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.

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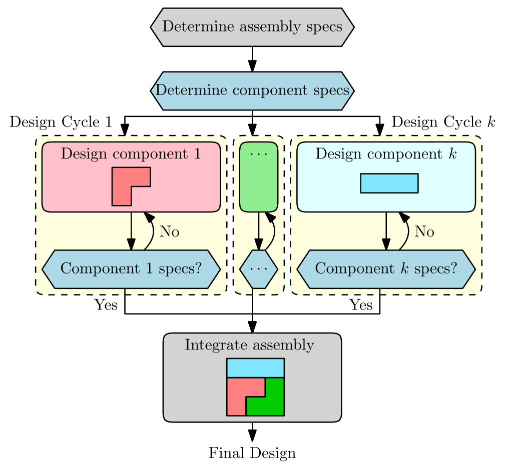
Introduction

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



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

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This publication is part of the project Digital Twin (*www.digital-twin-research.nl*) with project number P18-03 of the research programme Perspectief, which is (mainly) financed by the Dutch Research Council (NWO).

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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.

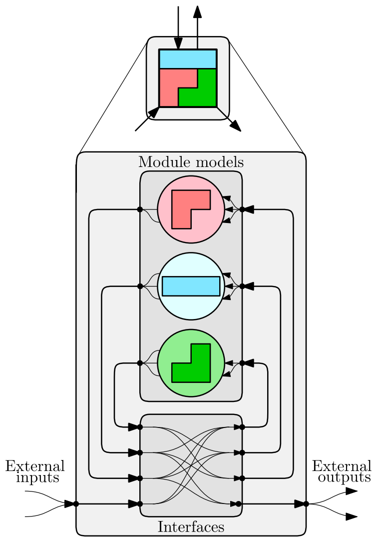
With these elements, the complete modular dynamic model can be defined, as illustrated in Figure 2. We call $G_A(i\omega)$ the (MIMO) original interconnected system FRF from the external inputs to the external outputs.

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.

system model. Specifically, the specification $\epsilon_A(\omega)$ is defined as a maximum allowed change in dynamics with respect to the original design, given by:

$$||G_A(i\omega) - \hat{G}_A(i\omega)|| \leq \epsilon_A(\omega).$$

With such a frequency-dependent specification, the system architects can define at which frequencies ω the dynamics of the original model are vital and limit the allowed change of these dynamics. Note that the system specifications $\epsilon_A(\omega)$ not only impose a bound on the allowed magnitude of $\hat{G}_A(i\omega)$, but, automatically, also in terms of allowed phase. Despite this system-level constraint, we aim to improve the design of the modules. Therefore, we need to find, given $\epsilon_A(\omega)$, what the maximum allowed change of the module dynamics, i.e.,

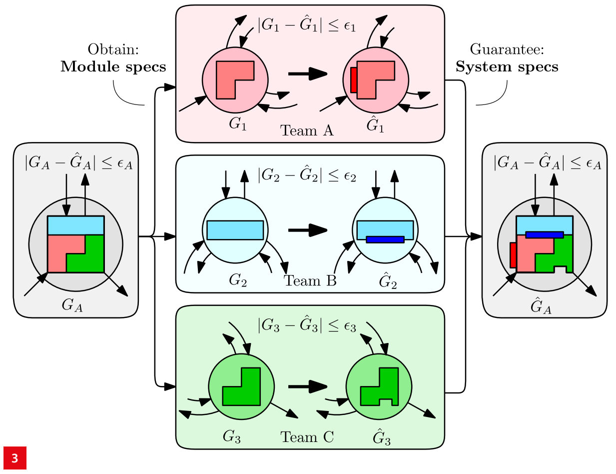
$$||G_j(i\omega) - \hat{G}_j(i\omega)|| \leq \epsilon_j\,(i\omega),$$

of each module $j = 1, 2, \ldots, k$, is.

As stated in the introduction, module design changes can be verified to meet derived module specifications on each module individually without the need for checking the resulting system-level dynamics. This means that a modular approach, illustrated in Figure 1, is now feasible. Within this framework, the following steps, as illustrated in Figure 3, are taken:

1. System-level specifications
   Define specifications on the interconnected system $\epsilon_A(\omega)$ using the original system FRF $G_A(i\omega)$.
2. Module specifications
   Compute the module specifications $\epsilon_j(\omega)$ for all modules using the mathematical framework introduced in [7]. In this approach, a distribution of allowed module specifications $\epsilon_1(\omega), \ldots, \epsilon_k(\omega)$ is obtained. Note that the complexity of this computation relies on solving a linear matrix inequality (LMI), for which standard tools are available, e.g., in Matlab, and that the complexity scales with the number of interface connections.
3. Module redesign
   Each module can now be independently redesigned by the responsible team of engineers, i.e., without the need to communicate intensively with teams responsible for other modules. The redesigned module FRFs $\hat{G}_j(i\omega)$ only need to satisfy the local, module-level specifications $||G_j(i\omega) - \hat{G}_j(i\omega)|| \leq \epsilon_j(\omega)$.
4. System integration
   If all redesigned modules are completed, the redesigned interconnected system FRF $\hat{G}_A(i\omega)$ is automatically guaranteed to satisfy the user-defined, system-level specification $||G_A(i\omega) - \hat{G}_A(i\omega)|| \leq \epsilon_A(\omega)$ as shown and proven in [7].

This redesign approach allows for module design teams to work in parallel, as they only need to verify a proposed design change in relation to their local specifications $\epsilon_j(\omega)$. To showcase the modular redesign approach, we apply the framework to an industrial wire-bonder system of ASMPT in the next section.



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Modular redesign process illustrated for three modules 1, 2 and 3, redesigned by teams A, B and C, respectively. Each team can independently redesign the module design within the module specifications ϵ_j*, while still ensuring satisfaction of system-level specifications.*

Industrial use case: ASMPT wire bonder

ASMPT is a manufacturer of equipment and solutions for the (back-end) semiconductor and electronics assembly industries. They produce a variety of equipment, including wire bonders for semiconductor packaging and assembly processes. Their wire bonders are high-performance mechatronic systems used in the semiconductor industry.

Wire bonding is a critical step in the assembly of integrated circuits (ICs) and other electronic devices. It is used to make electrical connections between the IC chip and the package or substrate that it is mounted on. These systems play a crucial role in the production of a wide range of electronic devices, from microchips to integrated circuits, by establishing the electrical connections needed for their proper operation.

The wire bonder is a three-degree-of-freedom motion system that moves a capillary tip in the x-, y- and z-directions with high accuracy and speed; see Figure 4a. The X-stage can move in the x-direction with linear roller slides connected to the machine frame. The Y-stage can move in the y-direction with linear roller slides connected to the X-stage, and the z-positioning is achieved in the Z-stage using a rotational movement through a leafspring cross-hinge connected to the Y-stage.

We define three modules: the machine frame (MIMO module FRF: $G_1(i\omega)$), the X-stage (MIMO module FRF $G_2(i\omega)$) and the YZ-stage (MIMO module FRF $G_3(i\omega)$); see

ASMPT Mechatronics Team

The Mechatronics Team of the ASMPT Center of Competency is responsible for innovations in the fields of mechatronics system development, control technology (linear, nonlinear, machine learning), system modelling and identification, dynamical analysis and simulation, motion planning and trajectory generation, embedded software development, digital twinning, systems engineering, and machine health management.
This team assists ASMPT by active collaboration with different ETG (Enabling Technologies Group, i.e. Research & Development) and Product groups, student and Ph.D. projects carried out in partnership with renowned academic partners, and cooperation with commercial vendors in developments of disruptive technologies.
The Mechatronics Team facilitates and organises diverse technical trainings for ASMPT professionals at different geographical locations. Dr.ir. Dragan Kostić is the head of the Mechatronics Team.

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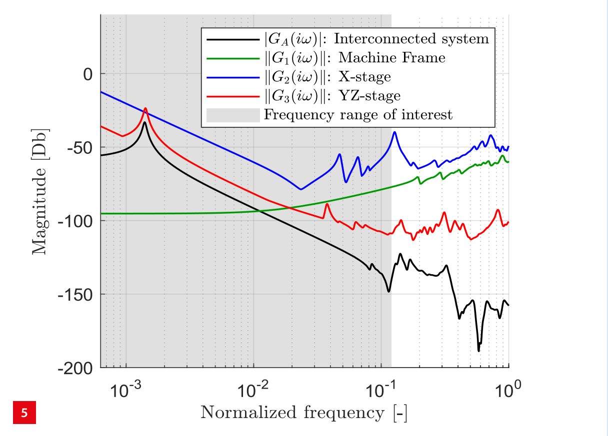
Figure 4b. All three modules are modelled using the finite-element method. The roller slides between the modules act as the interface between the modules. In the model, the rollers (18 per slide) are modelled as spring-damper interconnections. Although the proposed framework can be applied to MIMO systems, for this use case only the z-positioning using SISO (single-input-single-output) is considered. The interconnected system FRF from the external vertical force input on the Z-stage to the z-position of the capillary tip (see Figure 4b) is given by $G_A(i\omega)$. The FRFs of the interconnected system and the modules for a certain operational point are given in Figure 5.

Note: Currently, we are working towards extending this modular wire-bonder model to be position-dependent, i.e., accurate in the full operating range of the system.



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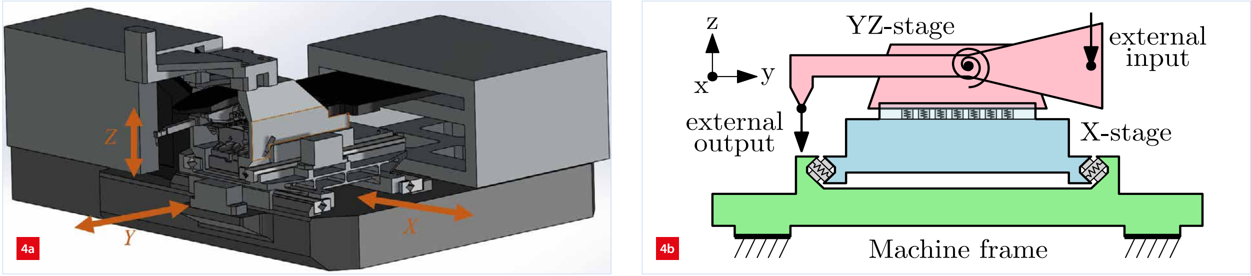
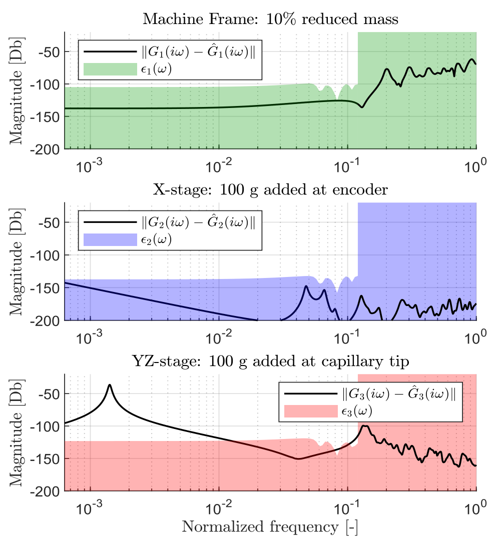
Modular wire-bonder model FRF of z*-input force to* z*-position. The module FRFs* $||G_j(i\omega)||$ *are the largest singular values (or 2-norms) of the MIMO modules FRFs* $G_j(i\omega)$*, which, when interconnected, form* $G_A(i\omega)$*.*

Now, we will show that the modular redesign framework can be used to verify, on a module level, proposed design changes to the modules:

1. System-level specifications
   For this use case, we require $\epsilon_A(\omega) = 0.1 \cdot ||G_A(i\omega)||$ for all $\omega \leq 0.12$ (normalized frequency); see the grey frequency range in Figure 5. This means that the changes to the modules are allowed to change the original dynamics of the wire bonder at most 10% for any frequency up to 0.12. Note that this decision is user-defined, and $\epsilon_A(\omega)$ can be any arbitrary (positive) value at any frequency.
2. Module specifications
   The module specifications $\epsilon_j(\omega)$ for the machine frame, X-stage, and YZ-stage are computed using the proposed approach and are shown by the coloured part in the left part of the graphs of Figure 6.
3. Module redesign
   All three modules are redesigned:
   a. Machine frame
      A new design is proposed in which the total mass is reduced by 10%. As a result, the machine frame also has its stiffness reduced. This change satisfies $\epsilon_1(\omega)$, i.e., the new FRF (black line) stays within the coloured region (Figure 6, top).



Wire-bonder system.
(a) Simplified CAD model.
(b) Schematic.



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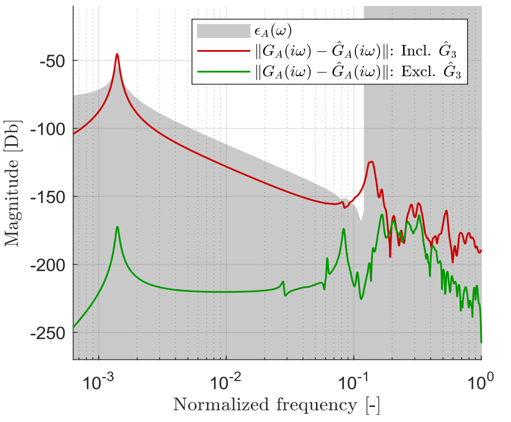
Redesigned module's changes in the FRFs $\|G_j(i\omega) - \hat{G}_j(i\omega)\|$ *and specifications* $\epsilon_j(\omega)$*.*

b. X-stage
The encoder ruler is replaced by a 100 g heavier version. This change satisfies $\epsilon_2(\omega)$ (Figure 6, middle).

c. YZ-stage
A 100 g sensor is added to the capillary tip of the YZ-stage, e.g., to be able to experimentally validate the model. This change does not satisfy $\epsilon_3(\omega)$ for all $\omega \leq 0.12$ (Figure 6, bottom).

4 System integration
Because the redesigned YZ-stage does not satisfy the specification expressed by $\epsilon_3(\omega)$, integration of all redesigned modules does not guarantee satisfaction of the $\epsilon_A(\omega)$. After integration, it can be verified that $\epsilon_A(\omega)$ is indeed not satisfied if the redesigned model for the YZ-stage is taken into account, as can be observed in Figure 7 (red line). If only the machine frame and X-stage are redesigned, then the total redesigned wirebonder design is automatically guaranteed to satisfy the user-defined specification $\epsilon_A(\omega)$, as can also be observed in Figure 7 (green line).



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Redesigned interconnected system's changes expressed by $\|G_A(i\omega) - \hat{G}_A(i\omega)\|$ *for the system, including the Z-stage redesign (red line) and excluding the Z-stage redesign (green line), and specification* $\epsilon_A(\omega)$*.*

With this example, we have considered design changes that change the mass and the mass distribution of individual modules and illustrate that we can locally (i.e., on module level) verify whether this change is allowed with respect to the system-level specification. Similarly, any other design change to the modules can be made and verified locally. Examples of such changes are replacements of parts and components, geometry changes and changes in material properties. Therefore, we are continuing to investigate the full potential of this approach and we strive to publish the underlying scientific results in the near future.

Conclusion

The adoption of a modular redesign approach presents a promising solution to systems engineering challenges for complex mechatronic systems, comprised of multiple interconnected modules. By deriving module specifications from system-level specifications, engineering teams can verify individual module designs independently, streamlining the design process and preventing delays in the development process.

Recent research has demonstrated the effectiveness of a modular approach in managing complexity in interconnected system models, and in this article, we have extended its application to the model-based modular redesign of mechatronic systems.

The introduced framework is demonstrated on an industrial wire bonder. We have illustrated how the proposed redesign framework can achieve decoupling of the (re)design cycles for individual system modules. It shows that design teams can independently verify the validity of their proposed design changes in the light of system-level specifications without the need for the system-level integration.

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