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Integrated Structural and Controller Optimization for Lightweight Robot Design

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***Abstract*— With the development of humanoid robots, lightweight construction and energy efficiency play an important role. In state-of-the-art processes and methods concerning structural optimization it is assumed that there exists a set of external loads or load functions acting on the part. But humanoid robots are very complex mechatronic systems. The fact that the system's dynamic properties and its overall behavior may change due to geometric modifications of a part caused by an optimization process is typically neglected. In order to take into account the interaction between the part, dynamic system, control system and the changing mechanical behavior with all its consequences for the optimization process, a simulation of the complete mechatronic system is integrated into the optimization process within the research work presented in this paper.**

A hybrid multibody system (MBS) simulation, that is, a MBS containing flexible bodies, in conjunction with a co-simulation of the control system represented by tools of the Computer Aided Control Engineering (CACE) is integrated into the optimization process. By an inner optimization loop the controller parameter are adopted new in each iteration of the topology optimization in order to provide realistic load cases. The research work presented in this paper is a contribution towards the integration of existing CAE methods into a continuous process for structural optimization. The benefits will be illustrated by an optimization of parts of the humanoid robot ARMAR of the collaborative research centre for "Humanoid Robots". The new process allows an efficient optimization of structures "within" their surrounding mechatronic system.

I. Introduction

Today, the usage of simulation tools is common practice in many fields of product development. Finite element analyses (FEA) are widely used regarding mechanical components, for example. MBS simulation is used to investigate the dynamic behaviour of mechanical and mechatronic systems. The integration of body elasticity led to more realistic MBS simulations and information about loads acting on bodies for structural analysis and optimization. Combining MBS with tools for the simulation of control systems allows the efficient simulation of mechatronic systems. E. g. Co-simulation [1] approaches allow to couple solvers for the mechanical and the control part of the system. Additionally structural optimization methods play an increasing role in product development. Topology optimization, for example, is widely used to derive design proposals for structural parts in early development stages [2]. By integrating MBS simulation into structural optimization processes bodies in dynamic systems can be optimized regarding the interaction between the body's mechanical properties and the overall system dynamics [3-5]. This integration of MBS simulation enabled also a new shape optimization of dynamically loaded parts with respect to fatigue [6], using a new homogenization criterion derived from the system behavior. A further extended topology optimization scheme integrates a controlled MBS simulation into the optimization process [7]. The scheme allows the topology optimization of a body within a MBS taking all emerging loads and the effects of the control system into account. In this paper the extended scheme is extended again by an inner optimization loop for the controller parameters. These parameters are adopted in each iteration of the topology optimization in order to provide realistic load cases during the whole process of structural optimization. In the future the presented methodology will be applied within the development of the next generation of the humanoid robot ARMAR [8] in order to meet the lightweight requirements.

II. Basic Concepts and Simulation Setup

In order to perform a structural optimization of a mechanical component within a dynamic and controlled system an appropriate simulation setup is necessary. The main idea for the work presented in this paper is to use state of the art software tools that are also used in industrial application as a basis and to add new elements or modules for new functionality.

A. Topology Optimization

Topology optimization is used for the determination of the basic layout of a new design. A new design is determined based on the design space available and the loads acting on the part. Today topology optimization is very well theoretically studied [9] and also a very common tool in the industrial design process [2]. The designs, obtained using topology optimization are considered as design proposals giving a assistance during the implementation of the corresponding CAD-model. The standard formulation in topology optimization is often to "minimize the compliance of the structure" corresponding to "maximize the stiffness" using a mass constraint. For the application of a topology optimization, a FEA must be carried out in each iteration of the optimization. From iteration to iteration the properties of each Finite Element (like Young's Modulus and density) are modified until the optimization objectives are fulfilled. Efficient algorithms like the well known Optimality Criteria

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based optimization algorithms are able to handle a huge number of Finite Element properties as design variables.

B. Hybrid multibody systems

Multibody systems are of great importance for the simulation of dynamic systems. For the structural optimization of parts in controlled dynamic systems - e.g. humanoid robots - the MBS is used to derive the loads acting on the mechanical components. As the interaction between components and system behavior including the effects of the control system shall be taken into account, there are particular requirements. The integration of both, the FE models and the control system, is necessary. Besides that, an appropriate interface for an automatization of the whole process is needed. Hybrid MBS are a combination of classical FE and MBS approaches. These "flexible MBS" are applied if the elastic behaviour of bodies in a dynamic system is of interest. If non-linear effects within the elasticity of a body are not relevant (e.g. only small deformations), the body's elastic behavior can be modelled by means of a component mode synthesis (CMS) approach as suggested by Craig and Bampton [10]. The deformation u of the deformed body is approximated at the time t as a weighted sum of the constant pre-computed shape functions $\boldsymbol{\varphi}$:

$$\mathbf{u}(t,\mathbf{r}) \approx \sum_{i=1}^{N} c_i(t) \cdot \boldsymbol{\varphi}_i(\mathbf{r}) \qquad (1)$$

The time dependence of the deformation is contained only in the modal amplitudes ci(t). As a consequence the number of DOFs can be significantly reduced, which allows an efficient MBS simulation. Within the structural optimization, the necessary FE representation for the optimization module can be used for the reduction.

C. Feedback control and multibody systems

For the simulation of mechatronic systems it is necessary to consider mechanical aspects as well as the behaviour of the control system. In the last years the abilities to simulate mechatronic systems within commercial software became more important. When using such an integration of control systems in a mechanical model or vice versa, today there is only a limited range of functionality in commercial program systems. E.g. the integration of complex FE-models in tools of Computer Aided Control Engineering (CACE), which is necessary for the topology optimization of parts, is not possible in an appropriate manner.

Therefore the usage of both, CAE and CACE tools, is necessary. In the field of this type of coupled simulations, one can distinguish mainly a tight and a weak coupling of the two domains as proposed by [11]. In case of a tight coupling all the sub models are integrated into one complete model. The equations are solved by one single solver. As solvers typically are developed especially with respect to one domain's specific requirements and properties, there are limitations in the possibilities to extend their application to more complex domains. The state of a system can be described by means of a set of differential equations which enables e.g. an exchange by using state matrices. By defining the input and output parameters in a mechanical system e.g., it is possible to release the matrices after a MBS simulation. Linear or linearized systems are required in this case. Another way proposed by [11] or [1] is the usage of symbolic code interfaces or function call interfaces. In that case sets of nonlinear differential equations are generated from the nonlinear MBS or the control system. When using Matlab/Simulink for control simulation, the integration of the mechanical system can be integrated as compiled s-function using certain interfaces. Mack [12] showed that these methods are not always suitable for complex mechanical models within the simulation of chassis and suspension systems. A co-simulation as a weak coupling provides the opportunity to consider non-linear effects in complex systems. Equations of the mechanical and control system are each solved by an own solver, which is suitable for it's respective domain. At a discrete time of the simulation, the data is exchanged between the solvers according to pre-defined interfaces. Within real applications the controllers also receive the sensor information only at discrete time steps. A possible input parameter in a mechanical model is, for example, a driving torque while the position of bodies is a typical output parameter. Although Kübler and Schiehlen [13] showed that the simulation stability is not guaranteed in general, recent works [12] showed good results for complex models in the field of automotive application. Cha et al [14] demonstrated the successful application of a co-simulation for the development of a control system of a paper feeding machine.

Therefore the co-simulation between a CACE tool and a flexible MBS can provide the possibility to simulate a complex mechatronic system while meeting the requirements of topology optimization.

III. A TOPOLOGY OPTIMIZATION PROCESS FOR CONTROLLED MULTIBODY SYSTEMS

A. Methodology

A "traditional" topology optimization scheme is basically an iterative process that integrates a finite element solver and an optimization module. Based on a design response like strain energy e. g. supplied by the FE solver, the topology optimization module modifies the FE model. The FE model typically defines a set of loads that are applied to the part. In the traditional state of the art scheme these loads do not change during the optimization process (e.g. see [15]).

In this paper controlled dynamic systems, namely mechatronic systems are considered. A control significantly influences a system's behaviour and adds additional dynamic properties to the MBS. The coupling between the mechanical system and the control system does influence the overall system's dynamic behaviour significantly. As a consequence, loads that act on a body in the system might be affected not only by the geometric changes due to optimization but also by the control system dealing with the new plant as well. In order to carry out a topology optimization, the optimization scheme was extended by means of integrating the control system. The co-simulation of the mechanical system and the control system covers the complete coupled dynamics of the mechatronic system. From this simulation a new, "updated" set of loads can be derived for the body to be optimized in the system. In topology optimization this is done during every optimization iteration. This approach provides realistic loads during the topology optimization process and covers all possible changes in the acting loads caused by any of the coupling effects explained above.

B. Implementation

The new topology optimization scheme has been implemented with the optimization code Tosca from the company FE-Design (see figure 1). For the controlled MBS simulation, MSC.Adams has been used in co-simulation mode together with Matlab. The complete process flow as well as all necessary input/output handling is completely automated.

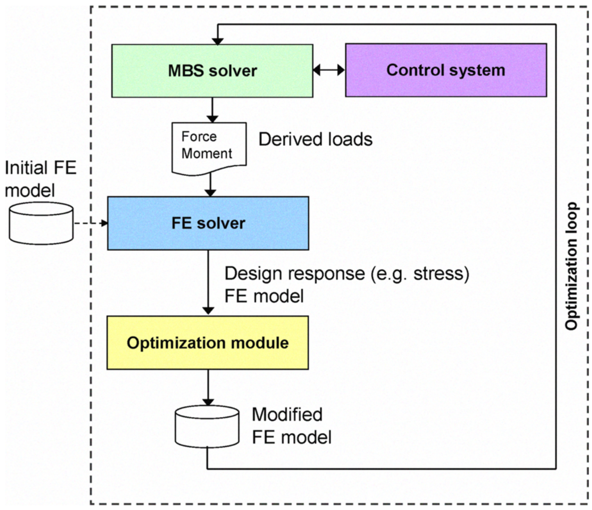

Fig. 1 Scheme of extended topology optimization

A topology optimization of a body "within" its mechatronic system can now be carried out straightforward. Due to the extended approach for the optimization an automated load case determination is required. A selection of the load cases on the basis of a-priori-defined times during the simulation is not appropriate since the load/time series in a controlled dynamic system may change throughout the iterations. A purely simulation time oriented approach would not be a suitable solution. According to the changed system behavior in later iterations, the relevant load cases might not be used for the optimization. Therefore the strain energy as an indicator for the external loads on the optimized part is selected as relevant value for the load case determination. At the end of each Co-simulation run, the n points of time with the highest load value of the part's total strain energy are selected. The equivalent load cases at the corresponding time instances are then used for the further FEA which provides the necessary input for the optimization module.

IV. ADAPTION OF CONTROL PARAMETERS

The "mechanical" optimization of a part within a controlled MBS might lead to a poor-adjusted control system. For an improved performance of the whole mechatronic system, an optimization of mechanical parts and the control system in one process covering all the interaction will be necessary. A first step towards this direction is an adaptation of the controller parameters in every single iteration of the topology optimization. The basic idea of this approach will be described in this section. The focus is not set on the design of a control system from the very beginning, but to enable a process allowing an efficient optimization of structures "within" their surrounding mechatronic system.

A. Adoption of Control Parameters

For the update of the controller parameters during each iteration of the structural optimization process a modular structured optimization process was implemented in Matlab for an adaption of the parameters of a PID controller. For evaluating the system's response features like overshoot, settling time, number of oscillations or energy consumption are used. A weighting constant W_i can be chosen greater than or equal zero for each of the n =7 evaluation attributes. With these constants and the following formula, a Degree of Performance (DOP) can be calculated for the evaluation of the system response:

$$total\ DOP = \left(\prod_{i=1}^{n} DOP_i^{W_i} \right)^{\frac{1}{\sum_{i=1}^{n} W_i}} \qquad (2)$$

Some features are contradictory in their effects, for example, fast settling time and low power requirement. By using a product instead of a sum it can be provided that system configurations which show very poor results for certain attributes do not obtain high values for the total DOP. By using weighting constant as exponent in formula (2) it follows that a single criterion has no influence, if the corresponding factor W_i is set to zero, which gives more flexibility to the user.

In order to provide a robust process for the adaptation of the control system's parameters within the iterations of the structural optimization a two-step process was implemented. In the first step an array of test points is defined in parameter space in order to find suitable initial values. After evaluating the Degrees of Performance in various parameter combinations it can be decided which initial values for a local optimization are of importance. This simple combination of a local and a global strategy has considerably better results regarding the retrieval of a suitable parameter set and of course regarding the computing performance, than using only a one-step method. The implementation in Matlab consists of various modules and uses basically the simplex algorithm "fminsearch", provided by Matlab.

B. Integration of Controller adaptation

To integrate such an adaptation of control parameters into the process of the extended topology optimization it is necessary to reduce the system's complexity to achieve reasonable computing time. The controller parameter adaptation, as introduced in the previous section, might use several hundred single simulations. Therefore the co-simulation including flexible bodies in the MBS is not a suitable way for the optimization of the controller parameters. The detailed description of the part's behavior is not relevant for the controller parameters in this context, as the intension of that adaptation is not to design a final control system, but to provide an update of realistic loads for the topology optimization. In a first step a state space representation of the control plant is deduced from the hybrid MBS. It can be used in a reduced order for the optimization of the control parameters. For the system reduction two different aspects are of importance. On the one hand high accuracy is desirable and on the other hand a short simulation time is a goal. Apart from that a stabile process is needed as the whole process is to be run in a fully automated way.

Model reduction is not in the main focus of work presented in this paper, but it has a long history in the systems and control literature. For model reduction different approaches are possible, which will be described in a very short way. Benner [16] gives an overview based on mathematical descriptions and presents examples that involve also Finite Element models. Antoulas and Sorensen [17] describe e.g. the Hankel norm approximation by means of a Singular Value Decomposition (SVD), which lead to the "balred-technique". The basic idea is that the Hankel singular values of many systems decay extremely rapidly. Therefore very low rank approximations can be achieved and accurate low-order reduced models will result.

Another function provided by Matlab is called "modred" (MODel order REDuction). In "modred" function assumptions are made that some modes are more important than other which means that they contribute more to the systems' output than others. This allows a reduction of the system using only the "important modes". A mathematical description is given e.g. by Faßbender and Benner [18], but in the context of the topology optimization process that reduction function was not robust and stable enough for an automated process. For lower reduction rates particularly simulation time was even enlarged were as for higher rates very fast simulations were possible. A further way to reduce a models' complexity is to cancel pole-zero pairs in transfer functions or zero-pole-gain model that are within a given tolerance. That function is also implemented in Matlab ("mineral") and shows good results for lower reduction rates, where as accuracy compared to the original system is not sufficient. Depending on the original control plant represented by a hybrid MBS model that function may easily lead to instable systems. Therefore the application within a fully automated controller parameter optimization is only possible if lower reduction rates can be used or longer simulation times respectively. Nise [19] compares second and third-order systems and describes that the effect of a pole far away from the dominant poles is negligible. The exact amount depends on the required accuracy and Nise suggests five time constants. That idea was implemented in Matlab whereas the amount of poles to be cancelled was assumed to be proportional to the reduction rate between zero and one (0 corresponds to the original system and 1 is the simplest version). Tests with typical systems derived from the models for the extended topology optimization showed good results concerning the simulation time, but the difference to the original system varied between a few percent and several hundred percent which is not acceptable in that context.

A modification of that idea leads to a new technique where the coefficients of the transfer function play an important role. It is assumed that small coefficients contribute not significantly the output whereas according to amount higher values are more important. Therefore coefficients of numerator and denominator of the transfer function are cancelled due to a certain reduction rate given by the user. The basic idea is illustrated by (3). A reduction rate of zero means that all coefficients are maintained and a rate equal one means that only the highest coefficient is not cancelled.

$$\frac{\cancel{\ldots+2.79\cdot10^{189}}s^3+3.61\cdot10^{199}s^2+\cancel{4.15\cdot10^{188}s}-7.16\cdot10^{190}}{\cancel{\ldots+3.66\cdot10^{185}}s^3+5.50\cdot10^{191}s^2+6.60\cdot10^{193}s-8.53\cdot10^{196}} \quad (3)$$

A positive effect is that the simulation time rises steadily while the reduction rates decays. For middle reduction rates that technique can lead to instable systems, but for higher rates comparable short simulation times in conjunction with low deviation of only a few percent from the original function can be achieved. These very short simulation times are of main importance for the integration of the parameter adaptation within the structural optimization. The whole automated process is show in figure 2.

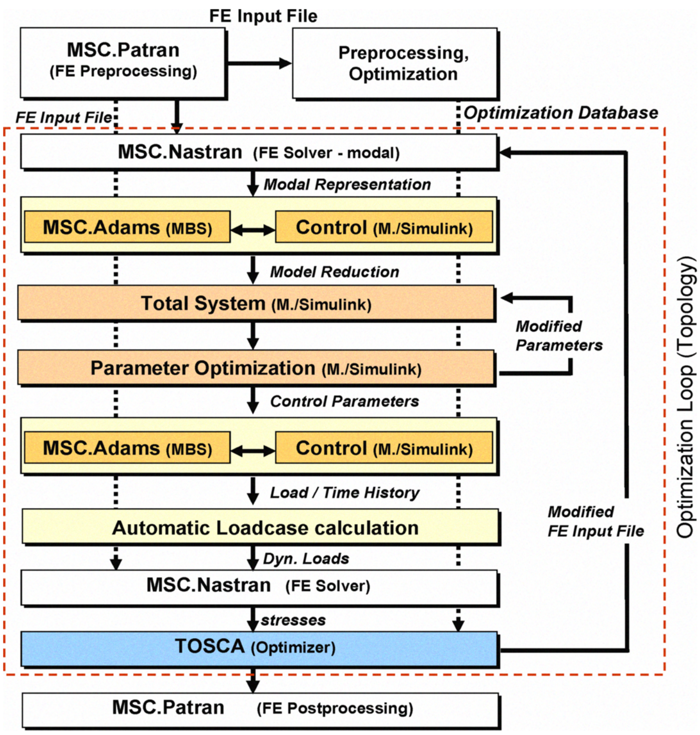

Fig. 2 Automated process of extended topology and controller parameter optimization

V. EXAMPLE

A. Model setup

The optimization scheme introduced in this paper is to be applied to a humanoid robot within the DFG Collaborative Research Centre 588 – "Humanoid Robots – Learning and Cooperating Multimodal Robots". The simple model presented in this section is a subset of the ARMAR III forearm [10]. The rectangular aluminum profile of the beam is investigated and represents the design space of the arm's support structure. The FE model of the flexible arm consists of uniform Hex8-Elements and has two interface points that are modeled as rigid body elements (RBE2). These points are used to connect the arm to the surrounding MBS. The load applied at the tip of the arm has a weight of 3.5 kg. The simplified system is limited to one degree of freedom that enables a rotation of the arm (see figure 3). A torque is used as an input parameter and the angle/angular velocity of the arm's joint are used as output parameters in order to control the system. The control system uses a simple PID controller and has a simple step function as input value. The motor behavior is represented by a transfer function in the simulink model, while a gear friction model is not included.

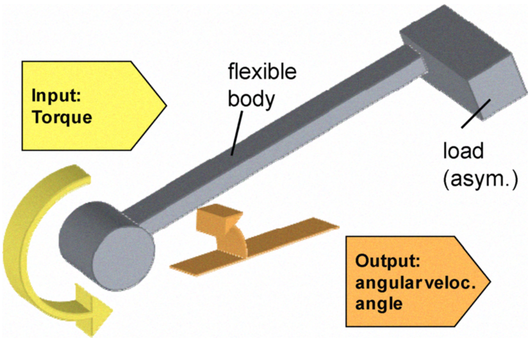

Fig. 3 Simulation setup with interfaces to the control system

For tuning the controller parameters, the optimization scheme introduced in the previous section is used also for the generation of the initial parameter configuration. Of special importance is on the one hand a small overshoot and on the other hand a short settling time which can be achieved by using adequate weighting constants (see figure 4) that are taken into account by formula (2).

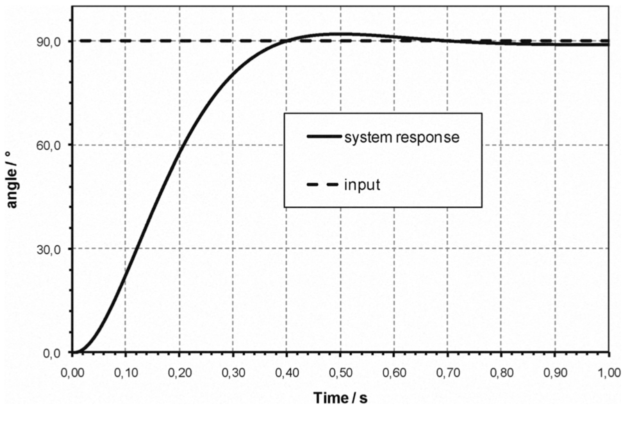

Fig. 4 Step function and optimized system response

B. Results

The goal of the topology optimization for the arm is to maximize the stiffness using a mass constraint that reduces the mass to 15 % of the original design space. That is approximately the mass of the arm's structure used for ARMAR III. A consequence of the mass being fixed outside of the arm's centre is an asymmetrical load situation for the body. The different design proposals for these boundary conditions can be seen in figure 5. These design proposals consist of a type of u-profile with different bracings in the lateral wall. That is a result of the simple load case caused by the rotation about only one axis. There are obvious differences between the first two versions, with and without load updates during each iteration. In particular, the influence of the torsion loads in consequence of the inertia of the asymmetrically fixed mass changes during the optimization. Especially in the mounting section of the arm, the design proposals obtained by the new process have advantages.

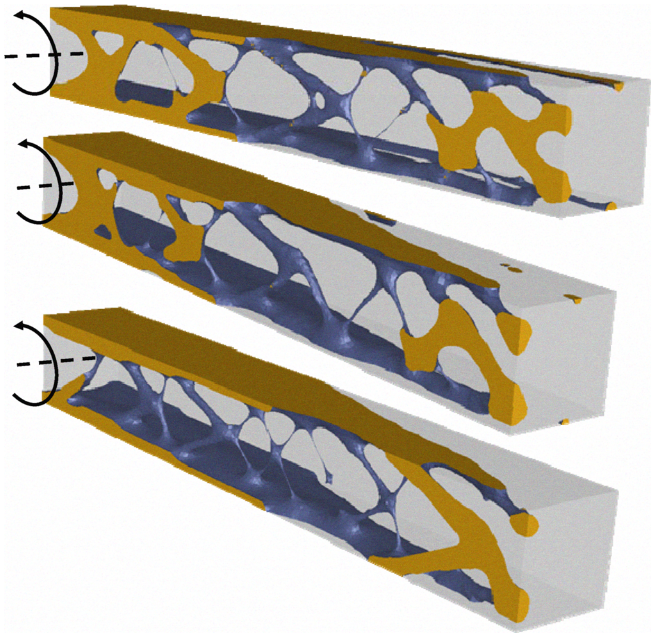

Fig. 5 Results of traditional (lower), extended (middle) topology optimization and in conjunction with the controller parameter optimization (upper)

If the design proposals of all optimized parts are integrated again in the system's co-simulation including control system and the step function for the 90° rotation as input, the results for the strain energy can be used for comparison. Figure 6 shows the bodies' total values of the three different design proposals using the optimized controller parameters from the last iteration of the integrated topology and controller optimization process

As there are no gravity or static loads the forces of inertia depend on the topology of the structure. The new, extended optimization processes show smaller values within this range. Even without a controller optimization, the extended process with load update leads to better results. The integration of the controller optimization in each iteration of the structural optimization can even improve theses results.

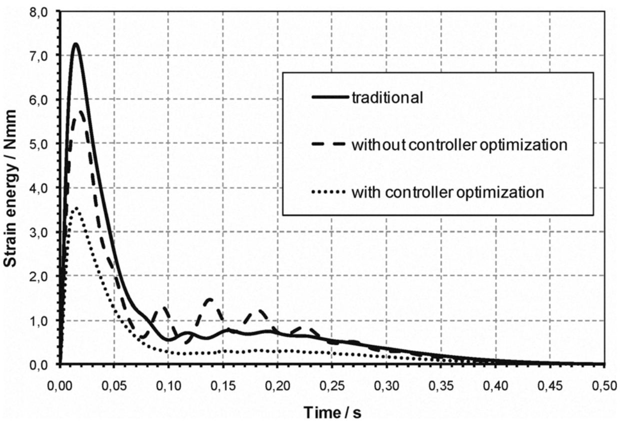

Fig. 6 Comparison of strain energy during the dynamic movement

Since the strain energy is directly connected to the stiffness of a mechanical part, it can be concluded from these results of the optimizations that an update or optimization of the controller parameters shows a positive effect.

On the other hand total calculation time increases significantly due to the additional optimization runs of the controller parameters and the additional FE runs to obtain flexible bodies for system simulation. While the traditional process takes two hours on a standard PC the new extended process takes up to five times longer. To refer the figure 2 the following times were needed for one iteration: 12 min. modal FEA, 28 min. controller optimization, 3 min. MBS simulation / loadcase calculation, 6 min. FEA, 0.5 min. optimization module.

VI. Conclusions

In this paper a new optimization process for topology optimization of structural parts in controlled dynamic mechanical systems has been presented. Different analysis domains, namely hybrid multibody system dynamics, finite element analysis, control system simulation and topology optimization are integrated into a straightforward, automatic way.

The process allows the topology optimization of structural parts within the controlled MBS with a full coverage of the coupling effects between the dynamic properties of the part, the mechanical system and the control system. Of great importance is the update of loads within each iteration of the topology optimization. For an optimization of the whole mechatronic system a suitable adaptation of the control parameters within each optimization iteration has been presented. This extension of the process is realized by a second optimization loop which is embedded into topology optimization process. In future it will be applied to more complex robot models.

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