

Methodical Support for the New Development of Cyber-Physical Product Families

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Abstract

The new development of cyber-physical product families currently lacks a methodically supported modularisation approach. This paper provides an approach for module-based mechatronic development, which provides design for future product variety. The state of the art in terms of mechatronic system design and modular product architecture design is presented. A modified V-model is then shown that integrates initial product architecture design and life phase modularisation. The method is applied and evaluated for the development of product family generations of robot units in a teaching course.

Keywords: product families, modularisation, mechatronics, cyber-physical systems, design for x (DfX)

1. Introduction

Emerging technologies promote the progress of digitalisation and enable the transition from classical mechanical systems towards Cyber-Physical Systems (CPS). Furthermore, these systems evolve towards the Internet of Things, which is associated with the global integration of CPS and embedded intelligence (Hehenberger et al., 2016). The shift from product-based to knowledge-based technologies redefines the nature of systems e. g. supply and demand behaviour of global markets and also asks for a redefinition of the design process since the increasing levels of complexity cannot be handled by individuals or even groups of individuals (Hehenberger et al., 2016). While modular product architectures offer a strategy to cope with increasing complexity (Krause and Gebhardt, 2018), (Askhøj et al., 2021), there has been limited focus on modularisation practices and the impact of modularisation on the mechatronic domains of mechanics, electronics and software, and development activities have often been split and still are (Askhøj et al., 2021). A modified V-model for the development of mechatronic product architectures with consideration of technical-functional and product-strategic aspects for modularisation is introduced and the procedure is applied based on a Cyber-Physical Product Family (CPPF) of robot units. The product family is iteratively developed into a modular platform and versioned in a teaching environment and serves as a case study for the methodological approach.

2. State of the Art

This paper aims to provide methodological support for the development of mechatronic systems, taking into account aspects of product variance, modularisation and product generation development. For this purpose, relevant literature in the fields of mechatronics, modular product family development are presented. Furthermore, development iterations are considered and its differences in terms of versions and product generations are described. For the last part, the PKT Approach for Development of Modular

Product Families and its application is presented in order to describe the initial situation of the following development projects.

2.1. Mechatronic Product Development

The field of mechatronics is characterised by the close integration of the interaction from the engineering sciences mechanical engineering, electrical engineering and information technology. The V-model describes the generic development procedure for designing mechatronic systems as a macro-cycle. It has requirements as inputs and products as the output of the development cycle ([Verein Deutscher Ingenieure, 2004](#)).

The V-model has been used as a baseline model for many applications but also for methodological changes. [Zheng et al. \(2017\)](#) present an extended V-model in which they distinguish processes at the macro and micro levels and provide extended support for both levels. The "system design" phase is refined by integrating the steps "requirements specification", "functional model" and "architecture model". A compatibility test is integrated with the right side of the V. If incompatible solutions occur, there is a need for action in the "system design" phase or in the context of discipline-specific design ([Zheng et al. 2017](#)). [Neumann \(2015\)](#) assigned different models to the system design phase. Various system-level models such as function and component structures as well as domain structures could be found and assigned, but specific architecture models are missing. In the next phase, the disciplinary design, cross-domain models could be found, but these are physics-based ([Neumann, 2015](#)) and do not aim at modularising mechatronic structures or architectures.

[Erens and Verhulst \(1995\)](#) follow four elementary design steps in their design for mechatronic product families. After the decomposition of a functional model, the assignment to a technology model is made. Composition takes place in the technology model, which is then validated against the functional model in the final step ([Erens and Verhulst. 1995](#)). The importance of a product architecture becomes clear, but modularisation usually takes place within each domain, with functional modules identified within a functional architecture, technology modules identified within a technology architecture, and physical modules identified for the physical architecture ([Erens and Verhulst. 1997](#)). Both the separate consideration of mechanics, electronics and software during the development cycle and the separation of domains during modularisation are not considered useful. To address this problem and identify cross-domain modules and visualise mechatronic product architectures, [Askhøj et al. \(2021\)](#) present the MESA (Mechanics, Electronics and Software Architectures) tool, which displays the structures of the different development domains and enables connections between the domains, both separately and linked ([Askhøj et al., 2021](#)). A common modularisation strategy in the definition of product architectures is the platform strategy. Technical-functional modularisation methods are classically used for module formation. For the design of modular product platforms for highly integrated mechatronic products, [Schuh et al. \(2016\)](#) present a design method in which the system is broken down into mechatronic functional modules. Following the rules of axiomatic design, a consecutive mapping of customer, functional, physical and process domains takes place. With a strong focus on functional modules, mechatronic modules are formed based on eight generic functions that are used to build the modules. The future product diversity that needs to be handled by the platform is managed by defining degrees of freedom for the design parameters ([Schuh et al., 2016](#)). Concerning the system life cycle, further adjustments were made to the V-model, leading to the model for multidisciplinary product development ([Eigner et al., 2017](#)).

2.2. Product Family Development

Since the terms product variants, product families and versions are used several times, they are briefly defined here. Variants are simultaneously realised technical systems with a high degree of similarity and the same basic functionality. They differ in at least one relevant characteristic. Variants are intended to cover different requirement areas and exist simultaneously. A related set of product variants forms a product family. A version is a precisely defined temporal status of an object within its life cycle. A version has its origin at a defined point in time and is linked to its predecessor and successor in a chronological sequence. Thus, at any given time, there is only one version of an object, but under certain circumstances there are several variants ([Krause and Gebhardt, 2018](#)). The version of a product family

and its subordinate variants are hereinafter referred to as the product family generation (PFG) according to [Küchenhof et al. \(2020\)](#).

Design iterations, product versions and product variants can be handled in different ways. Design for Variety after [Martin and Ishii \(2002\)](#) can be used to assess the change of future requirements and its impact on product components. Therefore, Quality Function Deployment matrices are set up and the Generational Variety Index is calculated ([Martin and Ishii, 2002](#)). [Simpson et al. \(2012\)](#) use this procedure presenting their integrated approach to product family design on the example of Unmanned Ground Vehicles. Changes are not only caused by differing requirements but also occur within design iterations to find suitable solutions. To integrate and harmonise development activities a model-based systems engineering approach can be used. With a focus on data management, [Nattermann and Anderl \(2010\)](#) present an extended V-model - the W-model for the development of adaptive systems. The approach incorporates modelling activities with the System Modeling Language (SysML). The virtual system integration is added to the centre of development activities. While [Nattermann and Anderl \(2010\)](#) differentiate into the hierarchy levels system, subsystem and discipline-specific components, [Barbieri et al. \(2014\)](#) take into account the differentiation into system and module and carry out the method using the example of an industrial filling machine. The division into hierarchy levels is not trivial, as care must be taken in the technical design of the system to ensure that, among other things, the mechanical properties of the overall system are correctly transferred to the individual modules ([Heyden et al., 2019](#)). To reduce existing external complexity induced by different customer requirements, the Integrated PKT Approach for Development of Modular Product Families has been developed. The approach provides methodical guidance for setting up a product architecture with regard to product variety but also technical-functional and product-strategic modularisation techniques ([Krause and Gebhardt, 2018](#)). To support new product development the approach has been tailored towards the initial systems design and demonstrated on the example of the Modular Robot Prototype (MoRty) ([Küchenhof et al., 2019](#)). The prototype has been used as a reference system for the development of the Design Education Platform (DEP) which offers a semi-open platform architecture for the problem-based learning (PBL) course Integrated Product Development (IPE) ([Heyden et al., 2020](#)). Development models that map different design domains support the development of the product architecture. The design domains used are product features, product functions, principle solutions and components, which are jointly modelled in a Feature Allocation Model (FAM). For the initial structure of a product architecture for product variety with the differentiation into standard, variant and specific design elements, see [Küchenhof and Krause \(2019\)](#).

The PFG development from prototype to product family level, resulting in a modular platform approach, was also supported by model-based systems engineering, with relevant data stored in SysML models ([Küchenhof et al., 2019](#)) and analysed using network analysis ([Küchenhof et al., 2020](#)).

3. Methods & Materials

In the following, the modified method is described and the resulting approach explained. Figure 1 shows a modified V-model. As has become clear in the state of the art, the V-model is on the one hand generally suitable for adaptations. On the other hand, the left-hand side is particularly qualified for locating the product architecture, since system models for properties, functions, operating principles and components, but also cross-domain structures have been located here ([Neumann, 2015](#)). Starting with the identification of the relevant requirements, the system architecture is created. For this purpose, the product features are derived from the requirements and the necessary product functions are defined. The product structure is mapped in the product model. By linking the three domains, the product architecture is captured and can be visualised and iteratively improved with the reduced FAM ([Küchenhof et al., 2020](#)). The reduced FAM is used in this case because the principle solutions are mostly domain-specific elements. Hence, they are considered in later iterations of the design in the mechatronic modules, which is the next step in the development. Instead of silo-driven single-domain development, the mechatronic modules already consist of mechanics, electronics and software and must be continuously synchronised. Since system architecture and modular design are inextricably linked, the Modular Architecture in the Loop (MAiL)-system is established which underlines the shared development activities. On the right side of the V, module integration takes place. By testing single components and modules, as well as assemblies and compounds, system properties can be assured. With respect to product variety, the result

of the development project is a CPPF with increasing maturity outwardly, beginning with prototype level in the first design iteration(s).

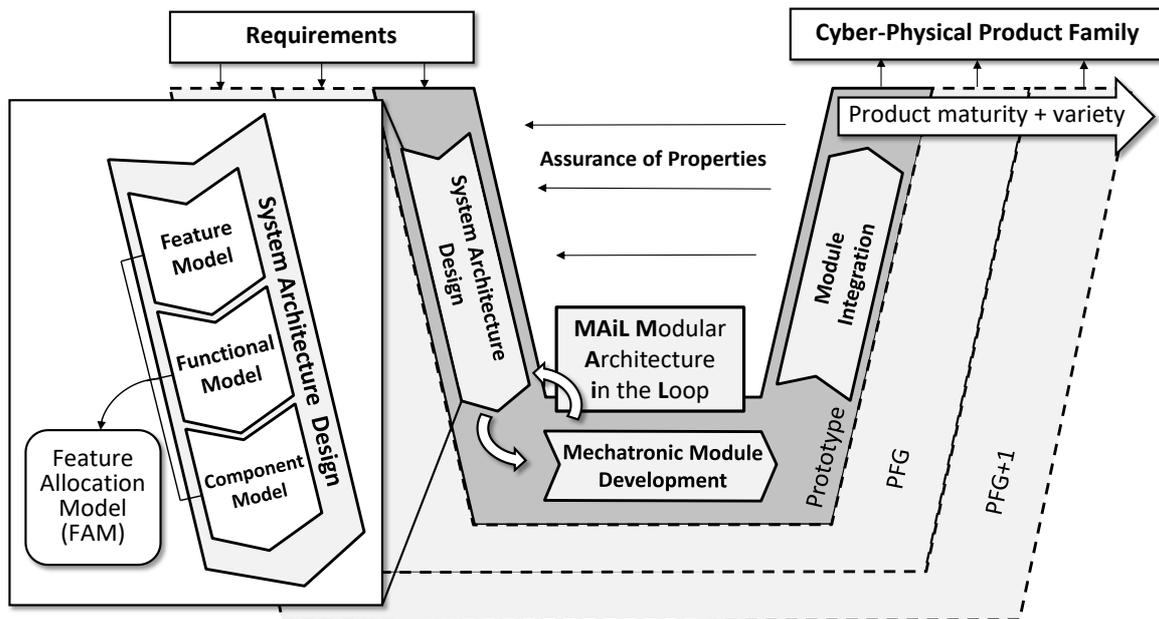


Figure 1. Adapted V-model for the development of cyber-physical product families

The chronological sequence of development activities and the distinction between development and product views as well as versions and variants of the product families are shown in Figure 2.

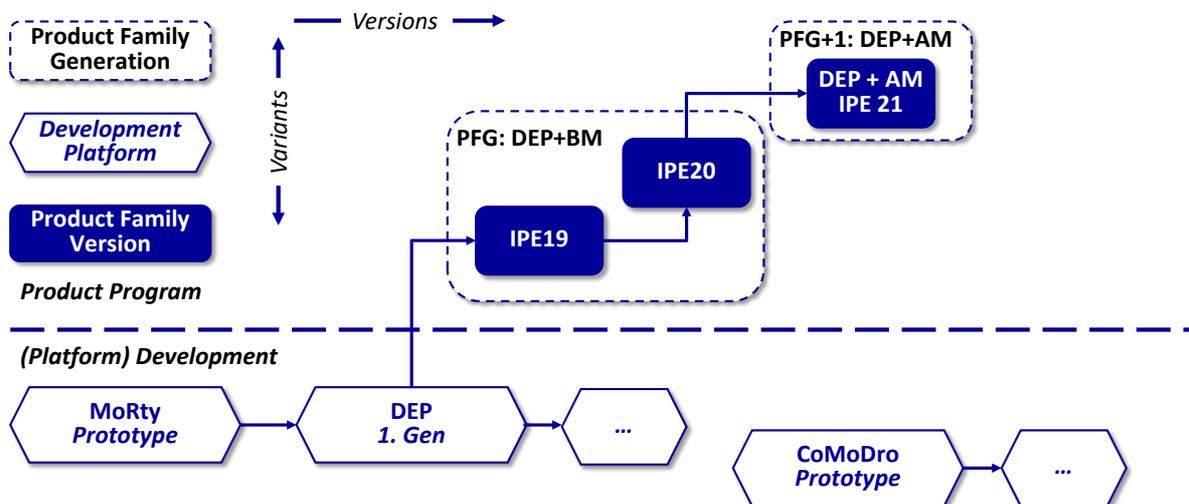


Figure 2. Roadmap of the described platforms DEP and CoMoDro

Figure 2 is divided into development activities at the bottom and the product program at the top. Versions of the PFGs follow the horizontal line while product variants that belong to one version of the PFG are placed on the vertical line. Each PFG inhibits product variants. MoRty represents the prototype within the product family development. With the development of the DEP based on MoRty, the first platform for the product family is created and released for subsequent development activities.

As part of the PBL in IPE course, two versions of the first PFG DEP+BM could be completed in virtual and physical form in the 2019 course year and in virtual form in the 2020 course year. Due to new requirements, a second PFG was used for the 2021 course, leading to the next PFG, PFG+1, in IPE21. While further product variants based on the DEP are being created in the IPE course, a new innovation

platform (CoMoDro) for new applications is being created at the same time on the development side. The novelty of the methodological approach presented is that the initial Design for Variety is carried out first in order to build up the product architecture and prepare a variant-optimised module structure for CPPF. The subsequent modularisation activities are supported by the MAiL system, which is designed to ensure the continuous optimisation and harmonisation of the modular product architecture.

4. Development of a Mechatronic Product Architecture with the Feature Allocation Model

In the following, the results of a product family developed according to the procedure for the development of CPPF is briefly presented. Afterwards, an outlook on the further development of other product families is given.

The DEP is designed for teams of engineering students (for more information about the interdisciplinary course see reference (Heyden et al., 2020)). Based on the platform, the teams develop physical product variants of a robot system and take part in a competition. In addition to learning how to create project plans, apply design theory and methodology, use software tools for CAD, PDM and FEM, teamwork and interdisciplinary skills, specific requirements from the task must be realised in the project (Heyden et al., 2020). The task and the associated requirements change from year to year, which means that new CPS have to be developed to meet these requirements.

The following properties apply to the DEP as the standardised core of the development:

- Standardised connections
- Reliable, close and safe design
- Compact and future robust design
- Technical requirements and specifications

From the described requirements, the product features are derived. These features build the underlying foundation of the general architecture of the product platform DEP. To portray the product architecture of the CPPF with relevant functions and components, a FAM is used. An excerpt of the full FAM is shown in Figure 3.

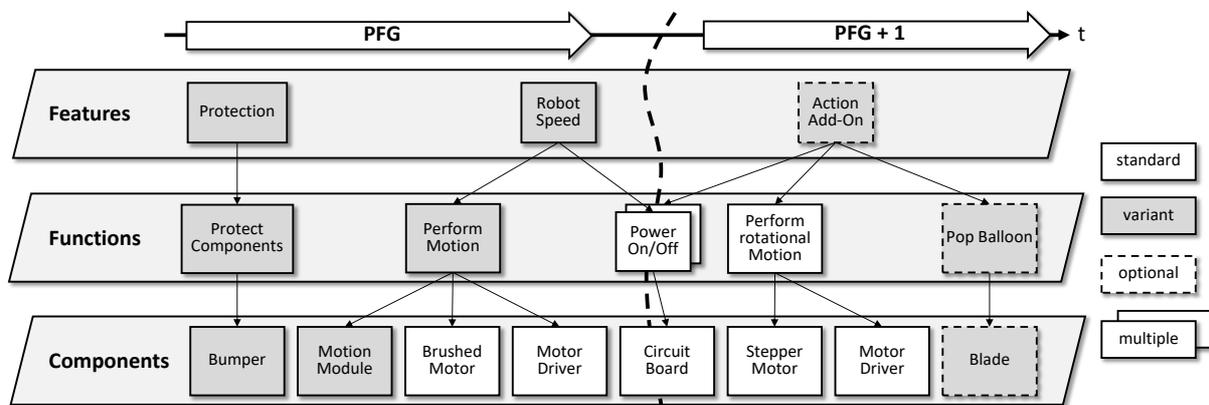


Figure 3. Excerpt of the feature allocation model of the DEP

In this FAM the feature *Protection* is connected to the function of *Protect Components*, which is further connected to the component of the *Bumper*. Hence, the overall architecture can be described in detail linking the three domains with each other and enhancing this information with the variance of all described elements. The FAM is used as a visualisation tool to iteratively adapt and improve the overall product family architecture. Additionally, the progress and planning of new features over the different PFGs is visualised, c.f. Figure 3 with the optional feature of *Action Add-On*.

With the description of the systems architecture, the different mechatronic modules are developed. To establish these modules, different approaches can be used.

4.1. Functional Structure and Modularisation

In Figure 4 an excerpt of the Product Family Function Structure (PFFS) and its environment, after the application of Stone's heuristics is shown. Based on the earlier described functions, it conducts the connection between the different states of the robot and provides an approach to modularise the architecture on a functional level. In the shown PFFS different states of the robot are connected via flows with the corresponding functions to describe the transition of states on a functional basis. All states and functions are augmented with their variance in the product family. Through the usage of different types of flows, the general mechatronic system of the robot can be further described. In this way, not only typical mechanically based flows like *Forces* or *Mechanical Energy* are described but also the flow of *Signal*, which can be located in the domain of information technology. Hence, the connection of various flows throughout the different domains of a mechatronic system is displayed together and thereby increasing the compatibility of the development. Other flows, like *Electrical Energy* or *Material*, are also valid types of flow, but could not be displayed due to the limitation of the provided excerpt.

With this general illustration on a functional level, which involves all domains of the mechatronic product, different modularisation approaches can be applied. One approach to modularise the architecture is by using functional modularisation according to Stone (1997), as is done with MoRty which can be comprehended in Küchenhof et al. (2019).

The modules are defined by using different heuristics, which are encircled in different colours and line shapes in the visualisation in Figure 4.

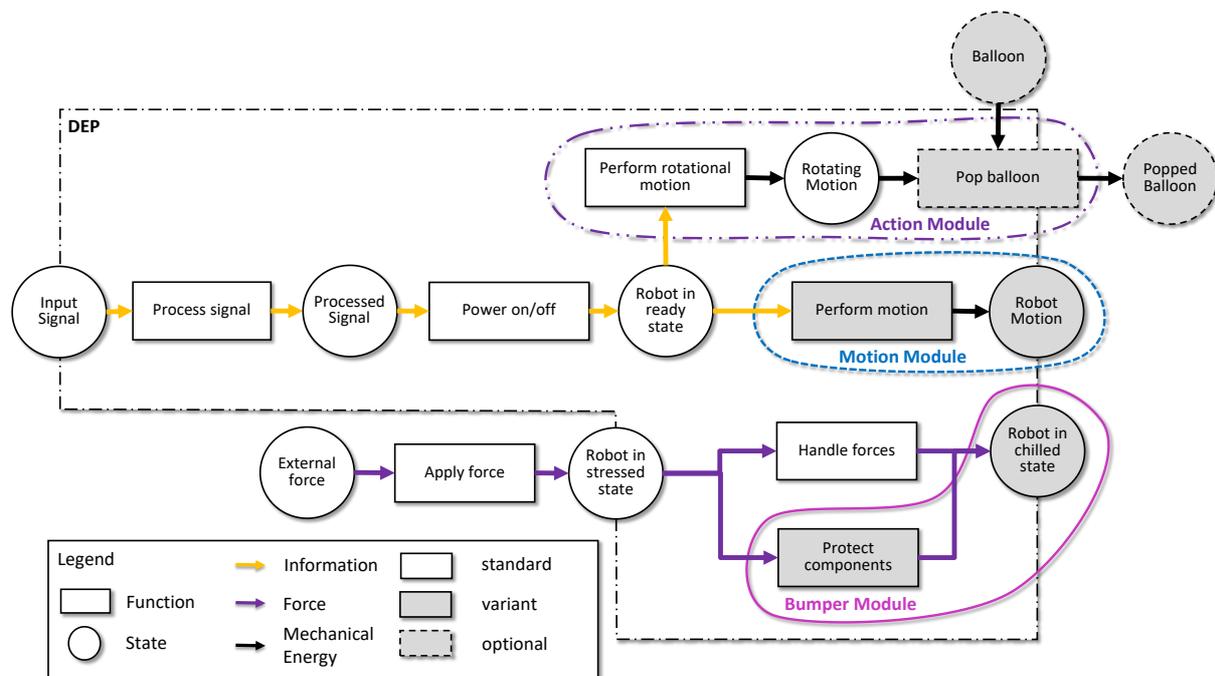


Figure 4. Product family function structure with functional modularisation

Other modularisation techniques can also be applied to the mechatronic structure. One example is the product-strategic life phase-modularisation with help of netplans according to Krause and Gebhardt (2018). Another could be technical-functional optimization with help of the Design Structure Matrix after Steward (1981). To align the different modular architectures and associated perspectives, the MAiL is used. In the MAiL different modularisation results are harmonised and the modular system architecture can therefore be iteratively enhanced.

4.2. Development of the Product Family Structure

To visualise the corresponding product structure based on components of the resulting product family a Module Interface Graph (MIG) is used. Figure 5 shows the MIG of the developed PFG. The MIG is a

suitable tool for visualising product components, their variety, linkages and interconnection flows throughout all mechatronic domains (Gebhardt et al., 2014) and is well established within different design methods of the Integrated PKT-Approach (Krause and Gebhardt, 2018). The white marked parts represent standardised elements, which are combined in this system on one platform, which is the DEP. The parts marked in grey and blue indicate variant (*Motion Module*) and design-specific parts (*Body Module*, *Bumper Module* and *Action Module*), these can be freely designed by the students. As described before, the scope of the product family is to provide a robust platform that is flexibly designable for the students. The requirements for the entire robot system are defined depending on the task to be performed. Since the design class is for mechanical engineering students, the electronic parts and software shares are included in the platform. The focus for the students lies in designing parts in 3D-CAD and structural analysis. The MIG itself is a suitable tool to represent different flows such as forces but also energy and software and can therefore support mechatronic development.

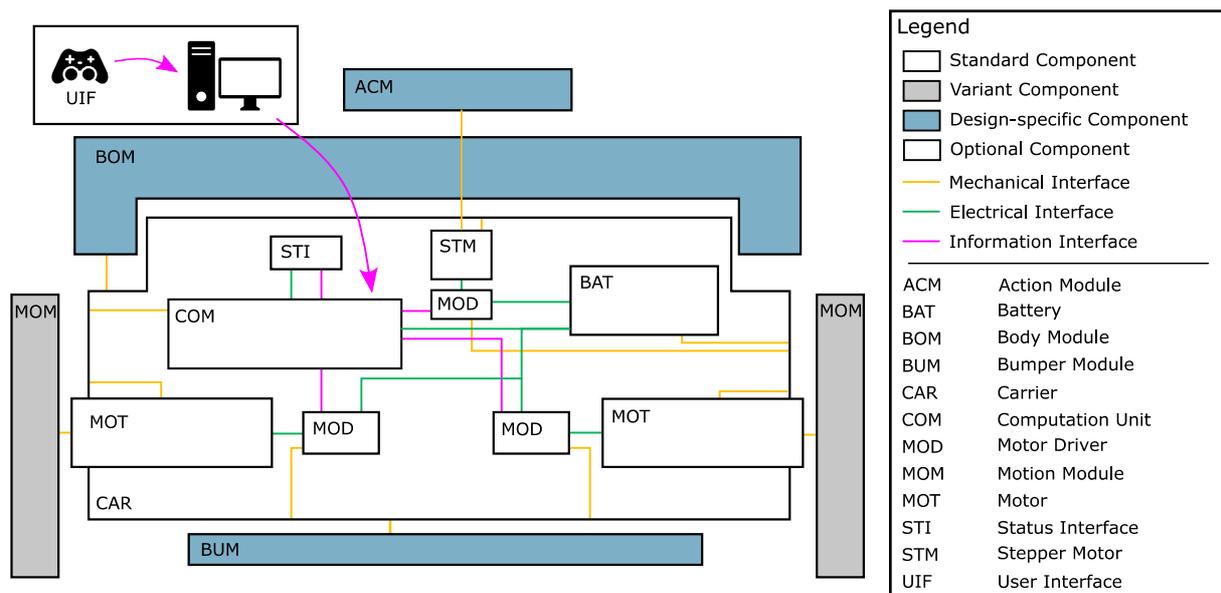


Figure 5. Module interface graph of the DEP adapted from Küchenhof (2020)

With the tools described, the modular product architecture is iteratively developed further and the modules can be jointly designed. Subsequently, the modular system architecture, consisting of its modules, components and respective interfaces, can be integrated to form the final CPPF.

4.3. Design of Product Family Generations

For the students working with the platform DEP, the following requirements apply to the entire robot system:

- The modules must be able to be connected to the standardised connections of the DEP
- Durable structure, that can withstand a collision
- Requirements for additive manufacturability of the attached modules
- Technical requirements from tasks (changes every year) and associated technical specifications

In 2019, the engineering students took part in a race in which the vehicles had to drive through a parkour as quickly as possible. Due to many bottlenecks in the course, collisions were provoked, which is why the focus is particularly on the design of the *Bumper Module (BM)*. The *Bumper Module* had to be designed in such a way that it can push away existing obstacles and opponents on the track. For this purpose, this module was structurally optimised for different load cases using FEM. In 2020, only virtual robot systems were developed. In 2021, the students were given the task of popping balloons as quickly as possible in a parkour; for which the *Action Module (AM)* was introduced. The DEP platform has a shaft for the optional *Action Module*, which is driven by a stepper motor. The arm-shaped modules had to be rotated to reach all the balloons placed and guided so that the mechanism works reliably.

Figure 6 shows the physically developed PFGs based on the requirements that were given to the student teams of 2019 (focus on *Bumper Module*) and 2021 (focus on *Action Module*). The robotic systems can be viewed in physical use in the parkour under the following references ([Youtube, 2019](#); [Youtube, 2021](#)).



Figure 6. Physical products for the DEP with the bumper module and with the action module

4.4. Findings on the Future Product Family of Drone Units

Building on the experience gained in the development of the DEP and the resulting PFGs, a further product family is to be designed. In this new CPPF drones are developed. With this development, the degree of freedom is rising. This introduces an increase in the complexity of motion of the system, which will make more simulation effort necessary. The Connected Modular Drones (CoMoDro) are developed to provide a modular platform for interconnected drones, which can be used in a swarm for surveillance and sensor measurements.

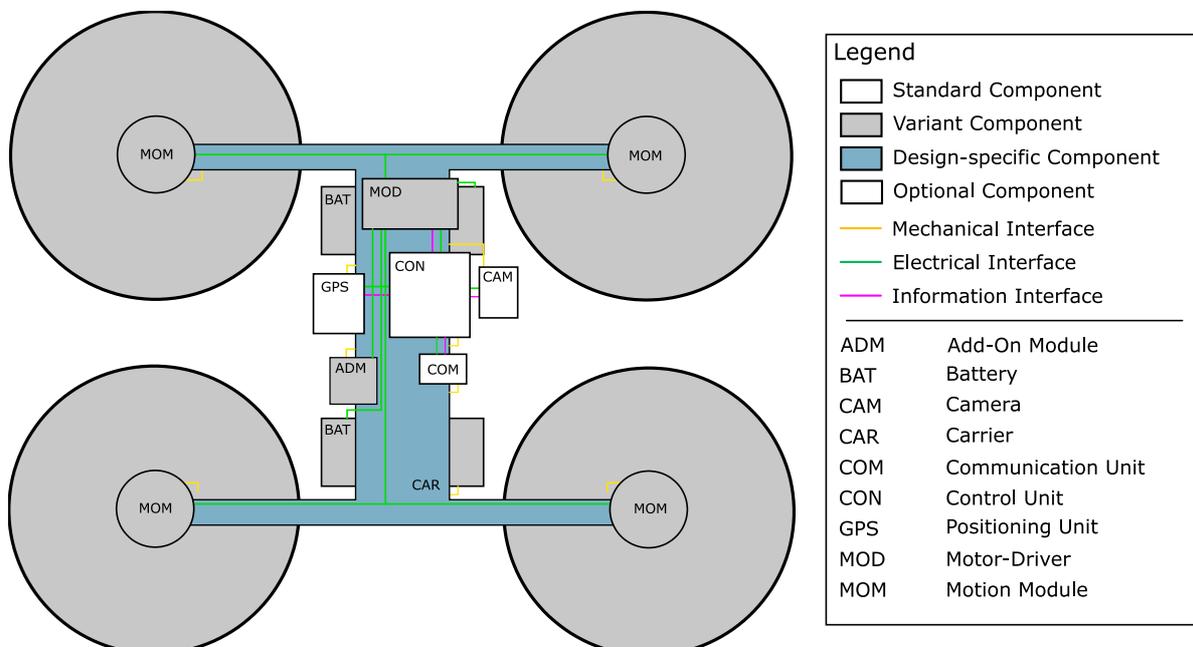


Figure 7. Module interface graph of the CoMoDro development prototype

The current development of the CoMoDros is in a prototype state. According to the described steps, the modular mechatronic architecture is now under development. In Figure 7, the current MIG of the

CoMoDro is shown. It gives a brief overview of all components and their connections and interactions. Figure 8 shows the physical realisation of the prototype in its flight-ready state.



Figure 8. Physical realisation of the CoMoDro

5. Outlook and Conclusion

This paper provides methodological support for the new development of CPPF based on modular product architectures. The presented approach extends the existing V-model by a modular product architecture design with the possibility of the use of technical-functional as well as product-strategic modularisation approaches. The developed modular platform is suitable for the design of different product variants and results in PFGs through necessary design iterations, which are also considered in the extended V-Model. The development of PFGs according to the presented method is then applied and evaluated on the example of robot units based on the DEP and it could thereby be shown that the approach is suitable for the initial product architecture design for CPPF.

In the future, the realised prototype of the CoMoDro will be equipped with different sensors for different applications and a modular product architecture will be developed to enable the development of future product variants. Depending on the task within the growing swarm of robots, different module variants may be necessary. For this purpose, different variants with different product characteristics will be designed based on the presented prototype to form a product family and thus realise a large autonomously communicating and coordinating drone swarm. Ultimately, a platform architecture can be developed, as has already been successfully done for the DEP, and a new PFG with new possibilities and functions and variants can be made possible for future courses. To subsequently use the product family for educational purposes, the same methodological procedure can be applied as for the development of the DEP, which was already presented in [Heyden et al. \(2020\)](#) and [Küchenhof et al. \(2020\)](#).

In addition, the DEP can also be extended to provide more tasks for the student teams. Perhaps by driving on different surfaces or performing different measurement tasks. The new requirements could make a new platform generation necessary and thus lead to a new PFG for the ground units. To realise new functions, new technical solutions may be necessary, which in turn require the redesign of components of the design of the electronics (e. g. through new sensor technology) and associated changes to the software. A harmonised system architecture that coordinates the interaction of the three domains, but also allows room for new technological integrations, is the goal of this modularisation strategy. Digital possibilities offer great potential for the functional expansion of the CPPF.

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