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Sensitivity Analysis Framework for the Evaluation of Modular Drivetrain Architectures

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***Abstract*—Modular drivetrains have already been introduced in literature as an approach to deal with load variations and provide an easily adaptable machine design. Although some research regarding the performance of a modular drivetrain has already been performed, a method to evaluate and compare several modular drivetrain architectures on multiple performance criteria is not yet available. This paper presents a sensitivity analysis framework that can be used to evaluate the different architectures against each other and to make a comparison with the traditional benchmark alternative. A benchmark case of a single motor driven shaft with variable loads and a dynamic speed profile is used to illustrate the functionality of the framework. Two modular variants of the benchmark system are presented. From the evaluation, the modular architectures are found to outperform the benchmark case regarding energy consumption and tracking error. However, a cost increase is observed. The trade-off between the additional investment cost and the increased performance can be assessed using this sensitivity analysis framework.**

***Index Terms*—Modular drivetrain, Simulation, Mechatronic systems, Sensitivity analysis**

I. INTRODUCTION

The design of industrial machines is often restricted by specific objectives, meaning that the machine performance is optimized for explicit process rates [1]. Alterations are often challenging to obtain or lead to a reduction in performance. More flexible drivetrain architectures that can handle different load cases are however more favourable in modern manufacturing [2], where flexibility implies that the architecture enables to easily create power or speed variants of the drivetrain. Rescaling of the mechatronic system does not require a new design each time. By using standardised components and implementing such a design approach, engineering cost and time are reduced [3].

Modularity is brought forward in literature as a possible solution to handle the need for flexibility [4], [5]. Modularity is defined by [6] as repeating several identical modules to form the drivetrain. Such a module consists of an electric motor and its power electronic converter and a mechanical drivetrain that can interact with other modules or a load.

Modular drivetrains obviously influence the machine performance. It has already been investigated to some extend. [7] provided a method to identify key system parameters to perform accurate simulations regarding modular drivetrains. In [8], the need for a proper control strategy to mitigate torsional vibrations in such architectures was explored, while [9] showed promising results on motion dynamics and failure tolerance of a modular drivetrain. One disadvantage of modularity is that the amount of components in the drivetrain increases and thus the chances of a component failure increases. However, the modular approach reduces the impact of a single failure and the design should allow the machine to keep working, at a lower power or speed rate if necessary, until maintenance can be planned.

The implementation of modular designs can already be found in several industries, such as weaving looms [10], crane applications [11], wind turbines [12], electric vehicles [13] and power electronics [14]. However, easily evaluating those modular drivetrains against the current benchmark architecture is not yet possible. A framework to compare different architectural designs on several key performance indicators (KPIs) is presented in this paper. A simple benchmark case of a single motor driven shaft with variable loads and dynamic reciprocating speed profile is chosen to highlight the functionality of this framework.

This benchmark application is selected because it is an excellent use case where modular drivetrains could outperform the standard application due to the presence of a slender shaft in the system. As slender shafts are susceptible to torsional vibrations, mitigation of these vibrations is required [15], [16]. By partitioning the shaft with multiple cascaded actuators, beneficial results where found by using soft start procedures [17]. However, the usage of multiple motors requires synchronisation of the actuators to maintain performance [18], [19]. Furthermore, actuator torque input is an important source of torsional vibrations in a mechatronic system. Interleaving has been successfully used to reduce the torque ripple [8], [20].

Additionally, adequate synchronization across the driveshaft needs to be maintained. Therefore, the shaft requires to have sufficient stiffness in order to avoid undesired torsional displacements. A traditional method to obtain this stiffness, is through using a thick shaft that provides the required mass and inertia in the drivetrain [21]. When using this strategy in a continuously rotating process, the added mass creates a highly robust system. On the other hand, this design has the drawback that the dynamics of the system are very limited. Changing the speed, or positioning profile, is difficult and often impossible. For some applications, instead of using a continuously rotating shaft, a reciprocating motion would be more desirable. Nevertheless, because of the slow dynamics of the system, this is not possible with the traditional design. A modular drivetrain could provide a solution on this matter.

The remainder of this paper is structured as follows. Section II describes the load case application and some modular architecture variants that are considered. Section III explains the sensitivity analysis framework methodology and how it is implemented for the use case. In Section IV the different architectures are compared through the framework. Finally, Section V concludes with an overview of the findings.

II. MODULAR APPLICATION ARCHITECTURES

Research about modular drivetrains suggests that these could offer some benefits over a similar benchmark architecture. To investigate these claims, a relevant test case is used. The application, shown in Fig. 1, is made up of a 1.4 m long shaft on which two variable torsional loads are applied. In the benchmark case, illustrated in Fig. 1a, a single motor is used to drive the application. This motor is connected to the shaft through a flexible coupling.

The long shaft and coupling result in some flexibility in the system. Therefore, in a high dynamic load application, some torsional displacement across the shaft is expected. This could result in synchronization issues. To cope with this, a stiffer and heavier shaft could be used. But this will reduce the dynamic characteristics of the application and increase the required energy consumption.

As previously mentioned, modularity could help to mitigate the drawbacks of the current machine design. Two drivetrain variants are proposed. The first drivetrain, shown in Fig. 1b, introduces a second actuator to the opposing end of the driveshaft. By adding an additional input, actuation torque is distributed from both ends which should result in a more balanced torque input across the shaft. As the required torque through the driveshaft decreases, the diameter could be decreased to maintain the same level of allowed displacement and the system behaviour will become more dynamic.

A second modular alternative is depicted in Fig. 1c. In this case, a similar approach is taken but now three actuators are used. This further distributes the actuation torque and therefore an even more slender driveshaft could be used. This results is a high dynamic drivetrain that can handle the variable load and speed better than the robust benchmark case.

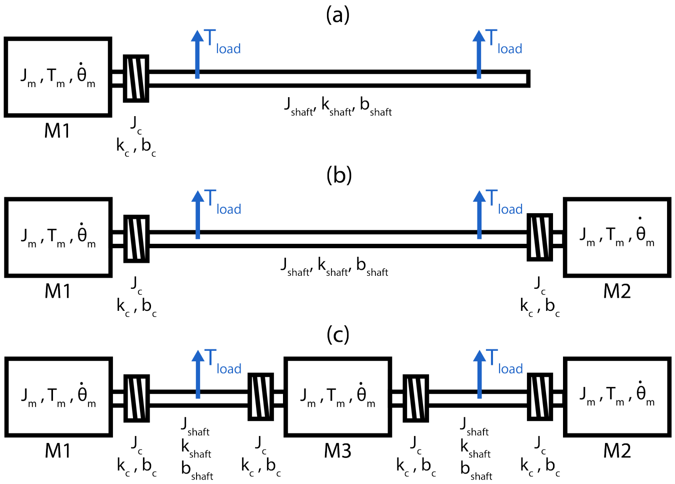

Fig. 1. Schematic overview of the drivetrain architecture variants of the application. (a) Benchmark; (b) Modular, 2 actuators; (c) Modular, 3 actuators

III. SENSITIVITY ANALYSIS FRAMEWORK

A. Overview

To compare and evaluate the drivetrain variants, a sensitivity analysis framework, displayed in Fig. 2, is developed to provide a structured guideline. The framework ensures that each architecture can easily be evaluated against the same criteria.

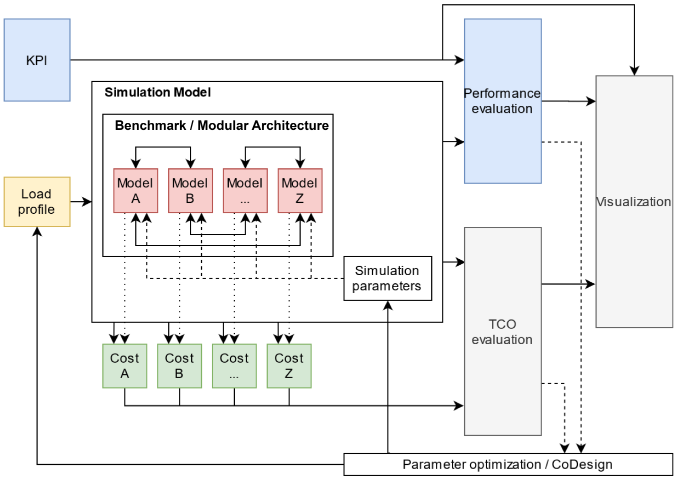

Fig. 2. Sensitivity analysis framework for modular drivetrain architectures. Each modular architecture and benchmark is built up around the component models, e.g. Model A. All architectures are simulated with the same load profile and KPIs are evaluated. Visualisation is possible through the spider plot functionalities.

The framework is constructed around four input categories. First, evaluation criteria are defined as KPIs to analyse different architectures. Various KPIs can be used, depending on the modular system under investigation. The sensitivity analysis framework currently contains generic criteria for mechatronic systems, such as investment cost, root mean square (RMS) and maximum torque and energy efficiency. Furthermore, some specific indicators are also included: positioning tracking error, speed error and torsional vibrations.

As a second input, the simulation models of the modular architectures are built with component models, indicated in Fig. 2 in red as Model A, B, etc. These component models, e.g. a motor, driveshaft model, can accurately predict the behaviour and are scalable to different system sizing. All modelling is performed using Matlab Simscape [22].

Third, cost models are linked to each component model to compare the investment cost. The architecture cost is calculated as the sum of all component costs. Exact pricing is however difficult to predict. Therefore, a relative comparison between the total investment cost of different architectures is used.

The final input category contains industrial load profiles that are relevant to compare the drivetrain behaviour. Each architecture is simulated using the same load case. System behaviour under the same conditions is evaluated. By using different load profiles, other drivetrain behaviour can be analysed. For example, one system might give better results in a continuous rotating operation, while another shows its advantages in a reciprocating motion.

By using this sensitivity analysis framework, each architecture is simulated. Initial evaluation can be done through the visualization tool that generates a spider plot figure to compare each architecture on all KPIs. Furthermore, optimization algorithms can be implemented to optimize design parameters. For example, the dimensioning of the shaft thickness in relation to the number of modules could be optimized through the evaluation framework.

B. Implementation on modular application

To demonstrate the functionality of the sensitivity analysis framework, a comparative evaluation of the application and the modular drivetrain architecture variants from Section II is performed.

To compare the architectures several KPIs are selected. The first criteria of interest that is selected is cost. It showcases the investment needed for certain performance gains. Second, the RMS torque is calculated. RMS torque can be used to provide insight in the energy consumption of the application, which is of high importance to calculate the operational costs. Combining both investment cost and RMS torque values can be used to estimate the return on investment (ROI). The tracking error across the driveshaft is a third performance indicator of interest for this specific application. By analysing the maximum tracking error, insight in the accuracy of the process can be found.

For evaluation of the KPIs, the architectures are all modelled using Matlab Simscape. The architecture model is created with the scalable component models for each drivetrain component. The Simscape library and custom-made parametrized models are used. The driveshaft and couplings are modelled as inertia-spring-damper systems that interconnect the actuators and loads. The motor controller is modelled as a standard PI speed controller. Motor inertia is modelled according to datasheet information.

The benchmark architecture uses a single servomotor with a nominal torque of 15 Nm. The other architectures are scaled down to match this total torque input (i.e. 2 motors of 7.5 Nm and 3 motors of 5 Nm respectively). Motor inertia is scaled down according to the datasheet information. The dimensioning of the shaft diameter can be calculated according to (1) [23]. With d the shaft diameter, T_{max} the maximum load torque and τ_{max} the allowed shear stress in the shaft. For first evaluation, the shaft dimensions are kept equal to the benchmark architecture in each architecture. However, the amount of torque that needs to be transferred by the shaft reduces when adding the additional actuators. Therefore, in a second simulation this dimensioning will be scaled down according to the resizing based on the actual torque in each architecture. Reducing this shaft diameter will create a less stiff application, but it will also help to reduce the total inertia that needs to be accelerated, thus helping to reduce the energy consumption of the system.

$$d \geq \sqrt[3]{\frac{16T_{max}}{\pi\tau_{max}}} \tag{1}$$

For each of the components, a scalable cost model is used to compare the investment cost of each architecture. Manufacturers price data is used to create the scalable cost functions. The scaling is performed based on the most important dimensioning data of the component, e.g. motor price is scaled based on output torque. As prices are volatile, and can be very different for different manufacturers, a relative comparison is used to give a more generic evaluation.

To examine the functionality of the different drivetrains, a set of external forces and process loads is required. For the setup under investigation, a high dynamic load case is chosen to represent an industrial application. The following motion profile cycle is selected. A rotation of 360 degrees of the shaft in 0.05 s, followed by a waiting period of another 0.05 s. This cycle is repeated continuously as shown in Fig. 3a. The rotation is performed through a 1/3 motion profile, meaning that during the first third of the motion the shaft is accelerated, during the second third of the motion a constant speed is maintained and in the final third the application is decelerated. During the rotation a variable load torque is applied to the shaft at the outputs shown in Fig. 1. The torque changes based on angular position, as shown in Fig. 3b.

IV. RESULTS AND DISCUSSION

The presented architectures from Section II are compared through the framework according to the load case presented in Section III to showcase the capabilities. A first simulation comparison of the three architectures is performed without rescaling. Only the motor inertia is updated and the required additional couplings are inserted. The shaft thickness remains constant for each simulation. An overview of the comparison results is shown in Fig. 4 and Table I.

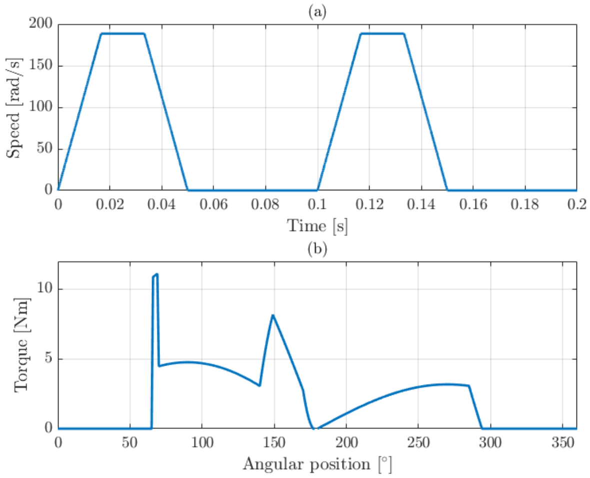

Fig. 3. Load case used during simulations. (a) 1/3 motion profile to implement a full rotation in 0.05 s and a 0.05 s waiting period. (b) Load torque applied on the drivetrain during a full rotation in each of the two outputs noted in Fig. 1.

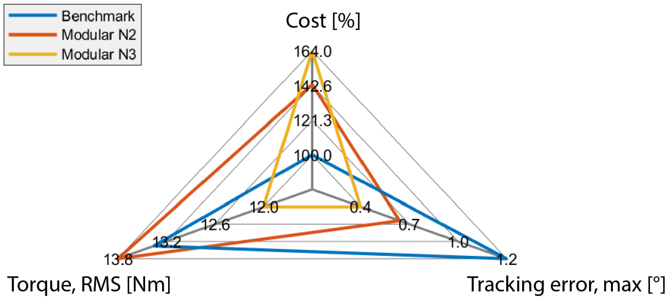

Fig. 4. Overview of simulation results for each architecture on all KPIs.

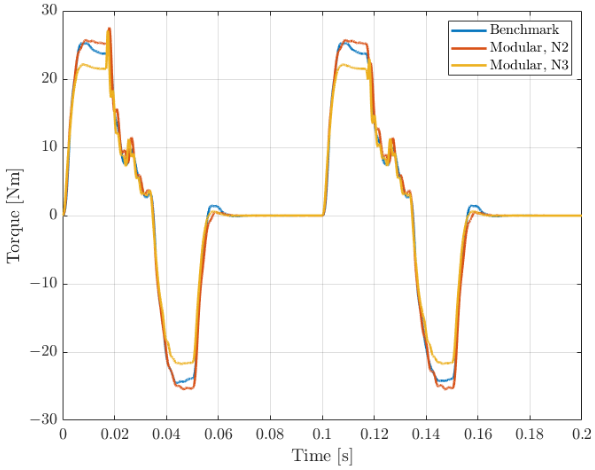

Fig. 5. Comparison of total torque output in each architecture of all motors combined.

At first, cost is observed. As anticipated, the usage of modularity increases the investment cost of the drivetrain significantly. Adding an additional actuator, and motor controller drive, requires an additional 43 % investment. For a setup with three modules, this additional cost is 64 %. Multiple smaller actuators and electric drives are more expensive than a single larger motor and drive option. Secondly, the required torque to run the application is observed. The RMS torque for the benchmark case is 13.4 Nm. For the modular architecture with 2 motors, the torque actually increases slightly to 13.8 Nm. This is caused by an increase in total inertia of the application. The modular case with 3 motors performs slightly better, and reduces the RMS torque to 12 Nm, because the long shaft is replaced by a motor and shorter shafts, which reduces the total inertia. When observing the torque in Fig. 5, it is clear that accelerating (first third of the action phase, 0 s - 0.016 s) and decelerating (last third of the action phase, 0.033 s - 0.05 s) the application with 3 motors is slightly easier, thus resulting in a slightly lower RMS-value. Here it is also clear that torsional vibrations increase caused by the varying load torque when using modularity. As these are still within bounds and don't cause problematic oscillations, no attempts are required to mitigate them.

A third KPI that is investigated is the positioning error across the drivetrain. In the benchmark application a maximum tracking error of 1.23° is observed at the second output. Here the modular cases already show their advantage. The modular N2 setup, reduces this maximum error with 50 % to 0.63°. The setup with 3 motors performs even better with a reduction of 67 % to 0.4°. It can thus be concluded that modularity gives beneficial results in the synchronization of the application.

In these presented results, modularity already shows some benefits. However, without rescaling the entire application, the full benefits are not yet visible. Since modularity uses multiple motors, the torque distribution across the mechanical drivetrain is improved. This means that the shaft can be made thinner, because the overall torque each part of the shaft needs to transfer decreases. In the first simulations, a shaft with a diameter of 36 mm was used for each setup. By reducing the shaft thickness, a more dynamic application is created that can offer even better results. After rescaling through (1), a shaft of 29 mm is used in the modular N2 case and a shaft of 25 mm is used for modular N3. The results are shown in Fig. 6 and Table I.

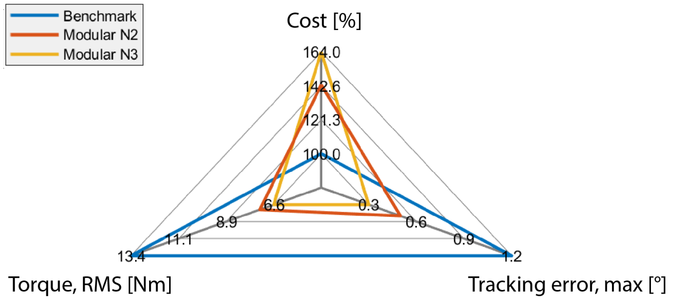

Fig. 6. Overview of simulation results for each architecture on all KPIs. With rescaled shaft for the 2 and 3 motor setups.

The impact on investment cost is limited, but a big improvement in RMS torque is visible. In this case, the 2 motor setup reduces the RMS torque with 45 % to 7.3 Nm. The modular N3 setup performs even better at 6.6 Nm (-51 %). From Fig. 7, it is clear that the reduction in mass has a massive improvement on the required acceleration and deceleration torque. However, the vibrations are more visible but remain stable. Another observation that can be made is that the current motor sizing, based on the benchmark, is no longer valid. Since the benchmark motor was dimensioned at an RMS torque of 15 Nm, the modular cases are now oversized. By reducing the sizing, the total inertia will further reduce and the cost can also be cut.

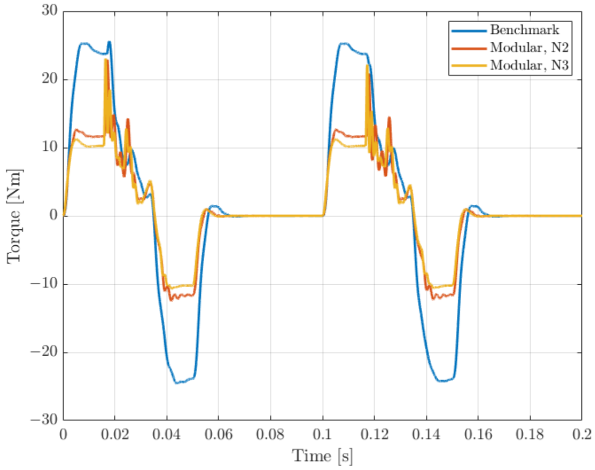

Fig. 7. Comparison of total torque output in each architecture of all motors combined for the simulations with rescaled shaft.

On the tracking error, again, an improvement is made. In this case, the 2 motor setup has a maximum tracking error of 0.54° (-56 %) and the 3 motor setup performs even better with 0.34° (-73 %).

Since the modular applications were oversized, a new iteration is made with rescaled motors based on the new RMS torque. The results are plotted in Fig. 8 and an overview of the results can be found in Table I. First, since total inertia is further reduced, RMS torque also decreases. Now the 2 motor case only requires 6.9 Nm (-49 %). The 3 motor setup reduces the RMS torque with 56 % to 5.9 Nm. Thus giving a slightly better result than the previous sizing. Second, cost of the motors and drives is reduced compared to the first sizing. The modular N2 case is now 32 % more expensive than the benchmark (previously 43 %). The modular N3 design increases investment cost with 55 % (previously 64 %). Thus making the investment in a modular setup smaller, and more accessible. Finally, the reduced inertia makes the drivetrains once again more dynamic, which results in a further reduced tracking error. Now the 2 motor drivetrain has a maximum positioning error of 0.46° (-63 %) and only 0.29° (-76 %) for the 3 motor case.

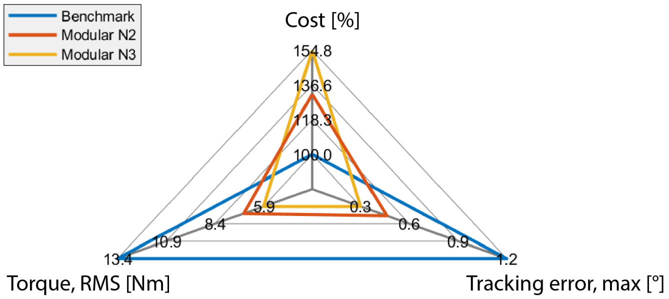

Fig. 8. Overview of simulation results for each architecture on all KPIs. With rescaled shaft and motors for the 2 and 3 motor setups.

To further evaluate these results a comparison between cost and the other KPIs is made in Fig. 9. Here a clear observation can be made of the impact of an additional financial investment on the performance of the drivetrain. By moving from a single motor setup to 2 actuators, a big improvement on the performance is made. Going to a 3 motor setup, both cost and performance gain still increase. However, the impact on performance becomes less pronounced.

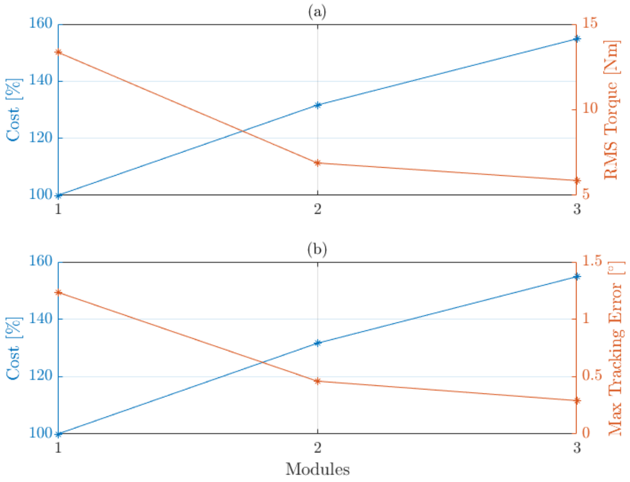

Fig. 9. Comparison of investment cost with different KPI, (a) with RMS torque and (b) with maximum tracking error.

V. CONCLUSION

Literature mentions modularity as a new design approach for electromechanical drivetrains. The impact on the drivetrain performance is however still underexposed. A methodology to evaluate modular architecture alternatives on KPIs and the sensitivity on design choices is yet unavailable.

This paper presents a sensitivity analysis framework that is implementable on evaluating several types of mechatronic systems and compare different drivetrain designs, based on selected KPIs such as tracking error, cost and RMS torque requirements.

This methodology is elaborated through a high dynamic use case with variable load and dynamic speed profile. Modular

TABLE I

OVERVIEW OF SIMULATION RESULTS. FIRST DATA COLUMNS SHOW THE RESULTS WITHOUT RESIZING OF THE SHAFT. THE SECOND DATA COLUMNS DEPICT THE RESULTS WITH THE REDUCED DRIVESHAFT SIZING. THE THIRD DATA COLUMNS GIVE THE RESULTS WITH THE RESIZED MOTORS FOR THE SLENDER SHAFT.

	Benchmark	Modular 2			Modular 3		
Cost [%]	100	143		132	164		154
Torque, rms [Nm]	13.4	13.8	7.3	6.9	12.0	6.6	5.9
Tracking error, max [°]	1.23	0.63	0.54	0.46	0.40	0.34	0.29

architecture variants are suggested. Through the sensitivity analysis framework, it is exposed that increasing the level of modularity, i.e. adding additional actuators, results in an increase in investment cost. However, this increase in cost results in a performance improvement. RMS torque requirement, and thus energy consumption, was reduced with up to 56 %. Furthermore, tracking error is significantly decreased, up to 76 %.

The sensitivity analysis framework outputs a lot of information on several KPI which an industrial manufacturer could easily use to evaluate the different architectures. The impact of an investment on several performance indicators is easily examined. The added performance improvement for the application, e.g. energy consumption, dynamic error, will determine which level of modularity is most suitable and economically viable.

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