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Function Integration through Design for Hybrid Integrating Additive Manufacturing Technologies

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Abstract

Additive manufacturing (AM) technologies enable the design of new products due to their potentials. The potential of function integration can be extended through a combination of AM with a component integrating technology forming a hybrid integrating additive manufacturing technology (hiAM). With a created development method optimization areas within a product are identified on a functional level using characteristics, structural configurations and integrated functional areas. These are derived analysing examples in literature. The method is applied to a mechanical arm and hand prosthesis.

Keywords: *design for x (DfX), additive manufacturing, design methods, hybrid manufacturing, function integration*

1. Introduction

Additive manufacturing (AM) offers new possibilities for the design of products, which are rooted in the potentials of the manufacturing technology, for instance flexible and tool-free production. Exploiting the potentials supports economic and flexible production of customized products (Achillas et al., 2015; Gao et al., 2015; Kumke, 2018).

Potentials correspond to positive properties that are exclusive to a given manufacturing process or significantly better than comparable manufacturing processes. They are derived from the exclusive process characteristics and are implemented in process-specific use cases.

The development of new additive manufacturing technologies is driven forward to expand the potentials and design possibilities. One way to achieve an expansion in function integration is to combine several technologies into a hybrid production technology enabling the integration of components during the manufacturing process to form an integrated part. Hybrid technology combinations that integrate additional components and use an additive manufacturing technology are referred to in the following as hybrid integrating AM technologies (hiAM). hiAM are already widely documented in the literature (Espalin et al., 2014; Glasschroeder et al., 2015; Lopes et al., 2006; Lopes et al., 2012; MacDonald et al., 2014; Periard et al., 2007; Ziervogel et al., 2021). In this contribution, the influence of the integration of components through an hiAM on the function structure is used to exploit the hiAM potential of function integration (Pahl et al., 2007).

Function integration describes the measures taken at the system architecture level that result in a component fulfilling two or more functions. This can be achieved by integral or composite design. Hybrid manufacturing enables the integration of components that provide defined functions. This integration opens new freedom in product design as for the conception design phase.

The comprehensive use of the potential of function integration lacks organised and condensed knowledge about the hiAM for the concept phase. The particular need for methods and tools enabling design to fully exploit the potentials of AM has already been outlined by design for additive manufacturing (DfAM) (Kumke, 2018; Laverne et al., 2017; Pradel et al., 2018, Steffan et al., 2020). Due to this state of the art, the following questions arise:

- What possibilities arise from the hiAM potential of function integration in the conception design phase?
- How to enable the developer to use the potentials of function integration during the conception design phases?
- How to structure these possibilities for the use for methodical support?

By answering these questions, new possibilities through the development of hiAM technologies can be classified in a structured way and prepared for the usage in the design process of products. To derive the answers, the known hiAM and their design possibilities are analysed referring to their impact on the function structure for example as a starting point for a variation. The results are documented as characteristics that are used during development with the presented methodical approach extended by hiAM. The extended methodical approach is applied to an exemplary development of an arm and hand prosthesis. Based on the findings of the methodical extension, the further development possibilities of the approach are derived.

2. Fundamentals

Only certain technologies are suitable for a combination with additive manufacturing for achieving the integration of functions. These combined manufacturing technologies are called hiAM and can be distinguished by the technology combined with the additive manufacturing technology. In this context, the number of available hiAM is increasing. New possibilities of hiAM are outlined in section 2.1 to show the extension of the potential for function integration in product design. The potential of function integration has already been considered for known additive technologies through an approach identifying areas for improvement within the function structure (Steffan et al., 2020; Steffan et al., 2021), as explained in the section 2.2.

2.1. Hybrid integrating additive manufacturing (hiAM)

Dynamic requirements for variability, autonomy and sustainability lead to a high demand for flexibility of a manufacturing process. One possibility to achieve flexibility is the use of hybrid manufacturing processes (hM). The hM combine two or more manufacturing technologies. One example is Electro Chemical Discharge Machining (ECDM), which combines EDM and ECM processes. Another example is grindhardening where heat of the cutting process is used for heat treatment.

According to Lauwers et al., these can be categorised according to whether different energy sources or tools are used (ECDM), or whether accompanying phenomena of a process are specifically used for taking over the task of a separate process (grindhardening) (Lauwers et al., 2014).

If one of the combined manufacturing technologies is an additive manufacturing technology, the combination is called hybrid additive manufacturing (hAM) (Gibson et al., 2021; Sealy et al., 2018). In this publication, the additive process forming the structure of the part is called the primary process, while the non-additive process is called the secondary process. In order to meet Lauwers' considerations, the primary and secondary processes have to run simultaneously or cyclically. One way to classify the hAM processes is by their secondary processes according to DIN 8580 (DIN Deutsches Institut für Normung e.V., 2003). Secondary processes, such as joining, forming and coating, introduce further functional elements to the additively manufactured body, providing additional functions. These are either generated by different manufacturing processes or consist of different materials. hAM processes whose secondary process integrates function carriers in this way are referred to as hybrid integrating additive manufacturing (hiAM) processes. The classification of hAM based on secondary processes according to DIN 8580 and the resulting subgroup of hiAM is shown in Figure 1.

Related research on hiAM enables new potentials for product design, which are represented by demonstration examples. The hiAM extends the AM process potentials by the possibility of function integration through the integration of components. Within a composite construction, different components are manufactured as one integrated part. This can be utilised in the form of compact and lightweight design, increased product performance and a lower number of parts and elimination of assembly operations (Joshi et al., 2012; Lopes et al., 2006; Pereira et al., 2021; Xie et al., 2020). The hiAM potential of function integration in the conception design phase results in possibilities of simplifying interfaces, reducing the design effort, saving additional function carriers and assembly processes, and integrating or optimising additional functions.

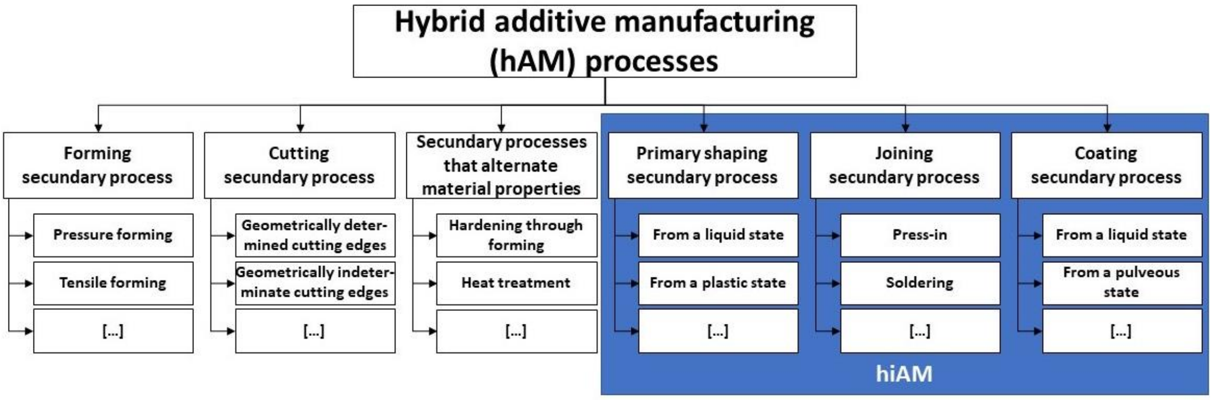

Figure 1. Classification of hybrid additive manufacturing based on secondary processes according to DIN 8580 with the subgroup of hiAM

The integration of conductors, batteries, sensors, wiring harnesses, nuts, fibres as well as surface mounted devices (SMD) such as capacitors, resistors, microcontrollers and LEDs is described in literature. Figure 2a shows an exemplary component, which combines the applications of hiAM in the literature of a variety of authors (Espalin et al., 2014; Glasschroeder et al., 2015; Lopes et al., 2006; Lopes et al., 2012; MacDonald et al., 2014; Periard et al., 2007; Ziervogel et al., 2021). In addition, efforts are expended to develop a hiAM process capable of integrating cables and bowden cables. Such a process is currently developed at the institute of product development and machine elements (pmd) of TU Darmstadt. This hiAM technology extends a fused filament fabrication (FFF) printing process by integrating components like flexible hollow cable tubes, traction cables and conductors. For this purpose, a base body is manufactured with a conventional FFF process, into which the filament is inserted either simultaneously or cyclically, depending on the orientation. An exemplary path of the cable tube with traction cable in a component is shown in Figure 2b.

The entirety of integrable components of all hiAM already known provides an enormous number of integrable functions. In order to use this possibilities, they have to be taken into account when modelling a system. The complexity of modelling the system increases because certain hiAM are only able to integrate selected function carriers, which leads to procedure-specific combination possibilities. Hence, appropriate support is required to exploit the potential of function integration through composite construction of hiAM technologies.

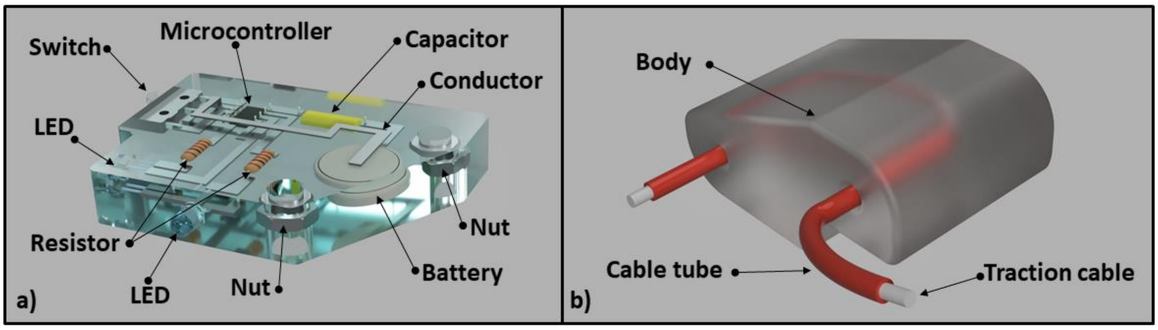

Figure 2. Examples for hiAM: a) SLA printed part with integrable embedded components based on the literature; b) Possible fused filament fabricated part with embedded traction cable

2.2. Extended Approach

One possibility to systematically consider potentials of additive manufacturing has already been presented at Design 2020 (Steffan et al., 2020). The aim is to support the product developer during the conception design phase by identifying a product's functions usable for variation.

Functional modelling is used to easily identify the interactions. A function structure of the product is created by analysing an existing product or synthesis of a purpose. The depiction and comprehension of the function structure is applied according to Pahl et al. (2007), where auxiliary functions are not represented in the function structure because they are not part of the main functions. In order to use the potentials of additive manufacturing, the relevant functions have to be identified. The function structure is examined for certain characteristics. These characteristics are derived from the knowledge of the potentials of AM. For example, AM eliminates the need for product-specific tools which allows to manufacture individualized unique items. In order to recognize components of a product that benefit from this potential within the function structure, it is investigated whether the corresponding functions have variable, customer-dependent inputs or outputs. The identified functions are further considered for integration in the development process according to VDI 2221 (2019). Their implementation using additive manufacturing is supported by means of DfAM approaches.

A detailed description of the overall procedure and characteristics is presented in the original paper (Steffan et al., 2020) and an exemplariy application to a transtibial prosthesis in Steffan et al. (2021). This approach is extended by new characteristics based on the potentials of hiAM.

3. Extension of the characteristic patterns

hiAM technologies have the potential of integrating functional carriers and allows the benefits of hiAM potential to be exploited, particularly using the functional structure. To enable the developer to use the potential of function integration during the conception design phase, usable characteristics for identification of suitable areas within the function structure are derived in the following. The characteristics are identified based on existing literature.

One literature example to derive a characteristic is presented to demonstrate the procedure. Navarrete et al. (2007) exploit the potentials of hiAM (Navarrete et al. use the term layered manufacturing) to design a wireless motion sensor system using GPS with a hiAM manufactured integrated part. The example is used in this paper in an abbreviated form to highlight the essential aspects leading to the results. Conductors transmit the electrical energy stored in the battery to the microcontroller. The microcontroller divides the current between the GPS and motion sensor, which further conduct the current. The energy flow is adjusted along the way. The two sensors convert the incoming GPS and motion inputs into signals. These are adjusted and fed back to the microcontroller along the conducting path. The processed output signal is then converted by a loop antenna and fed out of the system. Figure 3a shows the hardware setup of the sensor system and Figure 3b the corresponding function structure. The blue boxes highlight the functions that are realised by hiAM-integrated function carriers. As illustrated in Figure 3 the function *process signal* having most interactions in the function structure extended to adjacent functions is integrated in a single part.

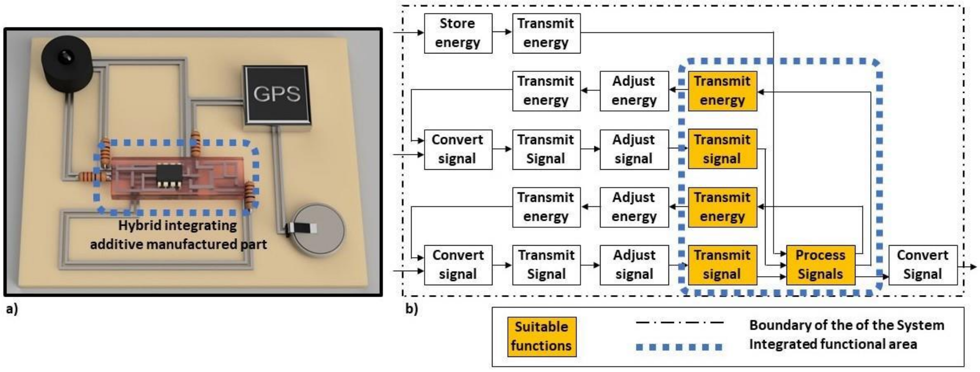

Figure 3. Wireless motion sensor system with GPS as seen from Navarrete et al. (2007): a) Hardware set up of the sensor system; b) Function structure of the literature sample

This integration eliminates various interfaces compared to a design with separated parts. One motivation for integration thus is the simplification or elimination of interfaces between the components. To visualise the integration potential, the set of integrated manufactured functions in the extended function structure is marked with a border for the integrated function area. The example shows that functions are interconnected through the subsequent integrated production of the function carriers in the form of components. These links are not visible in the known form of the function structure. Hence, the present form is extended to include the limitation due to functions that can be produced in an integrated way. This underlines the new possibilities of the potentials of hiAM. The observation of the presented example was also made in other examples and is used to derive the first characteristic.

Similar considerations from the literature, which were partially used to derive the exemplary component in Figure 2a, lead to the identification of five characteristics in total. The first three characteristics refer to the function structure immediately during or after its creation. The characteristics four and five are usable after the specification of the functional carriers.

Based on the analysis of the examples of hiAM in literature, three motivation reasons for integrated manufacturing are identified. The potentials of fuction integration using hiAM are structured by these three reasons for the methodical support.

1. The *interface motivated* integration for the simplification or elimination of interfaces between components
2. The *manufacturing motivated* integration for the simplified assembly of components during component production
3. The *functional motivated* integration for the functional expansion or optimisation

The five characteristics derived from the literature are presented below.

1. Integration of functions having many interactions with other functions

hiAM offers freedom in positioning and orienting of the integrated components. Highly connected functions can thus be integrated more easily. This holds especially if they are linked to functions already integrated and are spatially close to each other. The interfaces between the parts are not required anymore. This is an *interface motivated* use of the hiAM potential of function integration. Figure 4 shows an exemplary function structure consisting of five functions (F), two inputs (IP) and two outputs (OP). Function 4 has the most interactions. Thus, it is worthwhile to check its suitability for the use of hiAM. Various authors use this to integrate components with a large number of connections (Espalin et al., 2014; Lopes et al., 2006; Lopes et al., 2012; MacDonald et al., 2014).

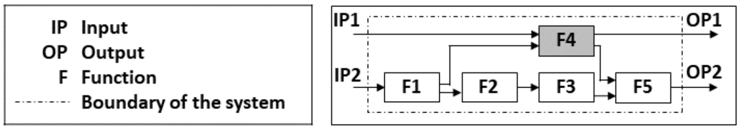

Figure 4. Exemplary function structure with highlighted function F4 with the most interactions

2. Integration of functions having no transitions across the system boundary

If the function carriers are integrated during production, for example no downstream assembly processes are necessary. The restrictions of downstream processes, such as possible collisions of assembly tools, are eliminated. This enables the integration of the components into one part and is a *manufacturing motivated* use of the hiAM potential of function integration. Figure 5 shows an exemplary function structure. Function 2 has no transitions across the system boundary of the part and lends itself to being examined more closely with regard to the suitability of a hiAM integrated function carrier. This is used in the literature to integrate electronic components (Espalin et al., 2014; Lopes et al., 2006; Lopes et al., 2012; MacDonald et al., 2014).

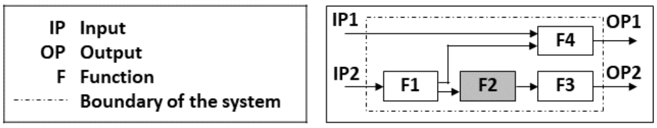

Figure 5. Exemplary function structure with highlighting of the internal function F2

3. Integration of functions that are fulfilled by other adjacent integrated functional areas

Integrable functions located in an adjacent, second integrated functional area may be suitable for integration into an integrated functional area. Aspects such as lightweight design and reduction of installation space can be considered, but new functions can also be achieved through the arrangement of the functional carriers among each other like the free routing of an electrical conductor in the structure. By integrating the conductor in a circular shape with multiple windings, a customized coil can be manufactured and integrated directly into the product's structure. This is a *functional motivated* use of the hiAM potential of function integration.

Figure 6 shows two exemplary function structures. The upper of the two structures represents the component to be reworked. Since function 5 from the right-hand structure is located directly at the system boundary, it should be examined more closely. Periard et al. use this to integrate the battery of a luminous toy directly into the product (Periard et al., 2007)

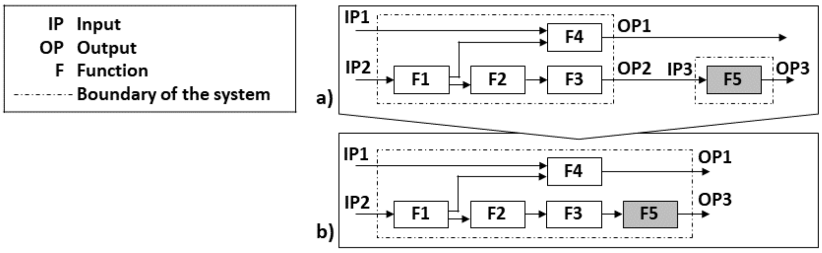

Figure 6. Exemplary function structure with highlighting of the adjacent and integrable function F5

The function structure is examined within the framework of product development until function carriers are identified. The specification of function carriers defines necessary auxiliary functions. These functions can be integrated with hiAM. For this reason, the auxiliary functions are examined for further characteristics.

4. Integration of auxiliary functions for minimal influence on the design

To fulfil the main functions, auxiliary functions have to be integrated. It is desirable that the integration of the auxiliary function has as little impact on the design as possible because these functions represent an additional effort that does not contribute to increase the product benefit (Pahl et al., 2007). The ability to freely position and orient function carriers facilitates integration into an existing design. In literature this is used in particular to integrate the auxiliary function "attaching conductors" into the component by means of additively manufactured conductor tracks (Espalin et al., 2014; Lopes et al., 2006; Lopes et al., 2012; MacDonald et al., 2014; Periard et al., 2007).

5. Integration of auxiliary functions for isolation of function carriers

Additional auxiliary functions may be required to suppress disturbances. These disturbances can be caused by the environment but also by other functions. The isolating auxiliary functions can be integrated as well. An example is the possibility of integrating functional carriers into the interior of the component, which enables effective shielding against some environmental disturbances. Silva et al. use this to protect the internal metal skeletons of orthoses or artificial teeth from environmental influences such as water (Silva et al., 2017a; Silva et al., 2017b).

4. Application of the hiAM extended approach to an arm and hand prosthesis

A prosthesis is the replacement of a missing body part and artificially reproduces the body's own functions. About 15% of the world's population lives with a disability. Just under 3% have severe limitations as a result (World Health Organization, 2011). Furthermore, 3% of amputees in America have an amputation of the upper limbs (Braza and Martin, 2020). Various approaches for additively manufactured upper limb prostheses can be found in literature (Kate et al., 2017). The focus of this contribution is on arm and hand prostheses. These vary in size depending on their user and are available as mechatronic and mechanical versions. Mechatronic prostheses detect the desired arm and hand movements of the user using sensors and execute them with actuators. In comparison, mechanical prostheses transmit the body's own forces via cables to the hand prosthesis, which translates them into the desired movements.

Mechanical prostheses are lighter, independent from electricity and more robust against dirt and moisture than their mechatronic counterparts. For these reasons, they are especially promoted for outdoor use in harsh environments such as heat, dust or humidity. In addition, they are more precise and sensitive due to the muscle's own control system. Mechanical prostheses provide their functionality with the help of the body's own forces using power traction bandages, which are strapped around the upper body. In commercially available prostheses, forces are then transmitted via cables that lead along the outer surface of the prosthesis (Ottobock, 2021). The outer cables are disadvantageous in terms of the accumulation of dirt and getting caught in clothing or obstacles especially in outdoor use. For this reason, the cables are the focus of the revision within the scope of this work, regarding characteristic 5. The initial prosthesis for the improvement through the potentials of hiAM is shown in Figure 7.

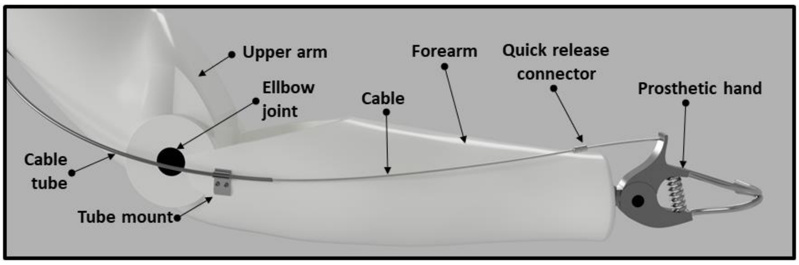

Figure 7. Exemplary mechanical arm and hand prosthesis

The prosthesis is attached to its wearer in the area of the upper arm, where, bracing forces are introduced into the system and transferred to the forearm first to the artificial hand second. The body forces for controlling the prosthesis are introduced into the system by means of a power traction bandage and divided into two traction forces transmitted via cables.

In the upper arm one of these two traction forces is combined with the bracing force. The forces are converted into a torque that enables the forearm movement. The second traction force is transmitted to the hand prosthesis directly and combined with the holding force similar to the upper arm. The resulting opening torque is used to overcome the stored energy of the handspring. The combination of the opening torque and the spring energy determines the opening and closing of the hand prosthesis. The principle of operation of the prosthesis is illustrated in Figure 8 using a function structure according to Pahl et al. (2007). In order to avoid overloading the figure, the focus is on energy and signal flows. Examination of the material flow does not lead to any further findings and is therefore omitted.

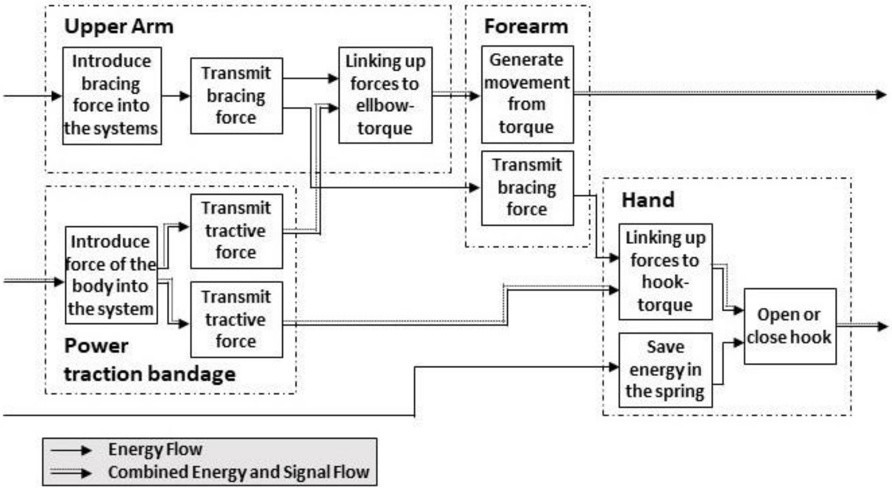

Figure 8. Function structure of a mechanic arm and hand prosthesis

The function structure shown in Figure 8 and the functions of the arm and hand prosthesis were examined using the procedure described in Section 3. If the characteristics apply to a function, it is intensively examined to what extent it could benefit from the use of hiAM. In particular, the function transmit tractive force, which appears twice, was found to be suitable for integration into the upper arm and forearm. Both functions are fulfilled by adjacent components. This corresponds to the presented characteristic 3. Furthermore, they are necessary auxiliary functions to enable the movements of the forearm and hand. Thus, they meet the features of characteristics 4. These auxiliary functions interact with the environment, e.g. getting caught in obstacles. Due to this interaction, they have to be shielded from environmental disturbances in order to fulfil the function. Therefore, they correspond to characteristic 5.

Consequently, the functions transmit tractive force are relocated in the components of the upper arm and the forearm where they can be integrated with the help of the hiAM's potentials. The result can be seen in Figure 9.

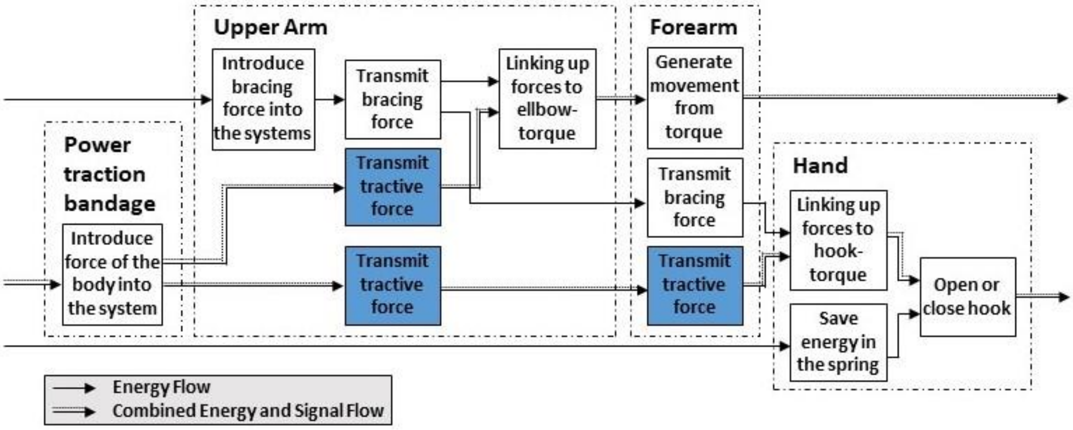

Figure 9. Function structure of the optimized mechanical arm and hand prosthesis with internal bowden cable. The integrated functions are highlighted.

The *transmit traction* functions are integrated into arm segments made by a hiAM, which form an integrated functional area. For the design of the prosthesis, the function carriers of the corresponding functions are relocated to the inside of the upper arm and the forearm in form of Bowden cables using hiAM's composite design. The Bowden cables are integrated into the additively manufactured forearm and upper arm during manufacturing of these two parts with hiAM. The functional carriers consequently are protected from damage due to environmental influencesand furthermore entanglement in clothing or the environment is prevented. Since the structure of the upper and lower arm, in addition to the main function (transmit bracing force), also takes over the auxiliary function of the tube mounts, these parts can be omittedand reduces the number of components and the associated construction as well as the assembly effort and improves the visual appearance of a more compact overall product.

Finally, the fixed friction partners determine defined sliding properties. The final design is shown in Figure 10. The forearm, the upper arm, the elbow joint, the internal cable tube and the cable can be manufactured as an integrated component with a hiAM process, capable of integrating cables and bowden cables. This is possible with the manufacturing process developed at pmd.

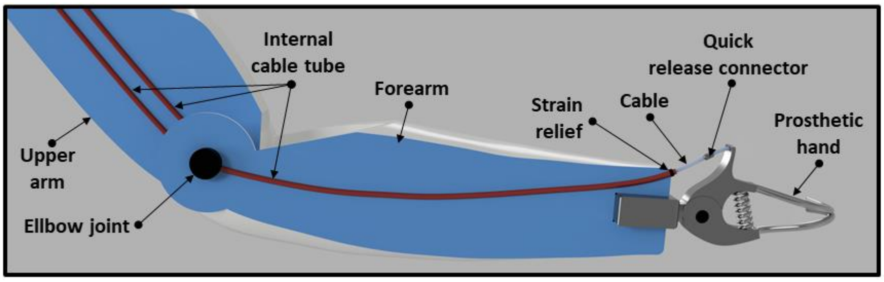

Figure 10. Cut view of the optimized mechanical arm and hand prosthesis with an internal bowden cable

5. Conclusion and outlook

This contribution deals with the systematic use of the potential of function integration using hybrid integrating additive manufacturing technologies. Especially in the conceptual phase of product development, insufficient methodological support is available in literature. Therefore, five main possibilities in the context of function integration of documented hiAM are identified and analysed. Based on the analysis, a possible structuring as well as a support in the context of product development shall be derived. For methodical support, an approach to consider potentials during the conception design phase is used. This approach identifies areas worth optimization within the function structure and is extended by the use of characteristics to realise the new potentials. Five characteristics are derived to use and transfer the potential of hiAM.

The hiAM extended approach is applied to a mechanical arm and hand prosthesis. The potential of function integration enables the integration of external components. This reduces component entanglement with obstacles, eliminates components, such as tube mounts, and reduces assembly effort.

Further research should be focused on two areas. The first area focusses the approach extended by hiAM. For the extension, the potentials of customisation and functional integration through the integration of components have been considered so far. In the course of further research, the linking of the potentials of function integration using the design possibilities of additive manufacturing can be considered together with the integration of components. Furthermore, the extended approach needs to be tested in a larger development project.

The second area involves further optimisation of the prosthesis. Other potentials of additive manufacturing, such as the production of customised products, can be included. Through this potential, user-specific lengths and shapes of the prosthesis are possible, for example.

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