Methods for Lightweight Design of Mechanical Components in Humanoid Robots

A. Albers, J. Ottnad, H. Weiler. P. Haeussler

***Abstract*— With the development of humanoid robots, lightweight construction and energy efficiency play an important role as these mobile, dynamic systems have to work self-sufficiently. The application of computer-aided (CAE) methods in the development process is one possibility to achieve the required weight reduction. On the basis of a classical topology optimization carried out on the robot ARMAR III, an extended system-based method for dynamic, mechatronic systems is presented. Different analysis domains, namely hybrid multibody system dynamics (MBS), finite element analysis (FEA), control system simulation and topology optimization are integrated into a straightforward, automatic way. For the use of fiber reinforced composit materials in such parts, a FE-based method for the determination of ply orientations and thickness relations is presented.**

***Index Terms*— Control, fiber reinforced composit, flexible multibody system, topology optimization**

I. INTRODUCTION

With the development of humanoid robots lightweight design plays an important role. These systems are to perform together with humans for example in a kitchen tasks of the daily life. Contrary to industrial robots the aid in the kitchen works not behind a barrier, but is to cooperate with humans. A result of this situation is specific boundary conditions for the development of such a system. Lightweight design offers thereby advantages in different areas, as e.g. in the case of a collision where a light arm is less dangerous compared to a more heavy one. Additionally the energy efficiency plays a large role, since the systems are to work self-sufficiently and the storage capacity is limited.

For this reason the design of lightweight structures is a major goal within the development of humanoid robots. In consideration of mass reduction, there are a various solutions. With appropriate configuration, for example placing the arm actuators in the torso of the robot [1], the energy consumption can be improved. For the realization of these concepts various approaches are suggested by [2], e.g.:

- Weight reduction by a change of the component’s design and by selection of adapted materials
- Improved utilization of material by more exact knowledge of the loads and the conditions on the material
- Use of modern composite materials, which make a clear weight reduction a possibility

Today, the usage of simulation tools is common practice in many fields of product development in order to realize these concepts in complex real-life components and systems. Finite element analyses (FEA) is widely used regarding mechanical components, for example. Multibody system simulation is employed to investigate the dynamics of mechanical and mechatronic systems. In this field, the integration of body elasticity is of major importance. This led to more realistic MBS simulations and provided information on body loadings for structural analysis and optimization [3, 4]. Combining MBS with tools for the simulation of control systems allows the efficient simulation of mechatronic systems. So-called Co-simulation approaches allow to couple solvers for the mechanical and the control system part. By integrating MBS simulation into structural optimization processes, parts in mechatronic systems can be optimized regarding the interaction between parts of mechanical properties and the overall system dynamics [5]. In the future, the presented methodology is to be applied to selected parts of humanoid robot ARMAR III, introduced in [6].

While using anisotropic materials, orientation of fiber is of special importance for the optimal use of material features. Based on the Finite Element Simulation, a new method is presented that uses the orientation of main stresses to determine optimal orientations and thickness relations of plies.

II. TOPOLOGY OPTIMIZATION

A. *Traditional Process*

Topology optimization is used for the determination of the basic layout of a new design. It involves the determination of features such as the number, location and shape of holes and the connectivity of the domain. A new design is determined based upon the design space available, the loads, possible bearings and materials of which the component is to be composed of.

Today topology optimization is very well theoretically studied [7] and also a very common tool in the industrial design process [8]. The designs obtained using topology optimization are considered as design proposals. These topology optimized designs can often be rather different compared to designs obtained with a trial and error design process or designs obtained from improvements of existing layouts.

The standard formulation in topology optimization is often to minimize the compliance corresponding to maximize the stiffness using a mass constraint for a given amount of material. Compliance optimization is based upon static structural analyses, modal analyses or even non-linear problems, such as models including contacts. A “traditional” topology optimization scheme as depicted in figure 1 is basically an iterative process that integrates a finite element solver and an optimization module.

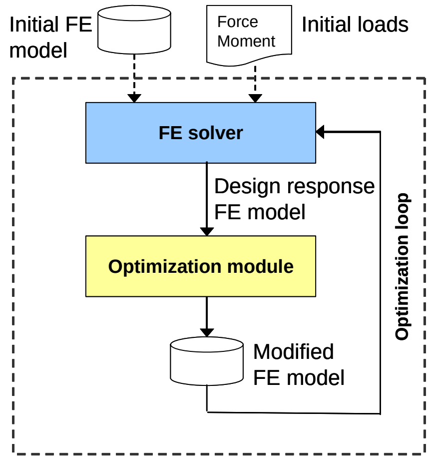

Fig. 1. Traditional process

Based on a design response supplied by the FE solver like strain energy for example, the topology optimization module modifies the FE model.

B. Thorax of ARMAR III

By the example of the humanoiden robot ARMAR III the application of the topology optimization is to be clarified. The thorax forms the support structure between the arms, the neck joint and the hip joint of the robot. The goal of the optimization was to find a structure which is as light and as stiff as possible considering several load cases. Apart from that the arrangement of mechanical and electrical components, which must be assembled in the thorax is of importance. For instance the four drive units connected by wire ropes to the elbows have to be integrated in the thorax to decrease the weight of the arms. The electrical components for the upper body, such as two PC-104s, four Universal Controller Modules (UCoM), A/D converter, DC/DC converters and force-moment controllers, are also considered for the spatial arrangement. Figure 2 illustrates the design space and the different load cases which were used for the formulation of the optimization task.

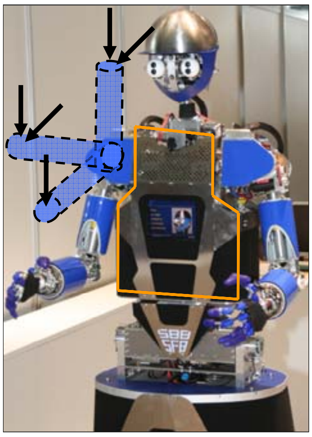

Fig. 2. Design space and loads for the optimization

In a first step however the design space for the different components was not considered, but the entire thorax was defined as design space. On basis of these first optimization results the PC's and the drive units were positioned and the design space for the final optimization was limited accordingly.

The design proposal as result of the optimization was then implemented into a sheet metal construction. Due to limited manufacturing capabilities, only milling and turned parts could be used. The result of that design process is a lightweight structure with a weight of only 2.7 kg.

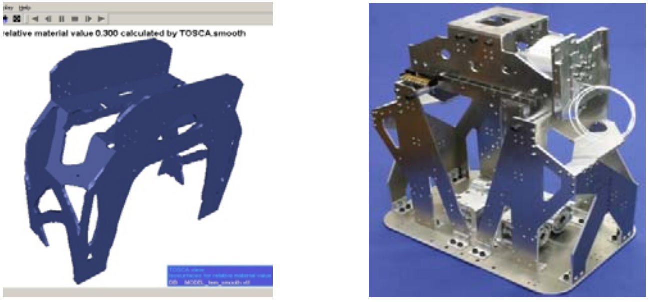

Fig. 3. Design proposal form the optimization and the manufactured design

III. SIMULATION OF CONTROLLED DYNAMIC SYSTEMS

In chapter 2 the scheme of a traditional topology optimization was described and illustrated by the example of the thorax of the humanoiden robot ARMAR III. In order to optimize parts, with which dynamic effects are relevant, it is necessary to provide an appropriate simulation setup.

A. Hybrid Multibody Systems

Hybrid multibody systems are a combination of classical FE and MBS approaches. These “flexible multibody systems” are applied if the elastic behavior 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 modeled by means of a component mode synthesis (CMS) approach as suggested by [9]. The deformation u of the body is approximated to the time t as a weighted sum of the constant pre-computed shape functions $\boldsymbol{\varphi}$:

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

The time dependence of the deformation is now only in the modal amplitudes $c_i(t)$. As a consequence the number of DOFs is significantly reduced, which allows an efficient MBS simulation

Regarding a structural optimization, a FE representation can be used, whereby the number of degrees of freedom is strongly reduce, which leads to an efficient dynamic simulation. Comparisons with a direct FE integration showed that in the ranges of the use of topology optimizations a modal representation is sufficient and brings partial substantial savings in the computing time [10].

B. Feedback Control and Multibody Systems

For the simulation of mechatronic systems like humanoid robots e.g. it is necessary to consider mechanical aspects as well as the behavior of the control system. In the field of simulation there are different ways to couple the models of the two domains.

At a direct integration of control systems in a mechanical model or vice versa all equations are solved by one single solver. This normally leads to faster calculating times; however, today there is only a limited range of functions in the commercial programming systems. The integration of FE structures for example is not possible in tools of control engineering. On the other side complex control models cannot be used or only in a reduced and simplified version within a multibody simulation.

The state of a dynamic system can be described by means of a set of differential equations which enables an exchange via state matrices.

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) && \text{Equation of states} \\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) && \text{Output equation} \end{aligned} \tag{2}$$

By defining the input and output parameters in a mechanical system e.g., it is possible to release the matrices (***A*** to ***D***) after a MBS simulation. Linear or linearized systems however, are required. There are various approaches for linearization that allow derivation of state state matrices that are selected by defined working points, where the subject of research is flexible FE structures [11].

A co-simulation provides the opportunity to consider non-linear effects in a system. Equations of the mechanical and control system are each solved by an separate solver. At a discrete time in the simulation the data is exchanged according to pre-defined interfaces. A possible input parameter in a mechanical model is for example a driving torque while the position of bodies is a usual output parameter. With this approach the specialized solvers for each domain are used, so that also complex models can be handled.

IV. EXTENDED TOPOLOGY OPTIMIZATION

A. Concepts

In dynamic controlled systems there exist interacting effects between part, system and control system. To consider these circumstances during the structural optimization, the traditional scheme of the optimization was extended. The FE model typically is used together with a set of loads that are applied to the model. In the traditional scheme these loads do not change during the optimization iterations. An MBS extended scheme as introduced by [4] can be employed to take the dynamic interaction between the FE model and the MBS system into account. The main difference is that the load set is determined anew in every optimization iteration by means of the MBS simulation. With this approach a body can be optimized “within” it’s surrounding mechanical system without neglecting coupling effects between the body’s and the system’s dynamic properties. This is of great importance since the body’s changing mechanical properties – caused by the optimization algorithm – may affect the system’s overall behavior which in turn may change the loads acting on the body.

In this paper controlled dynamic systems, namely mechatronic systems are considered. A control system adds additional dynamic properties to the MBS. The coupling between the mechanical system and the control system might 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 as well.

In order to carry out a topology optimization, the MBS extended optimization scheme must be extended again by means of integrating the control system as depicted in figure 4. For this a Co-simulation between the flexible MBS and the control system is done to provide an update of the loads resulting from the changed mechatronic system.

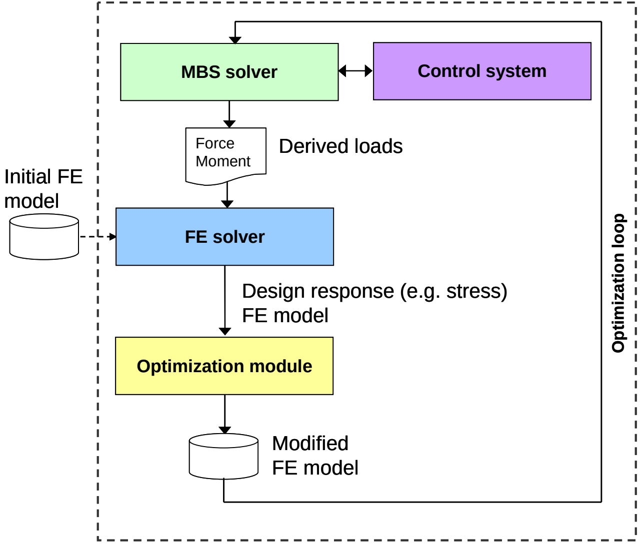

Fig. 4. Controlled MBS extended topology optimization

B. *Implementation*

The new topology optimization scheme has been implemented with the optimization code TOSCA from the company FE-DESIGN. For the controlled MBS simulation, MSC.ADAMS from MSC Corporation has been used in co-simulation mode together with MATLAB provided by the MathWorks. The complete process with all inputs and outputs of the different data is automated and illustrated in figure 5:

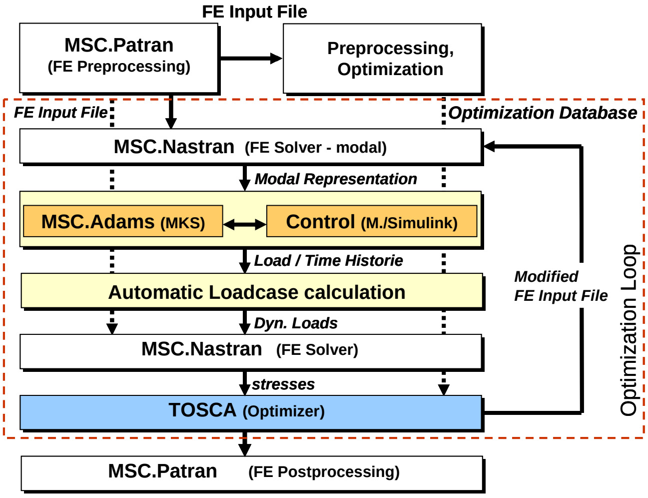

Fig. 5. Process of the extended topology optimization

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 thereby since the load/time series in a controlled dynamic system may change throughout the iterations. Figure 6 shows schematically the effects of a purely temporally oriented proceeding. According to the changed system behavior in later iterations, as opposed to the relevant load cases, might be used for the optimization.

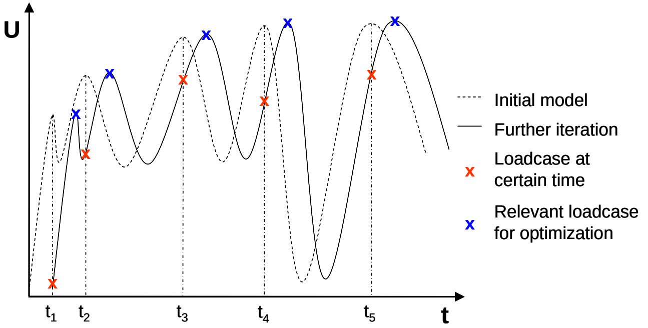

Fig. 6. Automated determination of loads based on strain energy

Therefore the strain energy of the optimized part was selected as relevant value for the load case determination. At the end of the each Co-simulation run the *n* points of times with the highest loads value of the part's total strain energy are selected. The equivalent load cases at the corresponding time points are then used for the further FEA which provides the necessary input for the optimization module.

C. *Example*

The optimization scheme introduced in this paper is to be applied to a humanoid robot within the DFG collaborative research centre 588 – "Humanoid Robots". The simple model presented in this section is a subset of the ARMAR III forearm. ARMAR III is the latest version of the demonstrator system of the collaborative research centre 588 [6]. The rectangular aluminum profile (cross-section 40 x 40 mm²) of the beam (length 300 mm) is investigated and represents the design space of the arm's support structure. The FE model of the flexible arm consists of uniform Hex8-elemnts 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 which is asymmetrically applied at the tip of the arm has a mass of about 3.5 kg (Mass of the hand plus an object) which ARMAR III can move dynamically.

The simplified system of this first stage of investigation is limited to one degree of freedom that enables a rotation of the arm as described in figure 7. The setup for the Co-simulation with the input and output values to the control system is also depicted in figure 7:

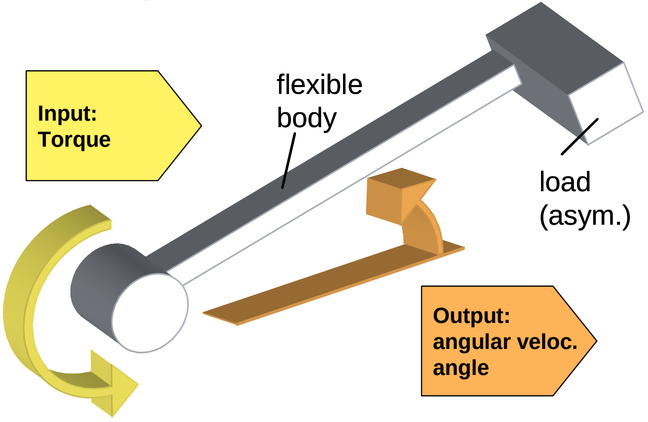

Fig. 7. Model setup

This simplification is justified due to the importance of the methodology of the optimization scheme at this stage. A torque, representing an electronic motor, is used as an input parameter and the angle/angular velocity of the arm are used as output parameters in order to control the system. These data are determined also at the humanoid robot ARMAR III by different sensors. The control system itself uses a PID controller. For the tuning of the controller parameters, state matrices were used as representation of the mechanical system. These matrices were generated by a reduced mechanical model set up with rigid bodies. The step function as input signal causes a rotation of the arm of 90°.

The goal of the topology optimization of the arm was to maximize the stiffness using a mass constraint that reduces the mass to 15 % of the original design space. A result of the mass fixed outside of the arm's center is an asymmetrical load situation for the body which is to be optimized. The design proposal for these boundary conditions can be seen in figures 8 and 9. This design proposal consists of a type of u-profile with different bracings in the lateral wall. The upper and the lower side of the support structure taper themselves within the front range of the load introduction. Here there are clear differences between the two versions, with and without load updates in each iteration. In particular, the influence of the torsion loads in consequence of the inertia of the asymmetrically fixed mass changes during the optimization.

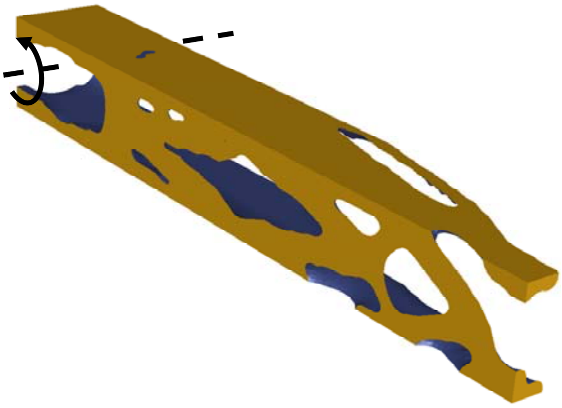

Fig. 8. Design proposal as result of the new topology optimizations

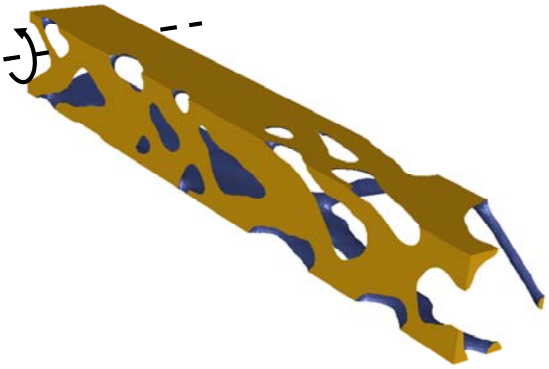

Fig. 9. Design proposal as result of the traditional topology optimizations

If the design proposal of the traditionally optimized part is integrated again in the system's co-simulation with the original boundary conditions, the following results for the strain energy are obtained.

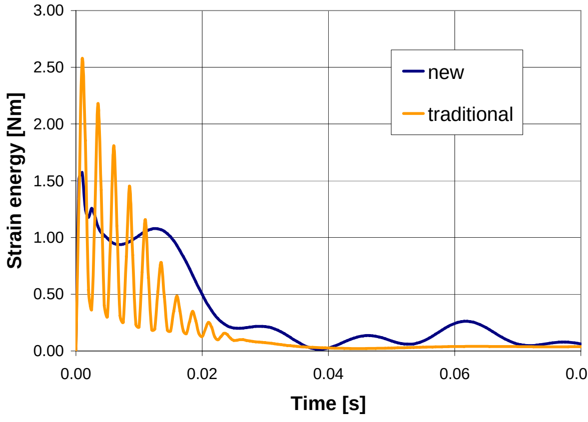

Fig. 10. Comparison between the new and the traditional optimization method concerning the strain energy

The relevant loads appear in the beginning of the arm's movement, since the largest acceleration values arise in this phase. As there are no gravity or static loads the forces of inertia depend on the topology of the structure. The new, extended optimization process shows clearly smaller values within this range. 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 the interacting effects between mechanical parts and the mechatronic system perform better than the classical approach.

V. FIBER REINFORCED COMPOSITES

A. Basics

In this paper, fiber reinforced composites are combinations of polymeric matrices, e.g. thermoplastic or matrices made of duromer plastics, and fiber reinforcements, e.g. glass, aramid or carbon fiber. Important is that the fiber is seen as endless and oriented, in contrast to the so called short- or long fiber reinforced composites.

Because the material is given as a laminate made of different oriented layers, so called plies, the designer has much influence on the material properties. Matrix and fiber has different tasks in the laminate: Function of the fiber is the bearing the loads, while the matrix fixes the fibers, transfers forces between the plies, supporting the fiber against shear, and jamming different plies.

Fiber reinforced composites have widespread employment for usually two-dimensional parts, e.g. in space technology (e.g. PEEK-matrix with carbon fibers), for sports airplanes (e.g. epoxy-matrix with carbon fibers), sports boats (polyester- or epoxy matrix with glass, aramid or carbon fiber), hardhats (aramid fiber) and so on.

As manifold as the application range are the manufacturing processes for the fiber reinforced composites, beginning with simple laminating by hand up to automated processes using presses or digester systems.

Even for isotropic materials, the design of complex parts is not trivial. For the design of composites, additional parameters have to be considered: Number and thickness of the plies and the orientation of fibers. Hence, design by intuition leads only in few cases to optimal parts.

For calculation of laminates, approaches are used that combine the properties of single plies to one virtual material by use of the "cross rule" [12]. The established theories are valid for the elastic range.

Several approaches for the determination of optimal fiber orientation has been presented in the past: Luo and Gea [13] use an energy based method. Setoodeh [14] describes an optimality criteria approach, while Jansen works with a generic algorithm. Ledermann [16] presents a method, that places the fibers in the direction of the first main stress in the finite element.

Most of those approaches only work for one ply, and are reduced on two dimensional problems.

B. A new approach for the design of composite parts

The method developed in our work has the following goals: Fast convergence, because the approach is intended to be used together with the Finite Element Method, an, in a second step, combination with topology optimization is planed. It has to be applicable to 2 and 3D geometries, and determination of two layered laminate structure (orientation and thicknesses) to be able to take multi-axial load cases into account.

The approach is based on a theory described in [16]: The optimal orientation of fibers is found, if it is equal to the orientation of the first main stress. To be able to take multi-axial load cases into account, the method creates two plies per finite element, with the second ply oriented in the direction of the second main stress. The relation of thickness of the two plies is proportional to the relation of the two main stresses. The orientation of the composite in space is defined by the surface created by the two directions of the main stresses. The third main stress is not taken into account, because 3 dimensional canvas are not used in real world applications.

The method starts with a finite element model with isotropic material. After determination of main stress directions, the material model is replaced by an anisotropic one with the parameters of a combined two-layer composite. Stress and ply directions are updated in an iterative process.

C. Examples

The example in figure 11 shows the application of a two dimensional plate with holes under a simple tension load. The orientation of the main ply is indicated by blue bars. It can be seen that the fibers are oriented around the holes.

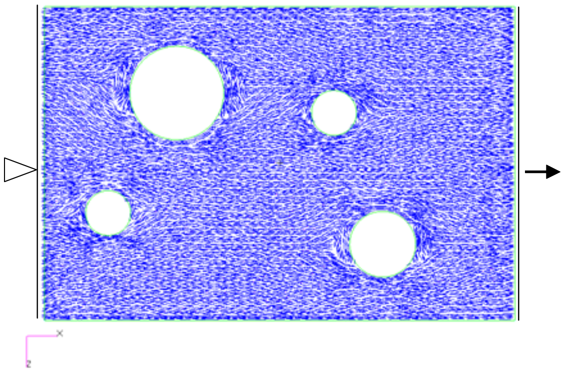

Fig. 11. Orientation of the first ply in a plate under tension

Figure 12 shows a plane parte, too. The plate is fixed at the lower left corner and loaded in horizontal direction at the lower right corner. Red arrows show the orientation of the first ply, blue arrows the orientation of the second one. The relation of length of the arrows indicates the relation of the ply thicknesses. It can be seen that in area A, the load is nearly one-axial, while in area B, both main stresses are nearly the same and thus, both plies have nearly the same thickness.

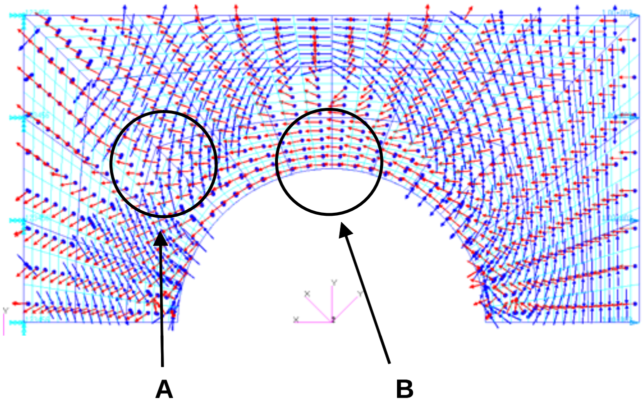

Fig. 12. Orientation and ply thickness

Image 13 shows a tube, fixed at one side, with a torsional load. The plies found by the algorithm have nearly the same thickness and are oriented in 45 and -45 degree to the axis of the tube. This is the expected result.

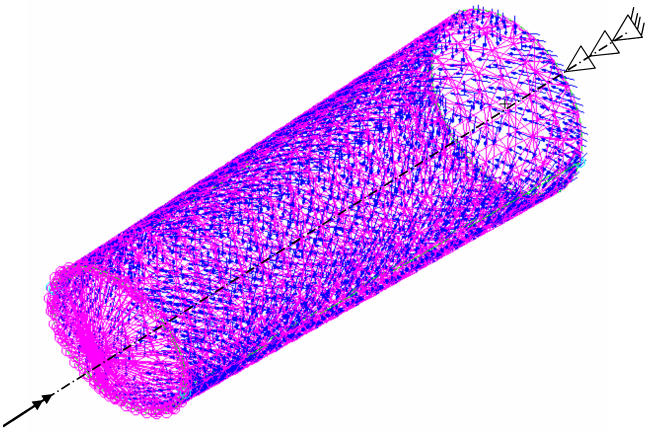

Fig. 13. Tube under torsional load

VI. SUMMARY AND CONCLUSION

In this paper two methods were presented for the computer aided development of lightweight structures. By means of a topology optimization for the thorax of the humanoid robot ARMAR III a stiff and light support structure was designed, implemented in a CAD-model and also manufactured. Beyond that a new optimization process for the topology optimization of structural parts in controlled dynamic mechanical systems has been presented. Different analysis domains, namely hybrid multibody system dynamics (MBS), finite element analysis (FEA), control system simulation and topology optimization are integrated into a straightforward, autonomous process. 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 the loads within every iteration of the topology optimization.

The second method allows the automatic determination of orientation and thickness relations of composite plies. The approach using the two first main stresses allows a fast converging algorithm.

The presented methods will be applied to more complex robot models in future work.

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