Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

An Automated Design Approach for Task-Specific two Finger Grippers for Industrial Applications

Andreas Schroeffer, Christoph Rehekampff and Tim C. Lueth, *Senior Member IEEE*
Institute of Micro Technology and Medical Device Technology (MiMed)
Technical University of Munich
Boltzmannstraße 15, 85748 Garching, Germany
andreas.schroeffer@tum.de

***Abstract* - Automatization is a central goal in the context of industry 4.0 to ensure the international competitiveness of whole economic sectors. In the production industry the handling of products is an important task thereby. With the ongoing trend towards individualization of products, more and more individual grippers are necessary to meet the high requirements towards the fulfilling of handling tasks. Additive manufacturing describes the layer wise step by step generation of individual parts and enables a possibility for a cheap and quick generation of individual parts. Thus, it's the perfect technology to generate individual and task-specific optimized grippers. Extrusion-based processes thereby not only allow high performant polymer materials, but also multi material combination in a part to realize resilient hard soft transitions.**

At the moment the time consumptive part in the realization of individual grippers is not in the fabrication anymore, but in the design phase. In this paper an automated design process for individual two finger grippers for the fabrication with additive manufacturing is proposed. The input information for the algorithm is given by a boundary representation of the object to be grasped and the desired gripping forces. A standard servo motor is used as drive and automatically selected from da database to fit to the task specifications. The linear motion of the gripper jaws is realized by a gear rack transmission. The gripper jaws are adapted to the handling object to allow a form closure grasp and an approach is proposed to reduce gripping forces by a compliant structure. A first prototype is presented, showing the concept. Experiments are performed to characterize the fabrication technology and the resulting gripper forces.

Index Terms* – *Gripper Design, Additive Manufacturing, Automated Construction

I. Introduction

In the context of globalization and increasing international competition, flexibilization and individualization in the production are important tasks for securing the competitiveness of whole branches and manufacturing sites. One way of reducing costs in the production industry is through automation. This allows both the reduction of personnel costs at the one hand and the assurance of a high throughput at constant quality level for monotonous tasks on the other hand [1].

The handling of components and semi-finished products thereby is an important task in an automated industrial production. A classification of handling tasks can be made between transport and assembly. The transport includes inserting components into tools or placing them on conveyor belts, where assembly includes mounting, manipulating or machining. The interface between the robot, executing the handling task and a work piece is represented by grippers and has a considerable influence on the fulfilment of the task [2].

There are many fields of application for gripper technology, such as the food industry, the automotive industry, or medical technology, where each of these industries has special requirements. Grippers can be distinguished in different groups by the principle of force transmission between the gripper and the handling object. There are three physical gripping principles: hold by force (friction, vacuum, magnetic or electrostatic), hold by material closure (gluing or freezing), and hold through form closure (pair of form elements or interlock) [3]. For transportation issues in production mechanical grippers showed to be very popular in industry (hold by friction force or form closure). Mechanical grippers can be subdivided into point-like, linear or three-dimensional contact types [4].

There are a few big suppliers for gripper technology on the market. Among the leading European suppliers are AFAG, Festo, Sommer Automatic and Schunk, who all established parametric modular systems of grippers. These systems include standard approaches for mechanical grippers such as 2 and 3 finger parallel grippers, radial grippers and vacuum grippers, with different sizes and forces correspondingly. However, the most sold and used in industry are 2 finger parallel grippers [5].

Individual grippers, with task specific gripper jaws for a contour close grasp or properties such as individual stiffness or force can realize a gentler gripping process. These properties can improve a gripper performance in the form of increased reliability and productivity for complex tasks like the grasp of breakable or deformable objects.

Especially in the background of individualization of production the automatization of design and manufacturing can be an opportunity to overcome the current challenges. For highly complex individual components additive manufacturing can be used for a cost-efficient fabrication of prototypes with a high degree of freedom of shape [6]. The design of functional prototypes and individualized products thereby is a complex task for mechanical engineers. The design and construction of grippers is an example therefore, because beside the pure geometric construction, also kinematic design and drive design are important parts to generate functional products. Compared to traditional manufacturing methods and processes, in additive manufacturing there is a change in effort from fabricate a product to design it. In addition to the pure fulfillment of the functionality, such as the realization of a handling task there are a lot of difficulties to take care of. Besides the compliance with

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

the fabrication limitations and minding the resulting part characteristics, there are numerous other optimization parameters, as explained and demonstrated by [7]. Other relevant quality-defining criteria for grippers can include lightweight design, reduction of fabrication time and material, choosing appropriate fabrication parameters and function integration to take the full advantage of the technology.

II. State Of The Art

A. Individual Gripper Design

As already mentioned in the introduction most gripping systems are designed just by choosing the best fitting gripper from the modular construction system of the original equipment manufacturer and adjust them to the problem by software solution or manual gripper jaw design. In this section the focus should lie on supporting systems and automatization approaches.

Automatization can cover all parts of mechanic gripper design, from, gripper selection, gripper conception, grasp planning and analyzation, dimensioning or construction.

A big focus to the research is on grasp planning. Input for these algorithms mostly are given by CAD data. In general, there are three different approaches: Analytical, heuristic, or data driven trials [8]. A comprehensive overview is given by [9]. The result of these algorithms is the position and relation of the gripper jaws to the handling object.

Also, tools for supporting the dimensioning of the gripper and automated selecting were developed. Pedrazzoli et al. suggest a simple rule based system for gripper selection [10]. Schmalz et al. implement a multistage process combining rules and simulations [11] and extends the selection of gripper with a dimensioning of the gripper jaws and adaption towards construction of gripper jaws for a form closure grasp [12].

There are a lot of individual gripper design studies in the literature, but most don't have the automation compatibility. There are modular designs, reconfigurable design and customized designs [8]. Modular designs work with a simplification of the handling object and choose the best fitting design from a library, such as shown in [13-14]. Reconfigurable designs change parts of the concept for example finger positions [15-16]. Customized design means a full design adaption of the gripper to the specific task, as realized by [17]. Furthermore, there are already approaches for optimizing single design steps, such as gripper mechanics or kinematics [18].

B. Additive Manufacturing

Additive Manufacturing describes the layer wise step by step generation of individual parts. For the fabrication no additional tools are necessary, only a digital 3D representation of the part. Usually Standard Tesselation Language (STL) is used, that gives a surface triangulation of the object. Compared to traditional fabrication techniques for polymers, like injection molding or extrusion the freedom of shape is nearly unlimited. But of course, based on the technology there are different restrictions and opportunities respectively [19].

The most important technologies at the moment are selective laser sintering, powder-binder printing, stereolithography and extrusion-based processes.

Extrusion based processes, such as Fused Filament Fabrication usually show a lower resolution compared to the other technologies, what goes along with a stronger staircase effect and bigger minimal wall thicknesses, but the range of available materials is bigger. Furthermore, it allows multi-material processing what is necessary to realize hard soft structures [20].

Plastic freeforming is an extrusion-based process that works with the generation of droplets from a thermoplastic polymer melt [21]. Fig. 1 gives an illustration of the manufacturing process. An unique feature of this process is, that it uses standard polymer material which is also used in conventional injection molding processes. The machine allows to process with three materials at one time, what allows to generate resilient hard soft parts.

C. Automated Construction for Additive Manufacturing

Additive Manufacturing enables new possibilities in term of freedom of shape, but also needs a high process understanding of the construction engineer. This is due to the nature of the layer-by-layer manufacturing process, which is associated both with inevitably resulting inaccuracies such as the staircase effect and with resulting anisotropic component properties.

To take advantage of the possibilities of this technology a new approach of design is necessary. Complex geometries and iterative infill structures can only be hardly realized manually in traditional CAD programs without violating process-based restrictions. This is the opportunity for new function-orientated design approaches, where the designer only specifies tasks and restrictions and an algorithm automatically designs the geometry taking care of all restrictions as described in [22].

The Institute of Micro Technology and Medical Device Technology develops a matlab toolbox for automated construction (SG-Lib) in the field of 3D printing now since over 10 years [23]. The toolbox works with boundary representations of the bodies and provides functions for geometry creation and manipulation, transmission calculation for linkages and gears multibody simulation, and FEM based topology optimization.

III. Concept

The idea is to have a simple specification of the gripper to be designed automatically using the SG-Lib. The only necessary input should be the geometry of the object to grasp and the necessary grasping forces. Fig. 2 gives an overview.

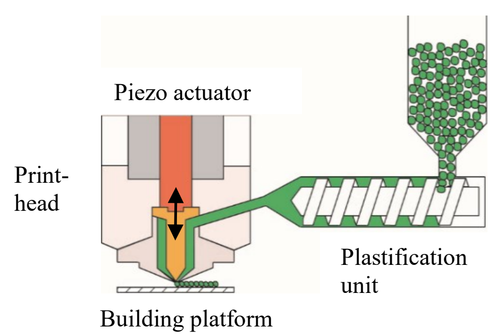

Fig 1. Illustration of the working principle of Arburg Plastic Freeforming (APF) based on [21].

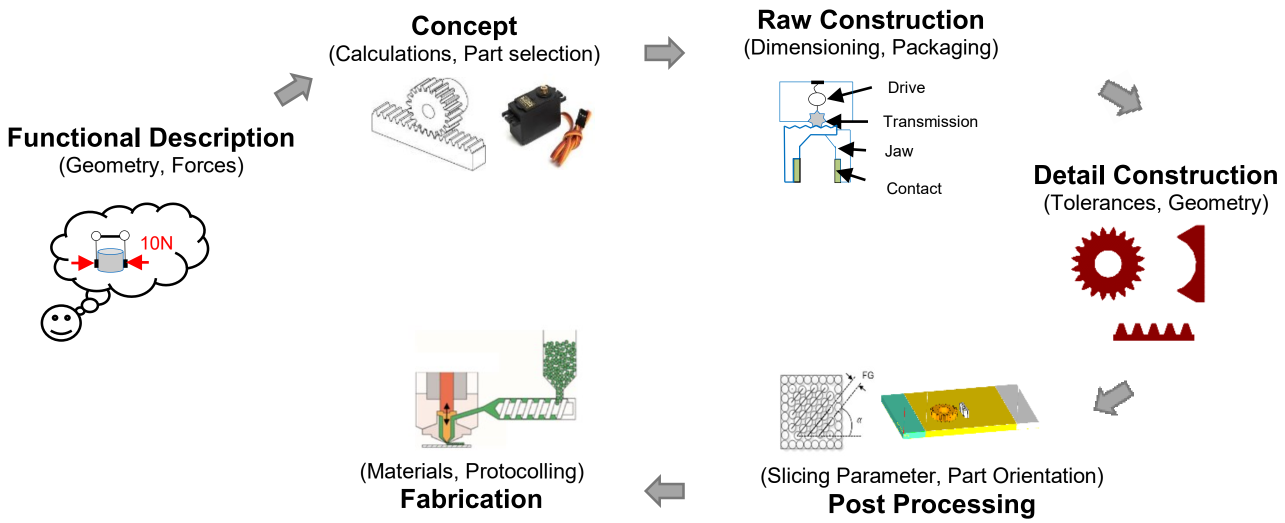

Fig 2. Concept for the automated design process of task specific individual two finger grippers. A functional description of the geometry and the forces are necessary to select the drive and calculate the transmission. With the servo motor and the jaw bounding box a raw constriction is made before the detail constriction is performed. Then the slicing parameter and part orientation is selected automatically. The last step then is the fabrication.

A. Functional Description and Concept

The input for the design process is given by the geometry of the object to be grasped in STL format and the desired gripping forces. If not specified differently the workspace of the gripper jaws (opening width) is calculated by the bounding box of the handling object with a security factor s = 1.5 according to (1). A servo motor is used to actuate the gripper. Servo motors are integrated electronic devices with a motor, a position sensor and a control unit. They are available in different sizes with different forces, thus a task specific selection is possible. A little data base is used for the presented work shown in Table 1. The control is realized with a PWM signal, where the length of the signal indicates the desired position. The angle $\Delta\vartheta$ range is limited from 0° to 180° by construction. The forces at the jaws can be described by the moment of the drive, the transmission ratio and losses through friction as described in (2). The transmission ratio d_{Gear} can be varied from 9mm to 35 mm in the current design. Accordingly, a spread in the gripping force from 13N to 135N can be realized, assuming that the friction is low in the first place.

$$s_{Jaw} = s \; x \frac{BB_{Obj}(2) - BB_{Obj}(1)}{2} \qquad (1)$$

$$F_{Jaw} = \frac{2 \; x \; M_{Drive}}{d_{Gear}} - F_{Friction} \qquad (2)$$

B. Dimensioning and Constructing

The construction mainly covers the housing, the transmission (gear and rack), the linear bearing and the gripper jaws.

The housing is necessary to connect all other functional elements together. There has to be an interface for mounting the servo, realize a plain bearing for the servo shaft and a connection to the linear bearing for the gripper jaws. Because all servos have other mounts and adapters an automatic feature surface detection is used, to allow an easy extension of the servo data base. Fig 3. shows the result of the servo analyzation including frames and contours for mounts and the shaft. The size of the housing is determined by the bounding box of the servo and the pose of the attached frames for mounts and shaft. A first easy bionic inspired 2D lightweight approach is used show more in detail in the realization section.

A dovetail guideway approach is used as linear bearing between the housing and the gear rack of the jaws. The fabrication parameters for the realization of a play bearing were determined experimentally and are presented later.

For the construction of the gear rack transmission the SG-Lib is used. For a more detailed description of the design of gears for additive manufacturing it should be referred to [24].

To generate a homogeneous force distribution and minimal pressure on the handling object the contact area between the gripper jaw and the handling object should be maximized. In the current state only the 2D problem is solved. The procedure starts calculating a bounding box (BB) around the handling object. The middle part is cut away to separate the BB to two separate raw jaws represented by closed polygon lists. Then in a second step the handling object is subtracted from the raw jaws by a Boolean operation. To solve the problems due to undercuts during the opening and closing process the jaws are iteratively moved translatively and the handling object over and over is subtracted. The procedure is visualized in Fig. 4a.

To make the jaws adaptive to compensate variabilities in the object geometry or alignment a first approach to make them kind of compliant is proposed. For this, through shrinking the contour to the inside and Boolean subtraction from the origin the thin jaw borders remains as visualized in Fig. 4b.

C. Data Postprocessing and Fabrication

Postprocessing includes automated slicing parameter determination and build job preparation. For example printing two border contours helps to improve the tooth flank resistance. The part positioning is solved very easy by evaluating the bounding boxes of the parts and moving the parts that long that there is no overlap anymore. A detailed description of the slicing procedures for droplet based AM is given in [25].

TABLE I
SERVO MOTOR DATABASE

Servo Name	Torque	Speed
Hitec HS-70MG	29 Ncm	$0.21\,\frac{sec}{60°}$
Hitec HS-645MG	77 Ncm	$0.24\,\frac{sec}{60°}$
Hitec HS-625MG	55 Ncm	$0.18\,\frac{sec}{60°}$

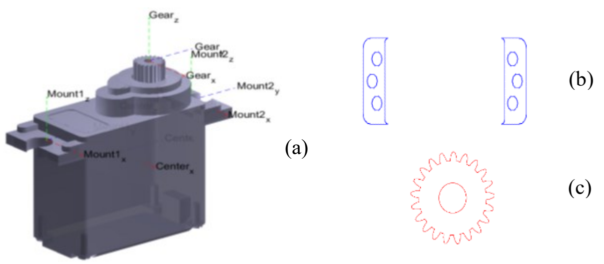

Fig 3. Autotmated feature surface detection for standard servos, based on slicing procedures. Geometry with attached frames for mounts and shaft (a), 2D geometry of the mount (b) and the shaft (c)

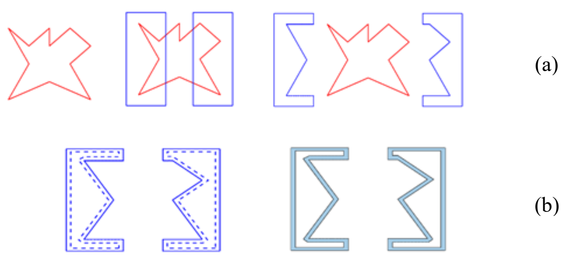

Fig. 4. Illustration of the construction algorithm to generate individuall gripper jaws. Object (a left), Raw jaws as in the middle cutted bounding box (a middle) and final jaws (a right). Shrinking contour approach (b) to generate a compliant structure for the jaws.

IV. Realization

In the first place the jaw construction algorithm was tested for different geometries. Fig. 5a shows a little selection. Different approaches for generating a compliant structure inside the jaws were tested. Therefore, shrinking contours were used to generate thin structures that appear to be flexible, thought the material is brittle (Fig 5b). The left approach showed to be the most promising. Fig. 5c shows the test set with different parameters for realizing a movable structure for a linear bearing and Fig. 6 gives the technical drawing. A space f of 0.3 mm enabled a good seat in the bearing with still low friction during the movement. In Fig. 5d a gear rack pairing is visualized. A complete mounted prototype is shown in Fig 7.

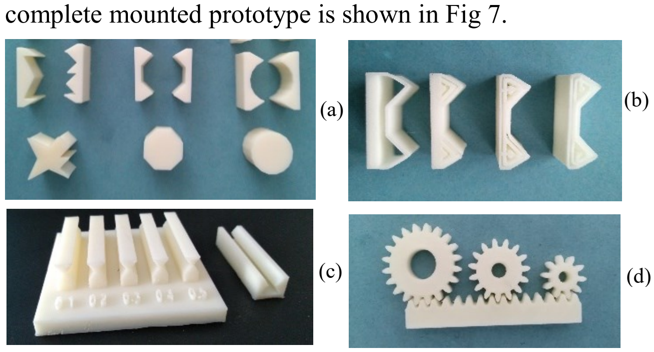

Fig. 5. Different individual jaw geometries (a), some approaches to generate compliant structures (b), a test set for the linear bearring (c) and a gear rack transmissiom 10mm – 20mm (d)

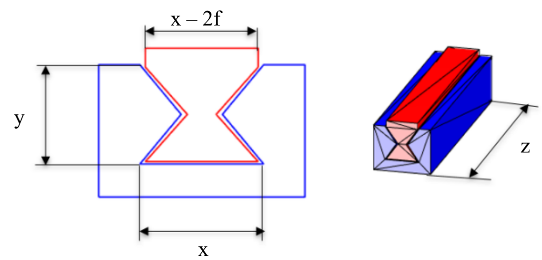

Fig. 6.Construction and parameters for th dovetail linear bearing. Experiments were performed with fixed x = 6, y = 6, z = 40mm and varying f showing the best result at f= 0.3

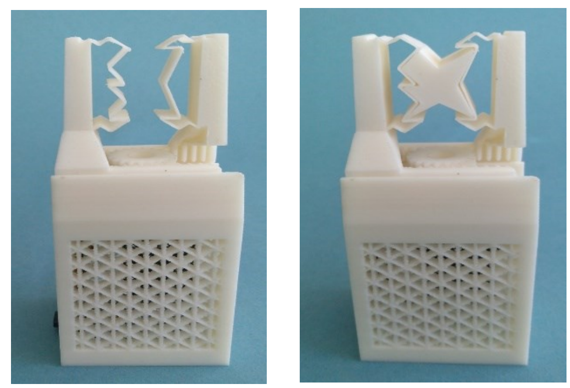

Fig. 7. Protoyp of an automated constructed two finger gripper for a specific task.

V. Experiments

All experiments were performed with a 2K Arburg freeformer. Acrylnitril-Butadien-Styrol (ABS), a very common polymer for additive manufacturing was used in combination with a water solvable polymer for support structures (ARMAT 21). The fabrication parameters are listed in Table 2. First some test parts have been fabricated to determine the tolerances of the 3D printer and to parametrize the construction algorithms. Afterwards experiments are shown to estimate of the friction forces $F_{Friction}$.

A) Printer Characterization and Tolerances

First constant shrinking factors were determined, that are used to scale the STL geometries before the fabrication to compensate shrining effects (Tab 3).

With the calibrated STL scaling parameters different test bodies have been fabricated to characterize the machine. Fig. 8 shows the printed test parts.

TABLE II
MACHINE PARAMETERS (ABS/ARMAT21)

Nozzle Diameter	0.2 mm / 0.2 mm
Layer thickness	0.2 mm
Extrusion rate	66%/ 60%
Droplet size	0,2 x 0,26 x 0,26 mm / 0.2 x 0.2 x 0.2 mm
Build Chamber Temperature	90 °C
Nozzle/Melt Temperature	230 °C / 235 °C
Print Head velocity	Discrete Disposure 12 mm/s Continuous Disposure 40 mm/s

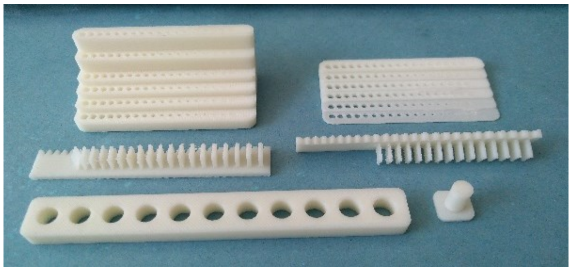

Fig. 8. Test parts to determine the printer tolerances.

B. Determination of the Friction Forces

The total losses, here called $F_{Friction}$ are caused by different reasons. The biggest issues probably are caused by the gear rack transmission and the linear bearing. Furthermore, linear deformation effects in the whole gripper probably also give a part to the losses. $F_{Friction}$ is a dynamic force but should be determined for the gripping process in closed state with (2). The used gripper, shown in Fig. 6 is equipped with a Hitec HS-645MG Servo with 23*Ncm* and has a gear diameter d_{Gear} of 20mm. Accordingly, the theoretical gripping force without friction should be 23N. A test bench was built to determine the friction. A visualization is given in Fig. 9. Therefore, a digiforce 9310 measurement device with a 50N force sensor (KD45 50N) was used. First trials showed that the velocity with that the jaws close have an impact to the gripping forces. Therefore N =10 grasp measurements have been performed at two different speeds to calculate a mean force $\overline{F_{Jaw}}$ according to (3) and the deviation of the forces between several grasp procedures according to (4).

$$\overline{F_{Jaw}} = \frac{1}{N}\sum_{i=1}^{N} F_{Jaw\_i} \quad (3)$$

$$\sigma = \sqrt{\frac{1}{N-1} * \sum_{i=1}^{N}\left(F_{Jaw\_i} - \overline{F_{Jaw}}\right)^2} \quad (4)$$

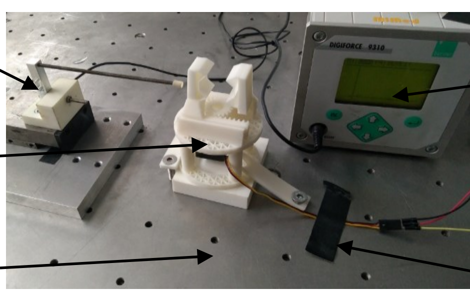

Fig. 9. Test bench for measuring the gripping forces and determining the friction force

VI. Results and Discussion

Table 3 shows the results of the evaluated constructive parameters and reachable tolerances for the used machine and material pairing. The achievable accuracy is, as usual for extrusion-based processes, in Z direction very much lower than in XY-direction. Anyway, that is no issue, due to the freedom of part orientation, and the knowledge-based alignment of critical parts, such as the gear tooth, or the linear bearing. The other parameters give constructive guidelines, e. g. for the bionic house design, where the wall thickness is chosen to two droplet diameters.

The results of the grasp force measurement are presented in Tab. 4. As already mentioned, the gripping speed has a significant influence on the applied gripping force. A reason for this can be that the velocity energy enables to reach a higher peak force and the friction that is lower during closing process (slip phase) works in the closed phase even with a higher altitude (stick phase) with the gripper jaws and is partially added on the gripping force. The deviation in forces was under 5% for both measurement series, what is a pretty good result considering to good design and predict the gripping force. Anyway, the result of reaching 62% respectively 73% of the theoretical possible force is a good result, considering that all parts of the gripper have been fabricated by additive manufacturing.

TABLE III
Tolerances and Constructive Parameters (Abs/Armat21)

Scaling Parameter	**Armat21**	**ABS**
X Axis	1.0	1.09
Y Axis	1.0	1.09
Z Axis	1.0	1.0
Constructive Parameter	**Determined Result**	
Minimal wall thickness (XY)	0.5 mm	
Minimal wall thickness (Z)	0,4 mm	
Minimal drill dimeter (h = 0.6 mm)	0.4 mm	
Minimal drill dimeter (h = 3.0 mm)	0.62 mm	
Movability tolerance cylinder/drill (assembly print)	0.25mm	
Movability tolerance cylinder/drill (non-assembly print)	0.2mm	

TABLE IV
Grasp force measurements and evaluation

Run	Speed 1 [cm/s]	Speed 2.5 [cm/s]
1	14.99	17,02
2	14,57	17,14
3	14,57	16,8
4	14,4	16,91
5	13,95	17,02
6	13,92	16,88
7	13,86	17,00
8	14,74	16,85
9	14,51	16,97
10	14,82	17,05
$\overline{F_{Jaw}}$	14,37	16,96
σ	0,346	0,098
$\overline{F_{Friction}}$	8,63	6,04

VII. Conclusion and Further Work

In this paper an automated design algorithm for individual two finger grippers for the fabrication with additive manufacturing is presented. Only the geometry of the handling object and the desired gripping forces are necessary. The servo drive is selected automatically, and an individual transmission is calculated to achieve the set forces. The construction is performed process-specific to ensure a high-quality and functional gripper. The output of the algorithm is a build job including the STL files of all parts, as well as the slicing parameters. Several examples are shown and measurements are performed to determine the losses due to friction.

At the moment the algorithm only works for 2D objects, due to challenges with Boolean operation on STL files. Future work will focus enabling 3D geometries. Furthermore, the full capacity of the fabrication principle should be used, combining hard and soft material in one build job.

ACKNOWLEDGMENT

The authors would like to thank Arburg GmbH & CoKG for providing a 2K Arburg freeformer and additional printing equipment to realize this concept.

REFERENCES

[1] H. Lasi, P. Fettke, HG. Kemper, T. Feld and M. Hoffmann : „Industrie 4.0“, *Business & Information Systems Engineering*, vol 6, 2014, pp 239–242.

[2] A. Wolf and H. Schunk: „Grippers in Motion“, *Carl Hanser Verlag, Germany,* 2018, pp. 14-45.

[3] H. Stefan: „Greifertechnik. Effektoren für Roboter und Automaten“, *Hanser Verlag*, *Germany*, 2011, p. 10.

[4] A. Thallemer, M. Danzer, D. Diensthuber, A. Kostadinov and B. Rogler: „Industrial Design optimization for 3D printed biometric grippers in titanium alloy “, *3dr International Conference on Process in Additive Manufacturing, Singapore,* 2018, pp. 262-267.

[5] L. Birglen and T. Schlicht: „A statistical review of industrial robotic grippers“, *Robotics and Computer-Integrated Manufacturing*, vol 49, 2018, pp. 88–97.

[6] T. Wohlers: “Wohlers report 2017”, *Fort Collins*, *Colorado, USA*, Wohlers Associates, 2017 pp. 176-201.

[7] G. Dämmer, S. Gablenz, A. Hildebrandt and Z. Major, “Design of an Additively Manufacturable Multi-Material Light-Weight Gripper with integrated Bellows Actuators”. *Advances in Science, Technology and Engineering Systems Journal,* vol. 4, 2019, pp. 23-33.

[8] M. Honarpardaz, M. Tarkian, J. Ölvander and X. Feng: „Finger design automation for industrial robot grippers: A review“, *Robotics and Autonomous Systems*, vol 81, 2017, pp. 104-119.

[9] A. Sahbani, S. El-Khoury and P. Bidaud: “An overview of 3D object grasp synthesis algorithms”, *Robotics and Autonomous Systems*, vol. 60, 2012, pp. 326-336.

[10] P. Pedrazzoli, R. Rinaldi and C. R. Boer: "A rule based approach to the gripper selection issue for the assembly process,", *IEEE International Symposium on Assembly and Task Planning*, *Fukuoka, Japan*, 2001, pp. 202-207.

[11] J. Schmalz, and G. Reinhart: „Automated Selection and Dimensioning of Gripper Systems “, *Procedia CIRP*, vol. 23, 2014, pp. 212-216.

[12] J. Schmalz, L. Giering, M. Hölzle, N. Huber and G. Reinhart (): „Method for the Automated Dimensioning of Gripper Systems“, *Procedia CIRP,* vol. 44, 2016, pp. 239-244.

[13] D. T. Pham, N. S. Gourashi and E. E. Eldukhri: “Automated configuration of gripper systems for assembly tasks”, *Proceedings of the Institution of Mechanical Engineers*, 221(11), 2007, pp. 1643–1649.

[14] F. Sanfilippo, G. Salvietti, H. Zhang, H. Hildre, and D. Prattichizzo: “Efficient Modular Grasping: an Iterative Approach”, *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, *Rome, Italy*, 2012, pp: 1281-1286.

[15] R. C. Brost, and R. R. Peters: “Automatic Design of 3-D Fixtures and Assembly Pallets”, *International Journal of Robotics Research*, 17(12), 1998, pp. 1243–1281.

[16] L. Balan and G. Bone: “Automated Gripper Jaw Design and Grasp Planning for Sets of 3D Objects”. Journal of Robotic Systems. vol 20., 2003 pp- 147-162.

[17] J. V.B. Velasco and W. Newman: “Computer-assisted gripper and fixture customization using rapid-prototyping technology”. *Proceedings - IEEE International Conference on Robotics and Automation*, vol 4., 1998, pp. 3658 – 3664.

[18] S. Krenich: “Multicriteria Design Optimization of Robot Gripper Mechanisms”. *Solid Mechanics and Its Applications*, vol. 117. Springer, 2004, pp. 207-218.

[19] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. W. Williams, C. C. L. Wang, Y. S. Shin, S. Zhang and P.D. Zavattieri, “The status, challenges, and future of additive manufacturing in engineering”. Computer-Aided Design, vol. 69, pp. 65-89, 2015.

[20] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. W. Williams, C. C. L. Wang, Y. S. Shin, S. Zhang and P.D. Zavattieri, “The status, challenges, and future of additive manufacturing in engineering”. *Computer-Aided Design*, vol. 69, 2015, pp. 65-89.

[21] K. Hehl, “Device for manufacturing a 3D object”, EP 2266782 A1, Patent, 2010.

[22] Y. Sun, L. Xu, J. Yang and T. C. Lueth: "Automatic Design in Matlab using PDE Toolbox for Shape and Topology Optimization." *2019 ASME International Mechanical Engineering Congress and Exposition, UTAH, USA,* 2019.

[23] T. C. Lueth, “SG-Library: Entwicklung einer konstruktiven MATLAB-Toolbox zur räumlichen Modellierung von Körpern, Gelenken und Getrieben“, 11. Getriebetechnik- Kolloquium 2015, Munich, Germany, pp. 183-204, 2015.

[24] M. F. Traeger, Y. S. Krieger, T.C. Lueth: „Automated construction of gear racks, spur gears and helical gears using Matlab & STL, files for rapid manufacturing, *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, *Wollongong*, *Australia*, 2013, pp. 1603-1608. 2013

[25] A. Schroeffer, J. Prša, F.Irlinger, T. C. Lueth: "A novel building strategy to reduce warpage in droplet-based additive manufacturing of semi-crystalline polymers", *IEEE International Conference on Robotics and Biomimetics*, *Kuala Lumpur*, *Malaysia*, 2018, pp. 1894 - 1899.