype or both. Once the prototype and models demonstrates comparable results satisfying the requirements then this phase of the re-engineering method is considered to be completed successfully.

2.3.7. The final validation tests of the prototype with flight data

For the last step, the flight tests are carried out on mission level and prototype performance is re-evaluated for final validation stage while the prototype is integrated into the rest of the systems of the aircraft. Since the prototype is the result of the tests in Model and SIL development environments, along with the prototype these environments are also updated per the results of the flight tests. Depending on the discoveries during the development work, the process is restarted from a previous step taking into account the newly learned lessons. The final acceptance stage of the prototype is considered to be successfully completed when the flight tests provide comparable mission simulation results to the ones executed in SIL prototype tests and also to the ones obtained in model development environment.

3. Conclusions and Recommendations

A novel re-engineering process is defined and demonstrated in seven steps at high level using a generic example. The approach utilizes model based systems engineering leading to verified and validated digital models of actual systems to be used for further design and development.

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