USING ADDITIVE MANUFACTURING TO DESIGN ADAPTIVE USER INTERFACES – LESSONS LEARNED FROM A DFAM PROCESS

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Abstract

The use of Additive Manufacturing (AM) is not limited to non-functional mock-ups, but can also serve to produce fully functional prototypes and end products. This paper outlines the development of a user-adaptive physical human-machine interface (HMI) to examine influencing factors of a Design for AM. For the development of the HMIs, an iterative design approach has been pursued using AM prototypes of shape-changing control elements in end user usability testing for the ergonomic development of the adaptive interface. With a systematic derivation of ergonomic and functional aspects, different shapes of the adaptive HMI are determined. Based on the compiled requirements of the user regarding the control element and the resulting requirements of using AM, four adaptive prototypes were developed. The prototypes are discussed and compared based on ergonomic, functional and manufacturing-related aspects and the conclusions of the process for designing the HMIs for AM are presented. Finally, statements are made concerning the findings for future development projects for AM and aspects that ought to be considered using AM for the design of physical human-machine interfaces.

Keywords: Design for Additive Manufacturing (DfAM), User centred design, Conceptual design

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 5: Design for X, Design to X, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

Additive Manufacturing (AM) technologies offer the possibility of producing complex shaped parts directly from CAD data. The use of AM is not limited to non-functional mock-ups, but can also produce fully functional prototypes for end user usability testing and end products. End products are marketable products with a lot size starting from one (VDI 3405, 2014). Even if it is unlikely that AM technologies will replace conventional manufacturing technologies in general, AM is already a valuable extension to available production technologies (Leutenecker et al., 2015). The use of AM processes is mainly restrained due to low productivity, relatively poor surface quality and uncertainty regarding the mechanical properties of the products (Bikas et al., 2016). In contrast to conventional manufactured products, the costs are almost independent of the complexity of the parts (Zäh, 2006). At the same time, the given freedom of design necessitates a change in the part design process. Whereas a design for manufacturing is paramount for conventional manufacturing technologies, a function- and assembly-oriented design should be more important with AM (Wegner and Witt, 2012). Design for AM (DfAM) leads to the high integration of functions that comes with part integration. The task is not only to speed up the manufacturing processes, but rather to improve the way of Designing for AM (Gebhardt and Hötter, 2016). Due to the restrictions of AM technologies, the solution principles within the product often have to change to fulfill the same functions with an additive-manufactured product as with a conventionally manufactured one (Weiss et al., 2016).

The common use of AM technologies for prototyping makes their use especially interesting as a tool for the ergonomic design of physical human-machine interfaces (HMIs), where various functional prototypes are indispensable for end user evaluation in different stages of the design process.

This paper demonstrates the development of a user-adaptive physical HMI using AM prototypes of shape-changing control elements to examine influencing factors of a Design for AM. The main research question of the paper is thus as follows: What influence does a Design for AM have on the development of small HMIs with internally complex kinematics?

2 DESIGN TASK – THE ADAPTIVE CONTROL ELEMENT

The optimal gestalt (dimensions, shape, material, surface texture) of a hand-operated, physical HMI basically depends on the user's perceptual, motor, anthropometric and cognitive abilities on the one hand, and on the user’s task on the other. This means that the design of the HMI concerned has to enable the users to fulfill their task to the best of their ability according to their characteristics and skills. Taking the example of a physical control element, such as a turning valve for water flow regulation, the user's task can substantially differ depending on the situation. While the primary purpose of a turning valve is to transmit high torque from the user's hand to the closing mechanism in order to open the valve, the user's task suddenly changes with completion of the first step. From then on, it is the user's main concern to regulate the water outflow as quickly and precisely as possible. Since the first task requires high forces, the users would most certainly use a power grip, while the demand for speed and precision would make them opt for a precision grip for the second task.

In order to prevent physical exhaustion, especially for weaker users like elderly persons, torque transmission must be optimized during human-machine interaction. This can be achieved by enabling a positive-locking fit between the human hand and the control element instead of a frictional fit, where a lot of energy is lost to maintain contact pressure for high friction forces.

So, in order to provide an optimal user interface, the shape of the turning valve control element has to adapt according to the user's task, characteristics and capacities, thereby illustrating two essential ways of HMI adaption. This was previously postulated by (Akyol et al., 2001), who stated three different types of adaption for human-machine interfaces: adaption depending on the situation, the task and the user. Petrov defines adaptive control elements by their ability to vary and adapt their gestalt (dimensions, shape) depending on the context of the human-machine interaction (Petrov, 2012).

The design of an adaptive control element for the previously discussed usage case was therefore chosen for this paper.

The decision to develop a task- and user-adaptive control element by means of AM builds upon several factors. There is no existing predecessor product, which gives the designer the opportunity to start development without restrictions and to take full advantage of the huge design scope of AM. Furthermore, the feasibility of the product and the market perspective are uncertain. Both factors justify the use of AM. It circumvents investment in tools and the technology can produce various prototypes in a short time for a repetitive user evaluation of the design. This is of special interest for a user-centered design.

3 METHODS

For the ergonomic development of the adaptive, physical human-machine interface (HMI), an iterative design approach based on guideline (VDI 2242, 2016) was chosen, which supplements (VDI 2221, 1987). The guideline proposes the consideration of both technical and ergonomic requirements in different stages of the iterative development process. Each iteration starts with a task clarification phase including the ergonomic criteria of HMIs, a definition of product functions and a determination of principle solutions and ends with the production of the product with AM and user evaluation. The realization – including a support evaluation – was partly performed by academic stuff and partly by Masters students. Findings for an improved Design for AM were analyzed and logged during the development.

Several design guidelines for AM were applied for the support of the design task for an additive-manufactured product in addition to standard literature about AM including (Gibson et al., 2015) and (Gebhardt und Hötter, 2016). The design guidelines implemented are (Adam, Guido A. O., 2015; Wegner und Witt, 2012; Kranz et al., 2015; EOS GmbH, 2016; VDI 3405 Part 3, 2015). For the final iteration, a design catalog for AM-compliant solutions as shown in (Weiss et al., 2016) was additionally applied. The classifying criteria of the design catalog are specified by generally valid functions, to make the catalog applicable to various design tasks.

4 HMI REQUIREMENTS AND INTERFACE-SHAPE DEFINITION

In order to predefine the different states of shape variation for the adaptive control element, standard (DIN EN 894, 2010) was applied, which includes a catalog for potential control element interface gestalts. The catalog rates gestalts of translational and rotatory control elements with regard to the main criteria "positioning accuracy", "positioning speed" and "force/torque transmission". According to the catalog, the shape of a star knob with three grip recesses was selected for the task of maximum torque transmission and the cylindrical shape of a turning knob was selected for maximum positioning accuracy and speed. In order to assess the two potential states of adaption during human-machine interaction, two turning knob shapes – designed based on ergonomic handle design guidelines (Schmidtke, 1989) – were produced from Acrylonitrile Butadiene Styrene (ABS) using Fused Layer Modelling (FLM). Images and dimensional information according to (Schmidtke, 1989) are shown in Figure 1.

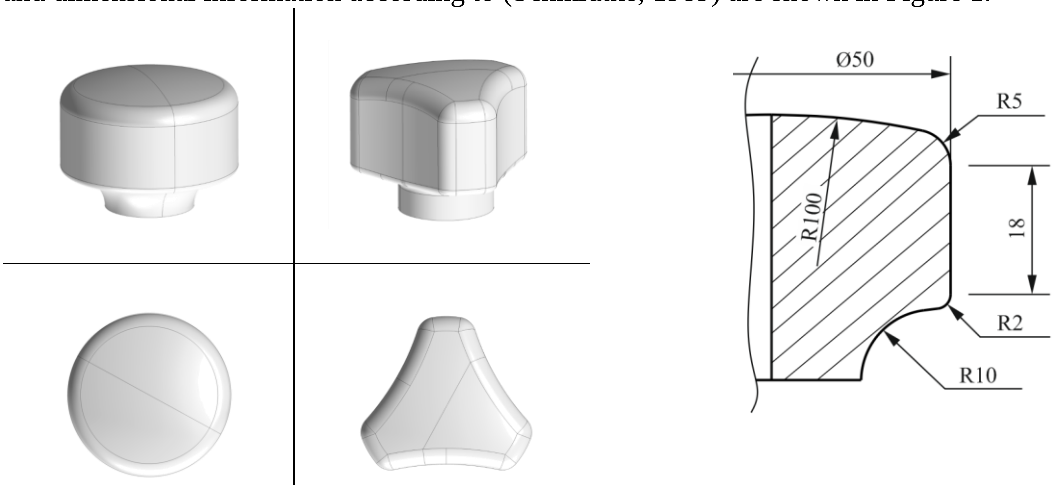


Figure 1. Test pieces (left) with half-section view (right), including dimensional specifications

As a next step, a user test was conducted to evaluate the theoretical assumptions above. 20 healthy participants were recruited from the student community of the university. They were divided into two groups (10 subjects each). The first group (average age 27.00 years, $\sigma = 2.49$ years) had to perform a maximum torque task where they had to apply maximum voluntary torque in a clockwise and counterclockwise direction while in a seated position using a 3-finger grip and a full-hand power grip (order randomized) (see Figure 2, left side). The torque tester (K20, Kolver, height 5.5 cm) used for this study was positioned on a table (75 cm height) and could be equipped with the two test pieces. The second group (average age 25.40 years, σ=2.73 years) had to complete a positioning task with the two different shapes; also while in a seated position (see Figure 2, right-hand side). They were instructed to move a digital indicator clockwise as quickly and precisely as possible to a predefined position visually marked by another indicator. In order to fulfill the task, they had to turn the knobs five times (1800°).

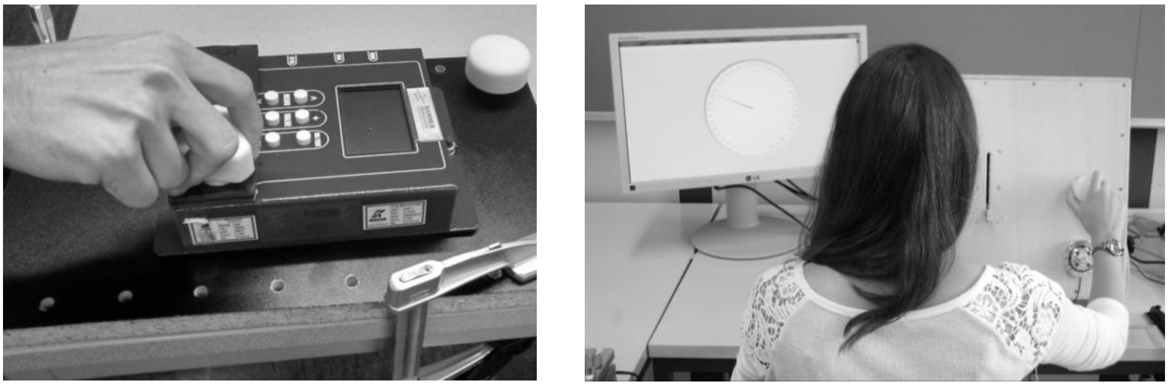
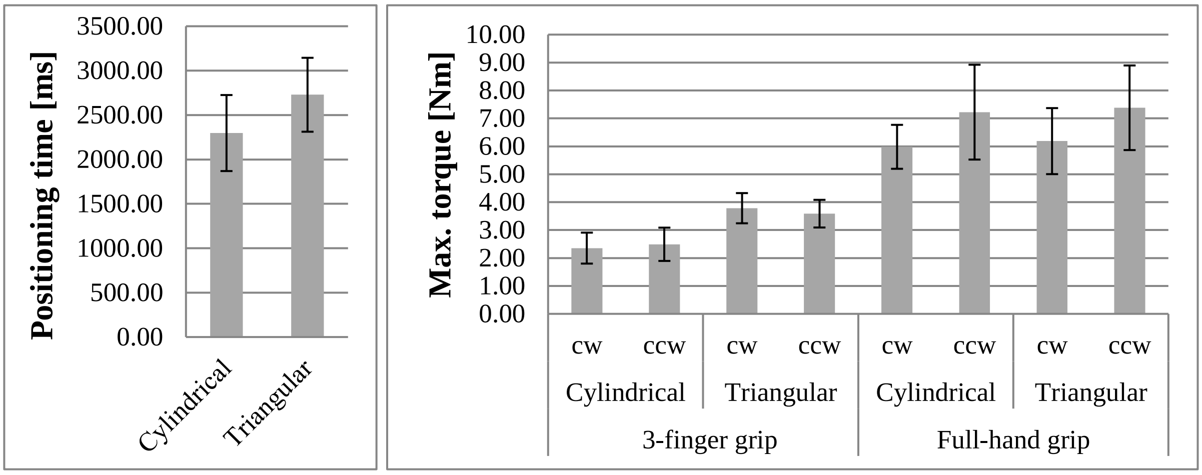


Figure 2. Experimental setup for maximum torque (left) and positioning task (right)

The results of the preliminary user study are shown in Figure 3. For the positioning task, the subjects achieved better scores with the cylindrical control element (Ø = 2297 ms, σ = 427 ms) than with the triangular one (Ø = 2728 ms, σ = 416 ms). Regarding the maximum torque transmission, a dependency on the applied grip could be seen. For the 3-finger grip, subjects achieved higher torque values using the triangular control element (both clockwise and counterclockwise). However, applying a full-hand power grip mean maximum voluntary torque values for the cylindrical and triangular shape turned out to be almost identical, with slightly higher values for the triangular variant. It is noticeable that the results show a strong correlation with the direction of rotation.



	Positioning time [ms]		Maximum voluntary torque [Nm]							
			cw	ccw	cw	ccw	cw	ccw	cw	ccw
	Cylin.	Trian.	Cylin.	Trian.	Cylin.	Trian.	Cylin.	Trian.	Cylin.	Trian.
mean	2297.10	2728.30	2.35	2.49	3.78	3.59	5.98	7.22	6.19	7.38
σ	427.97	416.15	0.55	0.60	0.54	0.50	0.79	1.70	1.18	1.52

cw: clockwise, ccw: counterclockwise

Figure 3. Results of preliminary user study for positioning and maximum torque task

The results show that it is possible to optimize human-machine interaction depending on the context of use. For positioning tasks, cylindrical shapes are more convenient, while triangular shapes prove themselves better for forceful tasks. Significant advantages for user-adaptive interfaces are to be expected for the use of a 3-finger grip that is basically applied to smaller control elements with a maximum diameter of less than 50 mm.

To summarize, the assessment of ergonomic human-machine interface requirements and the user evaluation led to the following main requirements to be considered for the development of the adaptive control element:

1. Two different shape states for maximum torque transmission and positioning task
2. High user comfort rating during human-machine interaction
3. Maximum diameter of 50 mm

5 FUNCTIONAL ASSESSMENT

The requirements of the developed adaptive control element partially result from a design for human-machine-interaction and partially from the pursued Design for AM. Besides the pure manufacturability, Design for AM is mainly characterized by high functional integration and low material consumption so as to reduce production costs and production time. These objectives add the following points to the requirements list:

4. Additive manufacturability
5. Few assembly steps
6. Low part volume

The realization of an adaptive control element can be implemented either by means of a mechanical or mechatronic system design approach. Based on the design task and the product requirements, an initial function structure according to (VDI 2222, 1997) was created to illustrate the functions of the adaptive control element. Due to its simplicity, the application-oriented regulation of the system is excluded in this function structure. The function structure in Figure 4 shows the main functions of the adaptive control element.

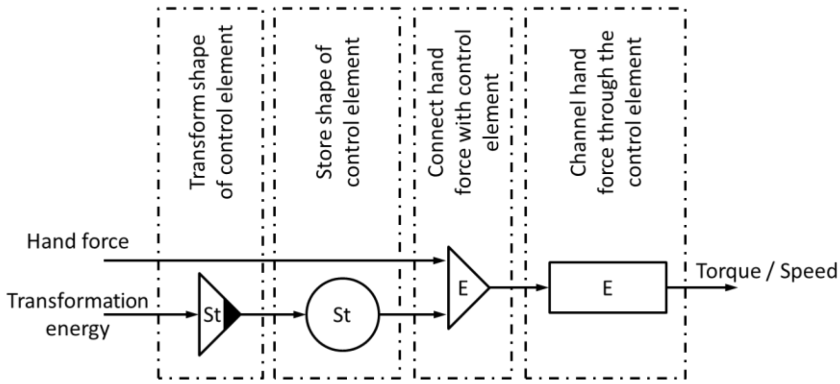


Figure 4. Function structure of the adaptive control element

The shape of the control element is transformed based on the user's task and sensorimotor abilities. The necessary energy is specified as the transformation energy. By means of another main function, the adopted shape has to be stored over the whole period of usage to maintain its stability. Depending on the adopted shape, the hand force is connected to the control element. That means that the hand force is channeled into the part by means of a positive-locking fit between the human hand and the control element in the case of a power grip, which results in high forces. In the case of a precision grip, the force is channeled into the part via friction, which leads to lower forces and higher positioning speed. The next main function of the control element is to channel the force into the connected part.

6 ITERATIVE REALIZATION FOR AM

In sections 6.1 - 6.4, four results of iterations in the development process of an adaptive control element are shown. The results are described, including their purpose, working principles and their main deficits, which leads to the next iteration. The illustrated parts are produced by laser sintering (LS) and Fused Layer Modelling (FLM).

Each result of iteration is presented with four pictures. From left to right, the pictures show a general view of the product, the holding position of the hand, the configuration for the power grip and the configuration for the precision grip.

The purpose of the first iteration (result No. 1) was to produce a mock-up to gain preliminary experience about the realization of complex kinematics in the adaptive control element and about the interaction between the user and control element. The results of the second iteration are two functional prototypes developed in parallel to test different kinds of activation of the shape change of the control element (results Nos. 2 and 3). The last iteration was conducted to simplify the product and integrate components and functions concerning a DfAM (result No. 4).

6.1 Result No. 1 – mock-up

The first mock-up was developed within a student project in a stadium, where the understanding of the interaction between the hand and the control device was nascent. The result therefore neither takes account of the requirement for a triangular shape, nor the optimum diameter that could be achieved. It was produced by means of laser sintering and is equipped with pressure sensors on each side to measure the radial hand force of the user according to (Janny and Maier, 2015). With the electric-motor-driven cam disc principle, the transformation of the shape can be continuously adjusted. Active shifting allows experience to be gained on different factors influencing the interaction with the control element, such as the influence of latency between the user task and the system response.

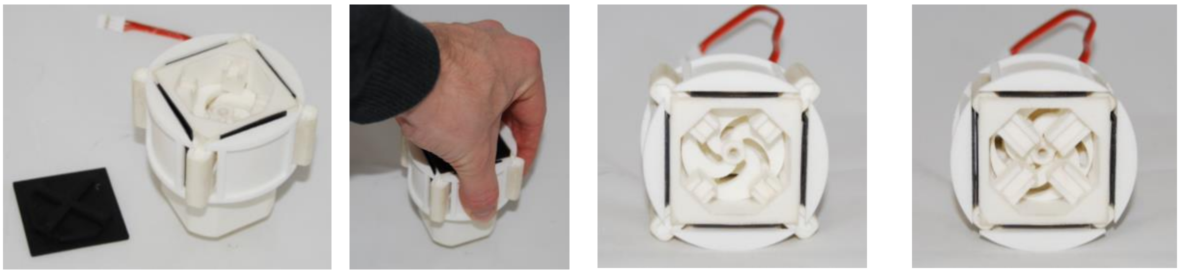


Figure 5. Result No. 1 – mock-up

The positive-locking elements of the mock-up are guided in tangential and axial directions by walls and in radial directions by the elongated hole in the cam disc. To prevent the different components from melting together during the production process, AM requires sufficient separation of the positive-locking elements and the guiding elements. For the EOS Formiga P100 LS machine used, the gap has to be larger than 0.6 mm (Wegner und Witt, 2012). Although the solution works in principle, the necessary cavity leads to inaccurate guidance of the positive-locking elements and reduced user comfort.

6.2 Result No. 2 – functional prototype

The first functional prototype uses extendable and retractable wedges that are moved by the kinematic principle of inclined planes to transform its shape. Normal hand forces applied during interaction are collected via force-sensitive resistors and read by a microcontroller. In case the collected forces exceed a force value indicating user exhaustion, a solenoid locking mechanism, which serves to maintain shape stability, is released and shape transformation by means of hand force is enabled. The diameter of the control element changes depending on the shape state and had to be slightly bigger than 50 mm in order to implement an adequate travel range of the positive-locking elements.

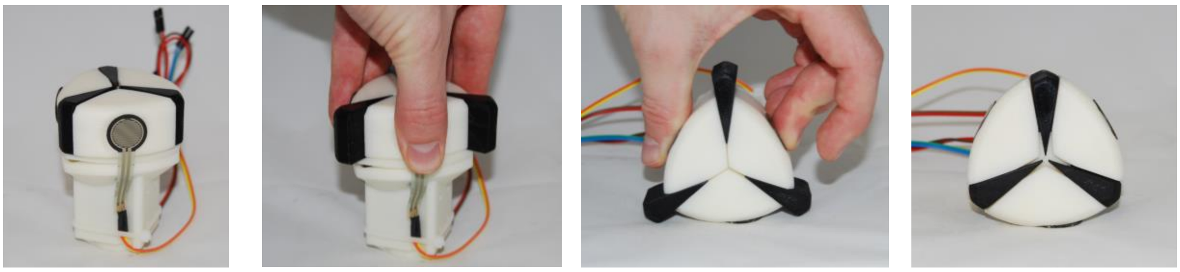


Figure 6. Result No. 2 – functional prototype

The prototype is assembled from FLM-produced ABS components, a solenoid and a retaining spring. During power grip interaction, bending deformation of the ABS positive-locking elements occurs, which reduces the user’s comfort and indicates insufficient stability characteristics for high torque values.

6.3 Result No. 3 – functional prototype

The second functional prototype uses the kinematic principle of a spindle drive to transform and maintain its shape. Normal hand forces applied during interaction can be collected via force-sensitive resistors, like in result No. 2, and read by a microcontroller. In case the collected forces exceed a force value indicating user exhaustion, an electric motor drives a spindle, which enables shape transformation. The axial movement of the spindle is converted into a radial extension of the positive-locking elements via a lever and swivel joints and is characterized by self-locking behavior.

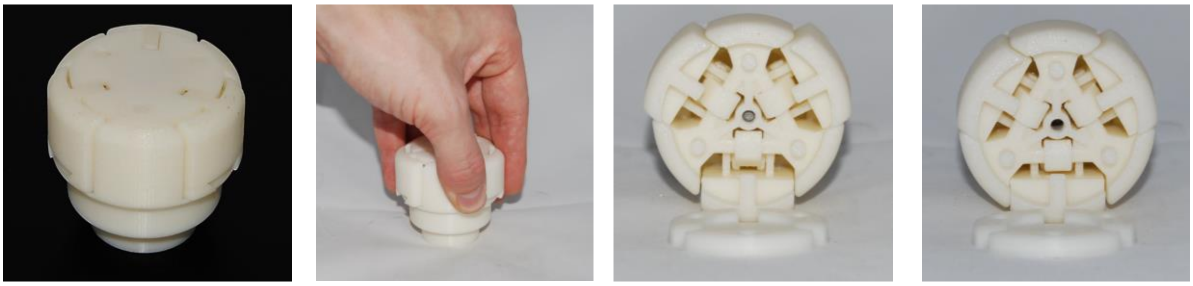


Figure 7. Result No. 3 – functional prototype

The second functional prototype is assembled from one FLM-produced ABS unit, an electric motor and a spindle. The travel range of the positive-locking elements of the second functional prototype is limited to 3.5 mm and therefore barely enables a full positive-locking fit for the transmission of greater forces. Due to the obligatory free space in the swivel joints with AM, the positive-locking elements show a certain backlash in radial directions. Compared with the first mock-up (Section 6.1), the guidance of the positive-locking elements is more accurate due to the increased number of suspension points and the dovetail guide.

6.4 Result No. 4 – preliminary end product

While designing the previously discussed prototypes according to classical engineering solution principles, attempts were made for the third iteration to substitute the classic solution principles with an AM-compliant design solution. To increase the level of function integration, it was defined as a requirement that the adaptive control element should be entirely produced by means of additive manufacturing and not depend on additional parts. An additional goal was to decouple the movement of the positive-locking elements. The used design solution of crossed flexible joints was selected from a design catalog as described in (Weiss et al., 2016). There, the solution principle is allocated to the channeling of energy and was selected based on the function to channel the hand force through the control element (Figure 4). The outcome is shown in Figure 8.

Figure 8. Result No. 4 – preliminary end product

Result No. 4 is produced as one piece and does not use sensors or actuators to fulfill the function of an adaptive control element. The design uses the solution principle of crossed flexible joints to enable and reverse a shape transformation. This enables the movement of the positive-locking elements to be decoupled. The solution principle fulfills the functions of providing a rotary degree of freedom for the transformation as well as providing the stiffness required for storing the cylindrical shape for positioning tasks. The shape transformation is initialized and controlled by the extent of gripping forces used during interaction. This means that the structural resistance of the joints ensures shape stability during interaction for small gripping forces used during fine motor positioning tasks. By applying high gripping forces, the joints deform, thereby enabling the fingers to perform a positive-locking fit with the control element. As soon as the external forces decrease, the elastic energy of the joints returns the shape elements to their initial position. Owing to the lack of external actuation, the level of force for the transformation of the shape cannot be adjusted variably, but rather depends on the form of the crossed flexible joints chosen prior to this. The solution principle comprising crossed flexible joints further fulfils the function of channeling the hand force through itself for both possible user tasks. The application-oriented optimization of the joints is the main design challenge. The required deformation force and the stability for channeling the maximum hand force need to complement each other. The reversion to the initial shape was not examined in long-term studies, but is sufficient according to preliminary tests. The configuration shown in Figure 8 includes several undercuts and is therefore only producible to a limited degree with conventional manufacturing technologies.

6.5 Comparison of the design results

To compare the results of the iterations in a more differentiated way, their fulfilment of the requirements presented in Sections 4 and 5 are assessed and their functional specifications are compared in Table 1.

Table 1. Summarized characteristics of the developed adaptive control elements

	HMI assessment			AM assessment			Functional specification				
	Two different shape	User comfort	∅ ≤ 50 mm	Conventional	Number of assembled	Material volume [cm^3]	Kinematic of shape-transformation	Actuating force (Δ→O)	Actuating force (O→Δ)	Maintaining shape stability	Detection of human level of exhaustion
Result No. 1	+	-	-	+	13	124	Cam disc principle	Electric motor	Electric motor	Holding torque of electric motor	Grip force measurement via force sensitive resistor-sensors
Result No. 2	+	0	0	+	12	117	Principle of inclined planes	Hand force	Retaining spring	Locking mechanism controlled by solenoid	Grip force collected via force sensitive resistor-sensors
Result No. 3	+	0	+	-	3	50	Spindle drive	Electric motor	Electric motor	Locking mechanism of spindle	Grip force collected via force sensitive resistor-sensors
Result No. 4	+	+	+	0	1	37	Flexible cross joints	Hand force	Elastic energy of deformed cross joints	Hand force	None

Each result fulfils the requirement of two different configurations for power grip and precision grip. This requirement therefore does not contribute to the comparison. The user comfort improves through the iterations and can be rated as satisfactory by result No. 4. The requirement for a diameter below 50 mm is fully met by results No. 3 and 4. The diameter of No. 2 may be slightly larger than requested depending on its state of shape. The manufacturability of the design with conventional technologies is an indicator of a Design for AM. While No. 1 and 2 can be manufactured with conventional technologies, result No. 3 is only producible using AM. Result No. 4 is designed for AM, but could be redesigned – for example for injection molding – with some adjustments. The requirement for few assembly steps can be addressed by the number of assembled parts. This number decreases with each iteration until it is reduced to just one part in result No. 4. The volume of the processed material shows the same tendency.

7 DISCUSSION AND OUTLOOK

The present paper describes the design process for an adaptive control element using additive manufacturing. The previously described development process shows that AM is a suitable tool for the design of user-centered interfaces. A key advantage is the cost- and time-effective production of numerous complex and functional prototypes for repetitive user testing and evaluation throughout the design process. The design task with several iterations could not be performed in the same time with only using conventional manufacturing technologies.

The available plastic materials for FLM technologies were entirely adequate for an adaptive control element, as ABS meets the comfort and safety requirements for skin contact and the occurring forces are relatively low. The emerging component properties were able to be reproduced in a stable enough manner for application in this paper and the possible lot size played a subordinate role. The easy removability of support structures was a particular difficulty in terms of the FLM technology used.

Apart from that, it could be observed that a higher number of physical and functional prototypes led to more creativity within the design process and more innovative solutions. The use of AM for prototyping and a Design for AM supported the development of creative solutions, even if the preliminary end product of this paper can be redesigned for production with conventional technologies.

The influence of a function-oriented approach in the Design for AM can be observed in the developed control element. AM-compliant solution principles differ from conventional ones, such as for machining. The results exhibit a tendency from simple shapes and complex solution principles to simple solution principles and complex shapes through the course of the iterations. To reduce the negative effects of the imprecision of AM on the product, the need for high accuracy has to be avoided by a clever, force-dependent design. This integration of function involves a part integration, which reduces assembly steps and the material needed for the product, however. In terms of production, the preliminary product has small dimensions, which reduces costs. During the development of the control element, it could be observed that the inaccuracy of the used FLM process without post-processing causes particular difficulties in the connections to more accurately manufactured parts such as the sensors and actuators.

During development, several steps of function and part integration had to be performed, including for example the implementation of double-sided, locked swivel joints. Accompanying these measures, continuous implementation of design guidelines proved to be essential for ensuring the manufacturability of the control element. The guidelines referred to did not provide support in determining the solution principles, but were indispensable for examining the detailed product design for the AM technology used. This means that they do not contribute to the conception of a design, yet help to verify the manufacturability of the embodiment design. The verification with technology-specific guidelines was needed repeatedly subsequent to major changes of the design for function integration. Although the guidelines referred to provided explicit values for determining the appropriate dimensions and shapes, it transpired that a verification of the design with iterations in the production could not be avoided because the manufacturing machines that were used created slightly differing results.

While the preliminary end product meets a high number of the defined design requirements, detailed user evaluation with a large group of subjects still has to be conducted in order to finalize the design. The main issue surrounding its applicability is the correlation of the required deformation force and the maximal fracture torque of the design, which may still limit its applicability.

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ACKNOWLEDGMENTS

This work was partially funded by the German Research Foundation (DFG) within the scope of the research project “Personalization options for hand-operated interfaces for the transgenerational user”, grant MA 4210/6-1.