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Topology optimisation of multiple robot links considering screw connections

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Abstract

This paper presents a method for the lightweight design of robotic links subject to dynamic loads and requirements on the overall system stiffness. It includes (1) a decomposition scheme to enable separate component optimization and (2) an approach based on topology optimization for optimal load path design of screw connections. The approach reduces computing cost and mass of designs with screw connections.

Keywords: topological optimisation, systems engineering (SE), lightweight design, screw connection design, system decomposition

1. Introduction

Topology optimisation made its way to practical applications and helps to increase the structural efficiency of various parts (Schramm und Zhou 2006). One application are robot manipulators which are applied in many fields and are often designed for high-precision motion with an end-effector load.
Sathuluri et al. 2023a draws attention to the growing need for cost-effective, lightweight, and reconfigurable robots in a world that is increasingly embracing mass customization and human-centric operations. When dealing with multi-component systems with high complexity, two problems emerge: First, the need for decomposition to reduce problem size and efficiently optimise the system (ElMaraghy et al. 2012), and second the connection of the parts in the physical system has to be addressed (Rakotondrainibe et al. 2020). Thus, the optimisation problem should first be **decomposed** on a mathematical level to make it addressable for fast and efficient calculations, and second the parts are to be realised and **composed** to a working system.

1.1. Decomposition

Topology optimisation is an established approach to generate efficient lightweight structures (Bendsøe und Sigmund 2004). However, in applying topology optimisation for robotic structures, there are two challenges: First, multiple load conditions might result from several linked or connected components with varying orientations due to several distinct postures and, second, time-varying loads make monolithic topology optimisation prohibitively expensive (Krischer et al. 2020). Krischer und Zimmermann 2021 addresses the first challenge by decomposing the monolithic system optimisation problem into several component optimisation problems for a comparatively small number of static load cases.
These top-down development processes have their merits (Sathuluri et al. 2023b), but they often lead to suboptimal decisions due to a lack of detailed information at system level. To address this issue, Krischer und Zimmermann 2021 introduce the approach "Informed Decomposition," which leverages meta

models to guide the design process. This approach allows for complete decoupling between system- and component-level optimisation, removing the need for extensive coordination between different departments and components after the initial decomposition. This approach, however, is limited to two spatial dimensions and requires elaborate preparation by training so-called mass and feasibility estimators. Also, dynamic loads were not addressed.

1.2. Composition

Concerning the configuration of the physical system and the incorporation of topology-optimised structures, due consideration must be given to the connectivity with adjacent components. Frequently, screws are employed as standard connection elements. Therefore, their effective treatment in the optimisation process holds the potential to enhance the structural efficiency of the resultant components. One necessity in application scenarios is to introduce cutouts, for example, due to spatial constraints imposed on the structure. To facilitate access for screw connections, assembly cutouts must be provided. In the simplest case, these are considered by predefined cutouts enclosed within the design domain. This approach, described by Bendsøe und Sigmund 2004 and referred to as the passive elements method, often proves inadequate due to changes in ideal load paths and the occurrence of local stress peaks. This is further complicated by the fact that screw connections typically belong to those structural areas with the highest shear loads and often exhibit the most critical local stress peaks.

The connection of an optimised component to adjacent components or the interfaces with a load-bearing environment is conventionally achieved with minimal effort by restricting degrees of freedom in all three spatial directions at defined boundaries Γ_{TC} of the design domain. This idealization most closely resembles a material-bonded connection with a significantly stiffer, rigidly supported foundation. More detailed modeling of connections allows for a more realistic representation of actual compliance. Common approaches include spring elements (e.g., Ambrozkiewicz und Kriegesmann 2021; Rakotondrainibe et al. 2020) or elastic beam elements (Zhu et al. 2014). Beyond these, models incorporating contact mechanics are usually too detailed and unsuitable for typical applications of topology optimisation, and as such, they are not common practice.

In the realm of topology optimisation and the interconnection of multiple structures, noteworthy contributions have been made (Liu und Kang 2018; Niu et al. 2019; Rakotondrainibe et al. 2020). Similarly, in the domain of designing systems comprised of multiple parts, significant research has been undertaken (Xia et al. 2013; Zhang et al. 2015; Zhu und Zhang 2010; Zhu et al. 2009; Zhu et al. 2008). The current state of understanding in screw connections revolves around the determination of optimal screw placements (Chickermance et al. 1999; Chickermane und Gea 1997; Kim et al. 2022; Li et al. 2016) This involves a thoughtful consideration of cutouts within the design space to ensure guaranteed tooling access and ease of part assemblability.

Characteristic of topology optimisation in general is the significant dependence of results on assumptions made about parameters and boundary conditions (Bendsøe und Sigmund 2004). This is particularly applicable to the design domain, making its configuration a matter of careful consideration. Two critical factors emerge in this context: First, the achievable component stiffness and structural efficiency decrease when cutouts or insufficient connection surfaces exist within the design domain, potentially forcing redirection of significant load paths. And second, noticeable constrictions lead to an increase in average cross-sectional stress, and without appropriate countermeasures, undesired local stress peaks may occur at internal edges of the design domain.

1.3. Scope

In this paper, we build upon the insights from these two aspects, (1) formulating requirements on the component level based on system level requirements which are able to deal with dynamic loads and not require previously trained meta models and (2) setup a detailed topology optimisation formulation for treating screw connections in the topology optimisation process by a altering the boundary conditions within the optimisation process.

In the following sections, we will introduce the decomposition strategy, outline our proposed approach, and present the results for the application example of a composed robotic arm. In the discussion and conclusion, we aim to explore the potential implications of our approach. We will consider its prospects

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for contributing to the enhancement of the design of multi-component systems, particularly within the context of screw connected parts.

2. Problem setup and system decomposition

This work aims in optimising a robotic arm consisting of four links. For the robot setup, the same robot introduced in Sathuluri et al. 2023a was taken based on the design approach from Sathuluri et al. 2023b with the aim of calculating optimised structural elements (OSEs) for each robot link. Based on the top-down design of the robot, the length of the structural links is prescribed. In order to improve the performance of the robotic arm, mass is to be minimized while maintaining the system requirement of a maximum deflection of the end-effector position.

For the optimisation of the OSEs, the dynamic time history of individual link module interfaces is extracted. The dynamic loads are considered by selecting specific extreme loading cases for each degree of freedom. This simplifies the dynamic optimisation problem to a static one. While maintaining the overall compliance of the system for each loading case, it is ensured that the total stiffness is sufficient throughout the dynamic response. The critical extreme loading cases are selected over a time history for each degree of freedom based on Equation 1 where the condition in Equation 2 ensures that there is no load with a higher wrench, i.e.,

$$\mathbf{F}_{jc}^{(i)} = \mathbf{F}^{(i)}(t_j) \quad with\ j = 1 \dots n \text{ dofs} \tag{1}$$

$$\left|\mathbf{F}_{jc}^{(i)}\right| \geq \left|\mathbf{F}_{j}^{(i)}(\mathrm{t})\right| \quad \forall t\ . \tag{2}$$

Herein, F_{jc}^{i} represents the robot's maximal critical wrenches of link (i) including forces and moments and it is depicted at time t.

From the system requirement of maximum deformation imposed on the robotic arm due to a payload, an overall compliance can be derived. This compliance is distributed among individual modules based on the ratio of the lengths of link modules to the total length. Consequently, structural optimisation can be carried out at the component level. The total compliance limit is given in Equation (3) based on the payload on the end-effector with $m_p = 1\ kg$ and a maximum allowed deflection of $u_c = 1\ mm$. The critical compliance for each link module $l_c^{(i)}$ is calculated as shown in Equation 4 to

$$l_c = m_p g u_c\ , \tag{3}$$

$$l_c^{(i)} = l_c \frac{s^{(i)}}{\sum_i s^{(i)}}\ , \tag{4}$$

with $s^{(i)}$ being the length of the ith link. The procedure of decomposing compliance requirements from the system level on to component level is called *uninformed decomposition* as it only requires the geometrical information of the system in order to derive requirements compared to the *informed decomposition* with trained meta models presented by Krischer et al. 2022.

A structure with the most efficient global load path of the robot link modules is the solution of the general problem statement

$$\begin{aligned} &\min_{\rho(\mathbf{x})} \ m(\rho(\mathbf{x})) \\ &s.t. \quad l_j \leq l_c^{(i)} \qquad with\ j = 1 \dots n \text{ dofs}\ . \end{aligned} \tag{5}$$

The screw loads for the connection design explained in Section 3 are considered in a separate load case. The compliance limit for the screw load case are

$$l_S^{(i)} = \frac{l_c^{(i)}}{s^{(i)} \cdot n_{screws}} \cdot d_{Fs} = 0.21\ mJ\ , \tag{6}$$

where n_{screws} is the number of screws used for fixing the part on the interface and d_{Fs} is the gap between the interface and the screw force surface. d_{Fs} is set to 3 mm for all links throughout the paper. The optimisation parameters are summarised in Table 1.

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This ultimately motivates the more specific problem statement

$$\min_{\rho(\mathbf{x})} \; m\,(\rho(\mathbf{x}))$$
$$s.t. \;\; l_j \leq l_c^{(i)}$$
$$\text{For } F \in \{F_j, F_s\} \text{ and } l \in \{l_j, l_s\} \;. \tag{7}$$

Table 1. Parameters for the parts to be optimised

	Length	Constraint global load	Constraint screw load	Load per screw
Link 1	150 mm	43 mJ	0.21 mJ	20 N
Link 2	100 mm	29 mJ	0.21 mJ	20 N
Link 3	50 mm	14 mJ	0.21 mJ	20 N
Link 4	50 mm	14 mJ	0.21 mJ	20 N

3. Screw connection design in topology optimisation

To enhance the performance of robotic arms, a new approach in topology optimisation was introduced to incorporate the interface connectors. In the current version (Sathuluri et al. 2023a), so-called interface connectors to the attachment points are implemented as circular plates, contributing significantly to the mass of individual components, thereby limiting the efficiency of components concerning weight optimality. By including the interface connectors in the design space, additional potentials for mass reduction emerge.

However, this formulation comes with the limitation that the area of the interface connectors can no longer be considered a fixed boundary in the topology optimisation. Currently, screws are used to fix the part directly on a neighbouring surface by treating the screw head contact areas of the components as fixed boundaries, substantially reducing the total area of fixed boundaries, and restricting the optimiser's freedom to generate structures.

The area of fixed boundaries can be increased again if the coverage of the joints can be used as a possible contact point to load support. However, contact support allows only for the support of compressive stresses. Areas where tension is applied cannot be supported by contact. To prevent the structure from lifting due to tensile stresses, screws are used. The structure connected to the screw loads should be positioned in a way that pressure can be applied to the areas where tension normally prevails, allowing the structures to be supported on the opposing plate and utilizing a larger portion of the boundary for support.

With the proposed new approach, the functionality of the screws is different from screw connections considered typically in topology optimisation (Chickermance et al. 1999). Thus, the screw forces are utilized to ensure solely compression stresses on the elements that are in contact with the neighbouring surface. With this change the possible connection area for the structure is larger, benefiting the beforementioned freedom of the optimiser. Figure 1 illustrates this idea with a truss-like representation of the problem. In classical optimisation problems, the boundary is treated as fixed in order to calculate the optimised result, neglecting the need for connection elements. In this example the ideal placement of the screws would be on the upper and lower end of the design space. The structure shown in Figure 1(a) is best to support the given load within the design domain. This structure appear as the boundary is able support tension and compression stresses (Γ_{TC}). In practice, this is generally not the case which is why screws are used to fix the part. However, screws need to be placed with a certain distance to the edge and cutouts have to be considered for tool access and assembling the part. Furthermore, the placement is often given and cannot be changed. Thus, screw placement is often inefficient where the screw is placed in the neutral axis of the bending load case. The typical way of considering screws is shown in Figure 1(b). Here the screw head is fixed with some prescribed material for the screw hole (blue). It is apparent that the design domain cannot be entirely used and thus the optimiser is limited due to the setup of the design problem. In the presented approach, the screw is used to maintain the optimised structure from (a) by ensuring that the fixed boundary condition holds even if the boundary can only support compression stresses. This is shown in Figure 1(c) where the screw force leads to compression stresses on Γ_C, making the support feasible for the optimal structure.

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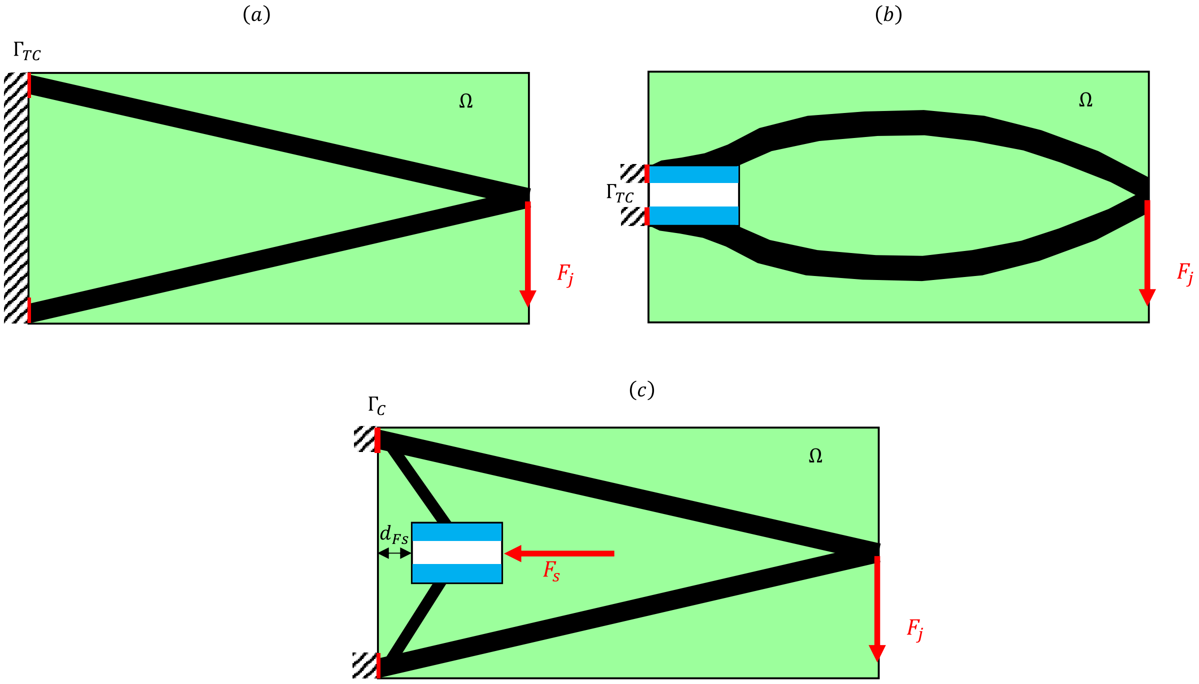

Figure 1. Results of topology optimisation (a) with a boundary that can support tension and compression, (b) with only the screw connection providing support, and (c) the presented approach, where the boundary can support compression and the screw connection provides sufficient axial tensile force

The condition of compression stresses on the boundary can be added to the initial problem statement of the decomposed system given in Equation 7. As a result, the problem statement will contain the decomposed system requirement and ensures physical composition of the final parts.

3.1. Original problem

To resolve the contact boundary condition and ensure that the screw force applies compression stresses in the contact area, the problem statement in Equation 8 contains the normal stresses, i.e.,

$$\begin{aligned} &\min_{\rho(\mathbf{x})} \; m\left(\rho(\mathbf{x})\right) \\ &\text{s.t.} \quad \begin{cases} l_j \leq l_c^{(i)} \\ \mathbf{n} \cdot \boldsymbol{\sigma} \mathbf{n} \leq 0 \quad \text{on} \quad \Gamma_C \end{cases} . \end{aligned} \tag{8}$$

The approach aims to minimize mass m, while satisfying the requirement on the compliance derived from the *uninformed decomposition*. Furthermore, the structure is not allowed to lift from the surface which is the case when the normal stress $\mathbf{n} \cdot \boldsymbol{\sigma}\mathbf{n} = \mathrm{t}_n$ on the contact interface Γ_C is smaller than zero and thus lead to compression stresses on the interface. Dealing with stress constraints in topology optimisation is generally very challenging (Bendsøe und Sigmund 2004). The fact that this formulation does not deal with a yield criterion and the constraint is only valid on Γ_C makes it a hard problem to solve directly. Furthermore, the derived problem statement cannot be implemented directly as the screws should apply the force only on the area where the part is attached. Hence, in the topology optimisation procedure, this is implemented over multiple load cases and a two-step optimisation process. The global load cases used to generate the structure are inherited from the extreme loading cases introduced in Section 2. The fundamental optimisation strategy has been retained. Through *uninformed decomposition*, compliance values are constrained, and the mass is the objective to be minimised. For all screws, a normal force of 20 N was applied to the screw head contact area via rigid elements (RBE2).

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For the screw load cases, the maximum allowable compliance was set to 0.21 mJ as mentioned earlier in Table 1. The following section describes the approach in detail which is feasible for any kind of topology optimisation solver as it splits the problem into two steps and only relies on the classical formulation for mass minimisation.

3.2. Two-Step approach

To apply the preload optimally to the structure through the screws, a two-step approach is employed. Essentially, in the first step, the global structure is optimised with the global loads, excluding the screws. In the second step, the boundary conditions in the optimisation are manually adjusted based on the results of the first optimisation and computed with all global loads and screw forces.

The individual components of the optimisation are depicted in Figure 2. The red colour indicates elements that belong to both interfaces. Blue coloured parts are related to the representation of the screws in the model. The green area is the design domain Ω where material can be freely placed by the optimiser. The white parts within the design domain represent cutouts necessary for accessing and tightening the screws. The edges of the design domain are free which results in the condition that no normal stresses can be supported.

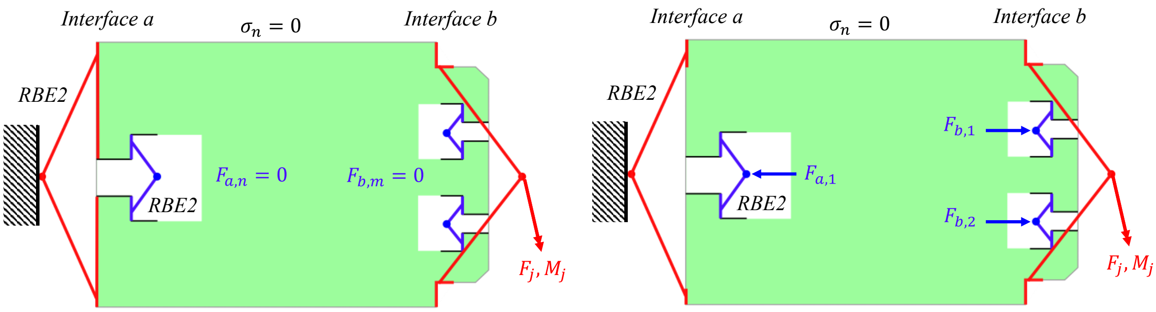

Figure 2. Schematic of the optimisation details for *Step 1* (left) with clamped *Interface a* and no screw forces and *Step 2* (right) with adjusted *Interface a* and screw forces

Each robot link has two interfaces. *Interface a* (left) can be broadly connected to the adjacent joints, with no functional restrictions to consider. At *Interface b* (right), a ball bearing mount is provided, which is subsequently bolted to the motor side of the joints. In the optimisation, the nodes of both *Interface a* and the contact surface with the bearing at *Interface b* are connected via an RBE2 element. The global loads are applied on *Interface b*, while *Interface a* is fixed.

In the **first step** of the optimisation, the global loads are applied to calculate the best possible overall structure. The complete *Interface a* is fixed with a boundary condition where $\mathbf{u} = \mathbf{0}$. After optimising the structure, the areas at *Interface a* where the structure connects to the boundary in an optimal sense are identified. This is illustrated by the red faces at *Interface a* in Figure 3. The green component represents again the design domain of the structure, while the red component is the optimised structure of the first step, indicating the areas where the structure ideally supports itself at *Interface a*.

For the **second step**, the connectivity of the RBE2 element at *Interface a* is adjusted regarding the connected nodes. The RBE2 element was modified such that the structure can only support itself at the interface area where material was positioned in step 1. This material represents the global load path that is optimized without screw connections. In addition to changing the support locations, in the second step, screw forces are applied in addition to the global loads, optimising the entire system. In this specific use case, the update of the boundary condition for the second step is only done on *Interface a*. This is because the shape of *Interface b* is given due to the bearing seat.

The comparison in Figure 3 between the resulting structure of the first step and the second shows that the overall structure changes, while keeping the attachments areas calculated in the first optimisation step. The red arrows illustrate an example for this behaviour. In step one, the two attachment regions are supported with individual legs. In step two, however, the structure is required to be supported from the screw loads. As a result, the lower right screw force needs to attach on the marked faces, changing the structure such that only one leg in the middle remains.

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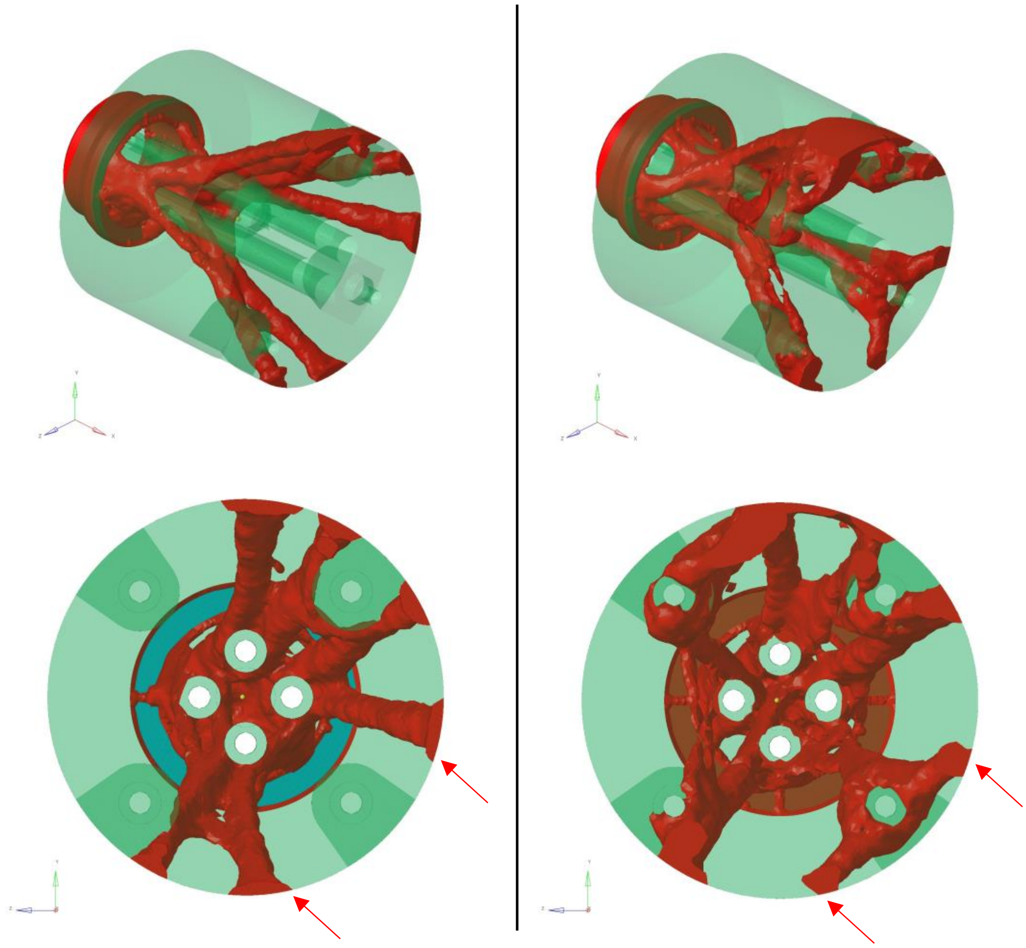

Figure 3. Result of the first optimisation step (left) and the second optimisation step (right). The optimal supports on the boundary of the optimised part (red) can be determined and used as an input for the second optimisation step

The greatest optimisation potential exists when the structure is allowed to support itself across the entire area of the connecting part, as this increases the optimiser's freedom. Especially relevant in this context is the outer edge of the design space, where material at these locations optimally increases the moment of inertia of the structure in terms of mass efficiency. In the present load cases, in addition to lateral forces, significant bending moments occur, requiring a high cross-sectional moment of inertia for support. The proposed approach allows for this behaviour, even when the screws are centrally positioned on the structure.

3.3. Workflow

In comparison to previous versions of the robot links, further minor adjustments have been made. Firstly, the cutouts addressed in Section 1 for cable routing have been significantly reduced compared to the results shown in Sathuluri et al. 2023a. The optimisation results exclusively demonstrate hollow structures with lateral cutouts designed for screw access. These perforated structures are sufficient to adequately guide the cables, eliminating the need for additional constraints in the design space for cable routing. The introduced topology optimisation workflow in the current version is associated with manual adjustments. After completing *Step 1* of the topology optimisation, the connection points of the topology with the boundary must be manually evaluated and input into *Step 2* of the optimisation. Since, in the second optimisation step, all scenarios involving global loads and screw forces are considered, the solution of this step can be directly regarded as the final design. For post-processing, the density field is initially converted into an STL file using the *OSSmooth* function in Altair Hyperworks. After conversion, this file can be imported into Altair Inspire and further processed. The initial post-processing step consists of smoothing the component to achieve a smooth surface. Subsequently, the part is adapted

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with a Polynurbs structure, meaning the structure becomes accessible for CAD programs. The fitting of the Polynurbs requires manual corrections of any deficiencies that arise during the automated fitting process before exporting the final structure for printing.

3.4. Results and discussion

In the post-processing step, the actual bearing support surface is added to the left side of the depicted components, which is essential for proper functionality. On the right side, the new methodology is illustrated, where the screw force is introduced into the system as preloading, thus preventing detachment of the otherwise optimised structure. The four OSEs are shown Figure 4. 3D printing was used to ensure manufacturability of the produced parts as they were not designed for classical manufacturing methods. As very high bending moments occur in the critical load cases, the structure mainly attaches to the outer edge of the design domain in order to ensure high bending stiffness. The exception is OSE 4, where also significant shear loads occur. Thus, the overall structure of the new optimisation procedure is able to support the global loads. The screw connections are also embedded into the structure by pulling the part towards the contact boundary ensuring the stress constraint on Γ_C to be met.

Figure 4. Optimised parts from OSE1 (left) to OSE4 (right). The top row shows the 3D printed parts and the bottom row shows the CAD representation

In Figure 5, two larger legs are presented to illustrate the functionality. Ideally, the structure will not support itself at the screw but rather further towards the outer edge. To prevent the structure from lifting, a force is applied to these contact points through the screw force.
The resulting masses of the printed links can be found in Table 2. For calculation and manufacturing of the parts, the material Rigid 10K from Formlabs was used.

Table 2. Mass of the 3D printed parts with Rigid 10K material from Formlabs

Link Module i	1	2	3	4	Total
Mass [g]	84	37	56	16	193

The total mass of the realised robot is 3.1 kg, it can lift a payload of 1 kg while satisfying the system requirement on deformation of 1 mm. The approach delivers lighter parts than the previous version of the robot. However, the approach is still limited in its execution. The limitation currently lies in assuming infinitely high friction between the structure and its counter plate. This is particularly evident in Figure 5. In this case, the stiffness of the structure is still sufficient, but this cannot be ensured in general. For the next version, there is an intention to address this issue directly in the optimisation process.

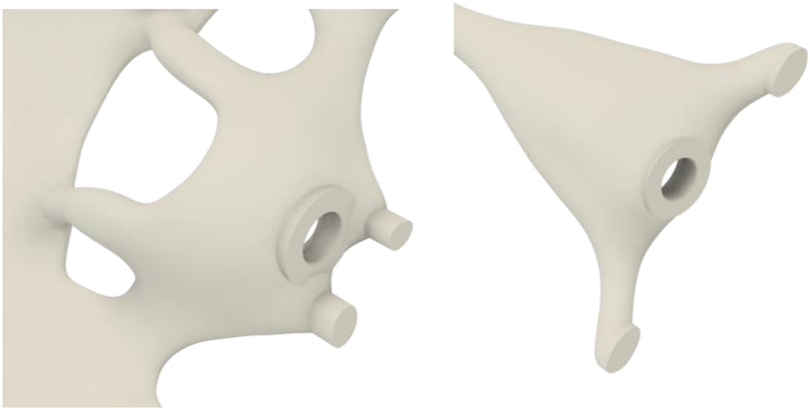

Figure 5. Detailed view of the screw connection design of OSE2 and OSE 4

To integrate the optimised components into an automated design process, it is necessary to combine the current two-step optimisation process into a single step. Both the execution of the topology optimisation and the post-processing with conventionally available programs are only feasible manually and time-consuming. By adapting the formulation of the topology optimisation, the calculation could be performed in a single step, and with simplification and standardisation of interconnected geometries, automated post-processing could be implemented. Initial attempts in this direction have been made, where the boundary conditions are modified during optimisation to unify *Step 1* and *Step 2* in a single optimisation. The size of the support points at the edges and the structure should converge together. An increase in the robustness of the screw connection is also required. Currently, no rotations due to tightening the screw and no deviations in the preload force have been considered. This should be realistically depicted in a subsequent step. Additionally, the performance of this approach will be compared to classical methods in future work.

4. Conclusion

This paper addresses the idea of optimising a complex system by doing component optimisations based on decomposed system requirements while including connection constraints to ensure that the physical system can be composed. The decomposition is done based on the *uninformed decomposition* approach allowing to deal with dynamic loads by calculating extreme load cases which are treated as static loads in the optimisation. For ensuring connectivity to neighbouring parts, the idea of an innovative screw connection design and its implementation is introduced. The design enables the structure to exploit contact to neighbouring parts by ensuring compression stresses on the interface of the parts by the screw forces. The approach is carried out on a two-step optimisation where the stress constraint on the connection interface is implicitly fulfilled. The resulting design shows a more lightweight design to the previous generation while maintaining the system requirement on the end-effector deflection.

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