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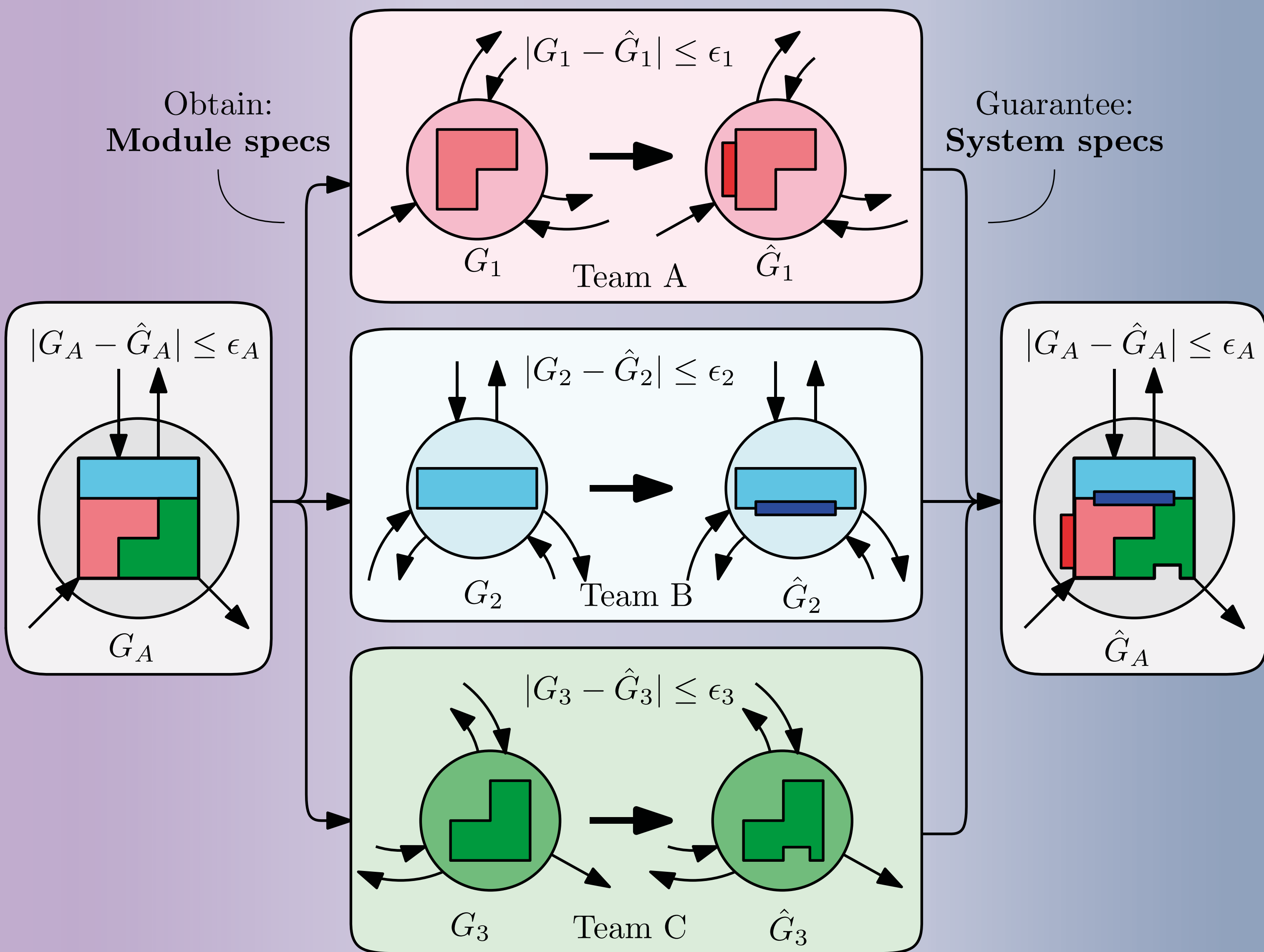

- THEME: SYSTEM ARCHITECTURE
- MODEL-BASED MODULAR REDESIGN WITH SYSTEM-LEVEL GUARANTEES
- IMPROVING THE REPEATABILITY OF KINEMATIC COUPLINGS
- COMPLIANT MECHANISMS WITH VARIABLE STIFFNESS
- DSPE CONFERENCE ON PRECISION MECHATRONICS 2023 REPORT

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Publisher
DSPE
Julie van Stiphout
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

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Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

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The cover illustration (featuring a modular redesign process) is courtesy of Lars Janssen (TU/e). Read the article on page 5 ff.

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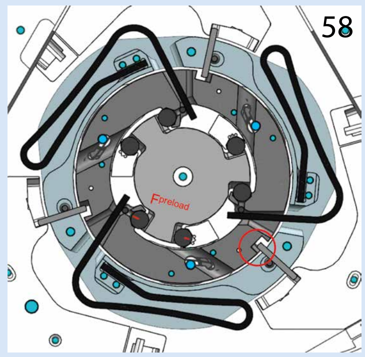
THEME: SYSTEM ARCHITECTURE



FEATURES

HOW TO EXPLAIN SYSTEM ARCHITECTURE TO THE UNINITIATED?

For thirteen years, I worked in the field of robotics. When a non-technical person asked me what I did for work, my answer was simple: "I work in robotics." That could still refer to a number of things, but I think everybody is able to imagine something about it. If I wanted to be more specific, I would say "I'm working on a home-care robot" or "I'm working on human-robot collaboration". These could still mean many different things, but nonetheless everyone would still be able to imagine something of what I meant.

Currently, I am working in the field of system architecture and systems engineering. This I find much harder to explain to people outside my direct work sphere. The word 'system(s)' is very generic; it applies to many things. Also, the word architecture is usually associated with buildings. Nor can I say anymore that I work on a specific machine or device; I have to say that I am working on how to make a machine or device. It is also hard to become more specific than that, because engineering involves methods and tools, project management and human aspects like leadership, collaboration and communication. The 'how' to make a machine can mean that I am working on any of those things. I notice it is even harder to explain to a non-technical person how complex system architecture and systems engineering actually are. I will make an attempt here using an analogy.

A system architect, for me, is a composer of music and the conductor of a philharmonic orchestra in one. In the orchestra there are many musicians playing different instruments. These equate to the domain engineers using their tools. Further, it being an international orchestra, the musicians speak different languages and interpret each other in their own ways. The role of the architect is to write the sheet music (design) and let the musicians play in harmony to create the music (system).

This already sounds complicated, but then for large musical pieces in this analogy there may be several composers and conductors who each write part of the music and each conduct part of the orchestra. Sections of the orchestra may also be located at different sites and do not continuously hear the other parts. Therefore, in order to create beautiful music, it is not strange that many rehearsals (iterations) are needed, that instruments need to be synchronised and in tune, and that unambiguous means of communication are needed. Figuring out how to do that is what I am working on.

This issue of *Mikroniek* contains several articles that may help with conducting the orchestra. I wish that you may become a better musician or conductor by reading them.

Michiel van Osch
Associate professor of Systems Design & Manufacturing, Fontys Engineering
michiel.vanosch@fontys.nl, www.fontys.nl/engineering

MANAGING COMPLEXITY IN INTERCONNECTED SYSTEM MODELS

Complex mechatronic systems are often developed by multiple engineering teams, each responsible for parts (modules) of the system (re)design. These teams face the challenge of jointly warranting the satisfaction of system-level specifications. To address this challenge, a modular approach is proposed. This allows for parallel (re)design cycles for each module, simplifying the design process and reducing overall development time. We present a model-based, modular redesign framework for mechatronic systems. The framework is illustrated on a model of an industrial wire bonder, showing possible redesigns of the wire-bonder modules while guaranteeing original system-level specifications.

LARS JANSSEN, ROB FEY, BART BESSELINK, JASPER GERRITSEN, DRAGAN KOSTIĆ AND NATHAN VAN DE WOUW

Introduction

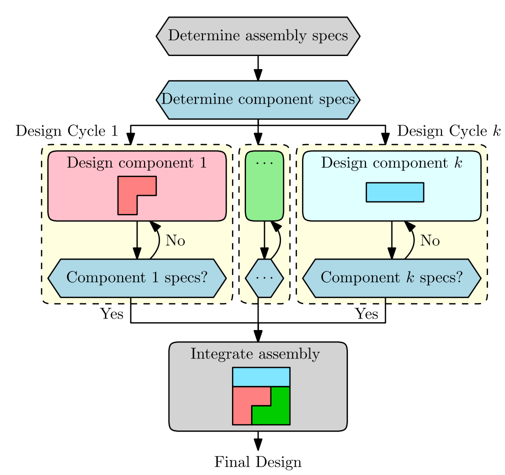
Industrial machines consist of multiple interconnected modules, with each (physical and/or functional) module having several components. It is expected that a well-designed machine satisfies given requirements and specifications (R&S's) on the system level. Often, modules and even components are developed independently by different teams of engineers from various disciplines. This can create a significant challenge of verifying R&S's on the interconnected system prior to physical integration of all the components and modules [1]. (Note: In this article, we will also use the notion of an interconnected system as a synonym for a complete machine, i.e., R&S's on the interconnected system are considered identical to system-level R&S's.)

If in that phase of machine development critical discrepancies from the system R&S's are discovered, unwanted efforts and costs may be needed to determine which system module(s) or component(s) are causing these discrepancies and to find appropriate design adaptations of (one of) these parts.

To avoid such late discoveries of non-conformance to system level R&S's, one can follow recent scientific trends towards a modular design approach that allows for separate module design cycles [2]. In such a modular approach, module specifications are derived from the system-level specifications, as illustrated in Figure 1. As the modules are designed independently, the satisfaction of their individual specifications can also be verified independently.

Theoretically, when all modules meet their specifications, the interconnected system can be integrated seamlessly, guaranteeing system level specifications.

In addition, the modular design approach facilitates parallel work by different teams, makes it easier to replace components, and helps to manage complexity of models and components effectively [3][4]. This relates to design using the V-model [5], as modular (re)design allows for verification and validation on module level instead of system level, i.e., integration issues are identified earlier, resulting in a more efficient (re)design process. However, implementing such a modular design approach requires several key elements, including clear module



1 *Modular design approach: by determining module specifications, the module design cycles are decoupled.*

AUTHORS' NOTE

Lars Janssen (Ph.D. candidate), Rob Fey (associate professor) and Nathan van de Wouw (professor) work in the Dynamics and Control group at Eindhoven University of Technology (NL), Bart Besselink (associate professor) works at University of Groningen (NL), and Jasper Gerritsen (mechatronics engineer) and Dragan Kostić (R&D director) work at ASMPT Center of Competence, Beuningen (NL).

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l.a.l.janssen@tue.nl
www.tue.nl/dc
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www.asmpt.com

definitions and interfaces, explicit system-level requirements, a quantitative framework to derive module specifications from system-level specifications, guaranteed system-level specifications when modules meet their requirements, realistic module specifications, and scalability to handle large and complex systems.

In practice, achieving all these elements from the ground up can be challenging. Therefore, multiple (re)design iterations may still be necessary, especially when system specifications change over time and over machine generations. Specifically, the need arises for modular redesign approaches, where existing designs can be used as a benchmark for future designs [6].

As mentioned above, in a modular redesign process, system-level specifications must be translated into module-level specifications, enabling the verification of proposed module updates without testing the entire system. In fact, the same key elements mentioned earlier remain essential to make modular redesign feasible.

In recent research [7], a modular approach has been introduced to address model complexity management. In this approach, for the purpose of model complexity reduction, accuracy requirements on interconnected system models are translated into accuracy requirements on models of parts of the system. This approach has specifically been applied to manage complexity in interconnected structural models [8]. In this article, we show that the underlying mathematical approach can also be used to facilitate the model-based modular (re)design of mechatronic systems.

First, we describe mechatronic systems in a general modular modelling framework and we show how frequency response function (FRF) specifications (related to dynamic behaviour) on the system level can be defined. Then, we show that these specifications can be translated into similar FRF specifications on a module level. Most importantly, this approach ensures that if each module meets its respective specification, it is guaranteed that the reduced-order interconnected system model also meets its requirements. This approach can be applied to a wide range of (mechatronic) systems. Here, we demonstrate it on a model of an industrial wire bonder of ASMPT.

Modular modelling

To employ the modular framework introduced in [7] for model-based modular redesign, we need the following elements:

1 Module models
The dynamic model of each of the modules $j = 1, 2, \ldots, k$ is available in terms of a multiple-input-multiple-output (MIMO) FRF $G_j(i\omega)$ with angular frequency ω.

2 Interconnection structure
All the interfaces between modules are modelled as connections from outputs of modules to inputs of (other) modules.

3 External influence
The relevant external inputs (e.g., disturbances, motor forces or input voltages) and outputs (e.g., sensors, points of interest) to the systems are explicitly defined.

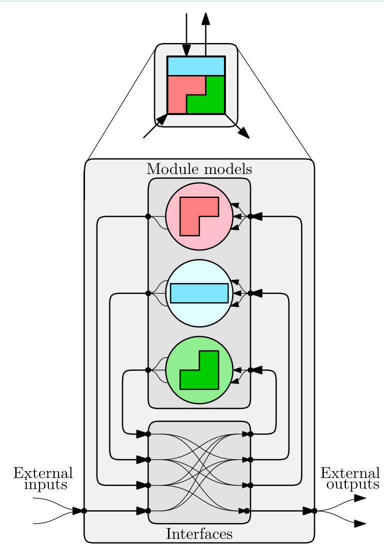
With these elements, the complete modular dynamic model can be defined, as illustrated in Figure 2. We call $G_A(i\omega)$ the (MIMO) original interconnected system FRF from the external inputs to the external outputs.

In this redesign framework, we assume that the original interconnected system performs satisfactorily. However, we aim to improve the modules, for example to enhance performance, reduce costs or increase reliability of the module, without significant effects on the system behaviour. Examples of such improvements are the addition of sensors, a change in material type, a spring stiffness or a damping constant, specific geometric design changes, etc.

We denote the FRF of a redesigned module design by $\hat{G}_j(i\omega)$. By changing the dynamics of modules, the dynamics of the overall system also change. We denote the associated changed FRF of the redesigned interconnected system by $\hat{G}_A(i\omega)$. Note that with this framework, we assume that the interfaces between modules remain unchanged.

Specification design

To enable a model-based modular redesign approach for mechatronic systems, specifications on the interconnected system model dynamics need to be defined explicitly. In this framework, the user can define frequency-dependent specifications $\epsilon_A(\omega)$ on the dynamics of the interconnected



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Modular model framework.

SINGLE SOURCE OF TRUTH AND DIRECT DESIGN VERIFICATION

Critical in the organisation of a product design process that enables quick iterations is eliminating outdated, ambiguous or duplicate information, as well as facilitating direct communication lines between different team members. This article presents an example to address this challenge using model-based systems engineering (MBSE) coupled to model-based design (MBD). The MBSE system model and MBD models are coupled to ascertain a single source of truth. This approach makes important decisions taken in the product design process explicit in an earlier phase of the design process and enables direct design verification. However, time must be spent upfront on the desired scope and architecture of the models as well as the corresponding interfaces.

PIETER DE JONG, JAN DONKERS AND GIORGIOS MAZARAKIS

Product design challenges

In modern-day engineering, product design is a complex process that involves a multitude of disciplines and a multitude of stakeholders. As mentioned previously in this magazine, a structured approach in product design is instrumental [1]. The approach should not only be structured, but it should also allow for iterations in product design.

Ideally, one would like to be able to iterate fast and obtain direct insight in the consequences, of a change in an early step in the process, on the following steps. Gained insights might also force the product design team to take a step back in the process and try to solve the blocking problems there. Furthermore, in order to allow for efficient and fast iterations, information management plays a key role: how to set up the product design process such that information is singular, unambiguous, and easily exchangeable between stakeholders?

Systems engineering and design models

The complexity in the product design and development process is managed by systems engineering, a trans-disciplinary and integrative approach to enable the successful realisation, use and retirement of engineered systems, using systems principles and concepts, and scientific, technological and management methods [2].

Many different process models have been developed in recent years that specify the steps that make up the systems engineering approach. Among them, the V-model is a widely used model organising the systems engineering activities and development lifecycle, as presented in Figure 1. It summarises the main steps to be taken in conjunction with the corresponding deliverables within system development. Looking from top to bottom, it offers a way to manage complexity by decomposition and a way to capture the development logic as you move from left to right. The left side of the V represents the decomposition of the system and its requirements as well as the creation of system specifications and design. The right side of the V represents integration and verification [3].

The use of the V-model is broad. In practice, without additional tools to assist in capturing, organising, and managing the required information, there are limitations on how well and efficiently this can be done.

As stated in the previous section, the desire is to set up the product design process such that quick design iterations can be performed, using this V-model. To this end, we want to make use of a model-based approach. Within the high-precision domain, it is common to use model-based design (MBD) approaches during the design phase of the system, i.e. for the lower part of the V. These models entail mathematical and visual methods to address challenges associated with designing complex systems. Typically, domain-specific models are used to estimate the performance and verify against the requirements of the system to be designed.

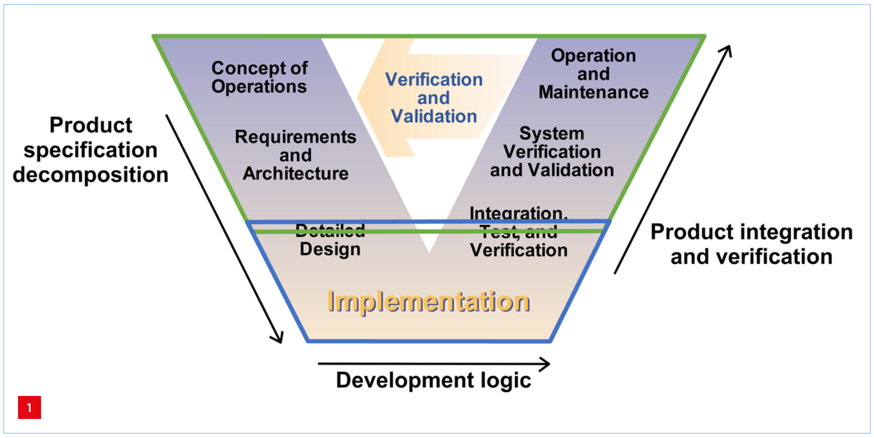
An elaborate example of such an MBD model is presented in [1]. Here, we want to combine this MBD approach with a system model that is used to capture the top side of the

AUTHORS' NOTE

Pieter de Jong (ASML), Jan Donkers (ASML) and Giorgios Mazarakis (TNO) worked at Philips Engineering Solutions in Eindhoven (NL) at the time of performing the work described here, but have changed roles since.

pieter.de.jong-pjpk@asml.com
www.philips.com

V-model. This means a model-based systems engineering (MBSE) approach is taken to capture the product design process [4] rather than the more traditionally used document-based approach (e.g., for requirement elicitation or system decomposition). The split between the MBSE and MBD models is visualised with the two trapezoids in Figure 1. While the goal of the MBD models is to estimate performance metrics based on a set of design parameters, the goal of the MBSE system model is to provide coupling between concept of operations, requirements and architecture, detailed design, and verification & validation. Its focus is more on traceability and making the links between choices made in the various stages of the V-model explicit.



V-model development process for the systems development lifecycle [5]. The scopes of MBD models and MBSE models, blue and green, respectively, are shown by the trapezoids over the V-model. Note that they overlap; this is the shared interface.

Motivation for coupling MBD with MBSE

Information management is challenging, especially with a document-based way of working. Typical challenges are with version control, change management, and systematically linking simulation and analysis models to the right versions and/or configurations of the design. This results in a lot of communication between most team members, via a lot of different channels. In turn, this leads to a high risk of either inconsistent information or a lack of information. Hence, this approach is error prone.

For information management, a trend is observed towards MBSE, using systems modelling tools to support system requirements definition, design, analysis, verification and validation activities in a single system model. It begins in the conceptual design phase and continues throughout the development and later lifecycle phases.

Since physical modelling is not a key strength of the system models in an MBSE approach (yet), coupling of the MBSE models with MBD models can be performed in order to obtain a set of models that can be used to iterate over V-model steps quickly. By this coupling, the physics-based models can be used to provide quantitative metrics of the impact of certain design decisions. Furthermore, they can be used to perform early design verification by linking the requirements stored in the MBSE models to the performance metrics calculated by the MBD models.

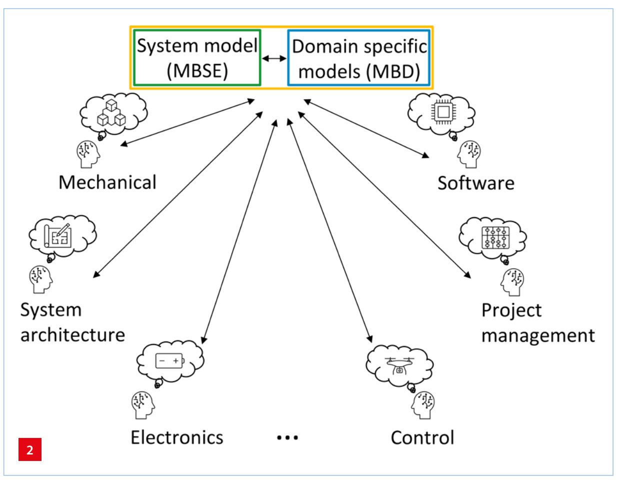
In addition, a single source of truth is obtained by directly linking both types of models; this linking removes the need for separately distributing the information to feed both types of models. Discussions between team members and many communication lines remain, but now both the documentation and the simulation models are obtained from a single source. This is visualised in Figure 2, which shows the coupling of an MBSE model to MBD models, and examples of modelling tools: Cameo Systems Modeler for MBSE (see the box), and Matlab/Simulink and Ansys for MBD.

An example case is worked out in the subsequent sections to demonstrate the coupling and allow for an elaboration on the value of this approach.

Case: Philips image-guided therapy system

The case worked out here is based on a simplified image-guided therapy (IGT) X-ray system. The IGT system can either be a floor- or a ceiling-mounted X-ray imaging system; see Figure 5 for a floor system. It has a multi-joint robotic arm, with one of the parts having a characteristic C-arc shape. The system moves around the patient, to provide vision to doctors during minimally invasive operations at different body parts, such as the brain blood vessels. The main system function is to provide images, and how well it is performed is directly related to how stable the machine is holding the X-ray source and detector with respect to the patient's body part.

For simplicity of the case, only a small part of systems engineering is performed in the Cameo Systems Modeler



Schematic of the ideal world where an MBSE model is coupled to MBD models. All disciplines are interfacing directly with the systems engineering model as well as the design models.
NB: not all disciplines are necessarily included in this schematic.