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Automated Configuration of Modular Gripper Fingers

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Abstract

The trend of individualization of demand presents companies with the challenge of preparing their production, on the one hand, for ever more extensive and complicated products, but on the other hand also an increasing variety of products. Handling, as a component of any automated process, plays an essential role in this context, since these non-value-adding process steps must run reliably and quickly, even for workpieces with a large number of variants. The performance of a handling system depends on the adaptation of the gripper's fingers to the respective workpiece since the fingers are the only components that have direct contact with the workpiece. Since the change of the gripper, as well as the production of new gripper fingers for adaptation, is time-consuming, modular gripper fingers are increasingly coming into focus. An overview of a holistic approach for the selection and dimensioning of gripper fingers from modules is presented in this paper. First, the requirements for gripper fingers are determined and converted into functions. Based on this, the overall structure of gripper fingers is broken down into modules according to technical and functional aspects. In the sense of variant-oriented product design, concepts for modules are developed, which are then designed together with the interfaces between the finger modules and between the finger and gripper. Gripping points with sufficient contact area on workpieces are determined with a gripping point determination. Based on the developed construction kit of gripper fingers for mechatronic parallel grippers and the characteristics of the handling objects as well as the determined gripping points, a method is then described that allows an automated configuration of gripper fingers with integrable sensors for a given number of workpieces.

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Keywords: Handling; Modular design; Design methodology; Adaptive manufacturing; Multi-function gripper fingers

1. Introduction

Handling processes are part of almost every automated process. In industrial mass production, where a few product variants are manufactured in large quantities, grippers must enable reliable, safe, and as fast as possible handling in order to save cycle time [2]. However, this paradigm of industrial production has changed in recent decades: The increasing individualization of demand and the accompanying increase in product variants illustrate a growing need for flexibility in production processes. The flexibility of a gripper is defined as its usability for a range of tasks without manual hardware changes [3]. To increase handling flexibility, grippers will have to realize fast, safe handling for an increasing number of different workpieces in the future. In addition, efforts are being made to use the non-value-added process steps of handling for additional process steps, such as quality control [4, 5]. Since grippers are the only components of the entire handling system that have direct contact with the workpiece the flexibility is largely determined by the finger design. This must be multifunctional for handling different workpieces and enable sensor integration, e.g. to inspect the objects during handling [6, 7]. Therefore, solutions have to be developed to assist in the design of grippers so that they can be quickly adapted to changing handling tasks.

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2. Background and Related Work

The flexibility of a gripper is determined by the number of different workpieces it can handle. Three approaches exist for handling multiple types of workpieces [4, 8]:

1. Replacement of the gripper for each workpiece.
2. Use of swivel systems. Here, several grippers are attached to a rotating wrist mechanism, whereby the appropriate gripper can be activated per task.
3. Use of multifunction fingers that allow handling of more than one workpiece.

Since multifunction fingers are cheaper, more effective and more reliable than end effector changes or swivel wrist mechanisms, the development of these fingers is increasingly becoming the focus of industry and research [9, 10]. Since the fingers are the only component of the entire handling system that has direct contact with the workpiece, the performance of a handling system depends largely on the functioning of the fingers [1]. As a result, several types of gripper fingers and gripper finger design approaches have evolved over time. Thus, a distinction can be made between simple, reconfigurable, modular, individual and flexible gripper fingers. Simple gripper fingers refer to fingers made of simple metal blocks without any adaptation to the workpieces to be gripped. Fingers which, on the other hand, can adapt independently to different workpiece geometries (e.g. soft or underactuated fingers) fall into the category of flexible fingers. Although flexible fingers can adapt to the geometry of different workpieces, these fingers can cause significant reconfiguration of the hand-object system, resulting in unwanted object movement [11]. Regardless of the type of gripper finger, the design of gripper fingers is currently still a predominantly manual and time-consuming development process that involves multiple iterations of finger design, fabrication, and testing [1]. So far, , however, there are some approaches that support or automate finger design, which are discussed below and essentially consider gripper fingers from the categories modular, reconfigurable and individual.

2.1. Design Support Approaches

Finger blanks, usually offered by gripper manufacturers, provide the least support for finger design. These are simple metal bodies whose dimensions and weight are within the manufacturer's specifications and which already have a suitable bolt flange for a gripper. The detailed design of the fingers and the effective surfaces is left to the user. The modular approaches, in turn, support the user in the design of the fingers by defining the modules and their combinability. Modules are physical groupings of components that can be treated as logical units. Modules should be designed in such a way that they can be used communally and combined with each other [12].

Li et al. [13] describe modules with an interface using magnets and gender design to design underactuated fingers for a two-finger gripper by combining these modules. The FiNGERKIT from Weiss Robotics is a gripper finger construction kit in two sizes for designing application-specific

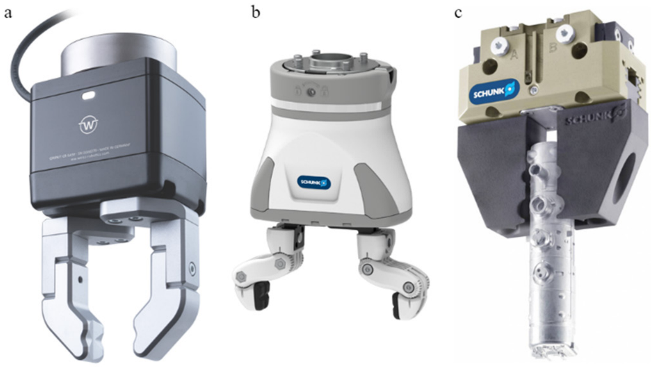

Fig. 1. Examples of three different design approaches: (a) Modular (Weiss Robotics FiNGERKIT); (b) Reconfigurable (Schunk flexible fingers); (c) Individual (Schunk eGrip)

gripper fingers from standard components [14]. In the area of reconfigurable approaches, the gripper fingers are designed in such a way that they can be adapted depending on the gripping task. The user thus no longer has to design the entire finger, but only its configuration. For the gripper EGH, Schunk offers flexible finger attachments with two joints each, which can be fixed via screws [15]. The Click&Grip system from PHD works similarly [16]. The fingers consist of a maximum of four elements that are connected via three joints. The angles of the finger elements can be adjusted by turning the joint elements in fixed increments and the finger shape can be fixed with screws. In addition, the finger bases can also be attached to the gripper perpendicular to the gripping direction. In Canali et al. [17] , a different number of identical and independent fingers can be attached to a base body and configured for a handling task. In the described approaches, the user is supported in the finger design by limiting the degrees of freedom. However, the final shape of the fingers is still determined by the user.

2.2. Design Automation Approaches

Approaches have already been developed for further support up to the finished design of fingers for handling tasks. In the area of modular fingers, there are approaches in which the shape of the workpiece is first simplified to basic geometries (e.g., sphere), and then suitable finger pairs are determined from a finger library [18, 19]. In Sanfilippo et al. [20], the gripper fingers are built up from identical modules that have one degree of freedom (DoF). An iterative procedure is used to determine the minimum number of required and combined modules to perform a task.

In the reconfiguring design approaches, e.g. cylindrical pins are automatically arranged like fingers on a base jaw of the gripper designed as a perforated plate, depending on the handling task [21, 22]. These approaches are quick and easy to implement, but many technical inputs are required to obtain reliable finger configurations [1]. Due to a consistent data flow and the enormous design scope, additive manufacturing processes are increasingly used in the design of handling systems and their components [23]. As early as 1997, [24] dealt with the design of individual gripper fingers for mechanical grippers using additive manufacturing processes. With the eGrip software, Schunk launched a commercial product for the automated design of gripper fingers in 2016 [25]. Here, the fingers are modelled as solid blocks from which the geometry of the workpiece is subtracted. The remaining block is additively manufactured. Further approaches for designing fingers for handling multiple workpieces are described in [1, 23, 26].

Although the described approaches simplify the design of gripper fingers, the supporting approaches still require considerable amount of expert knowledge. Furthermore, the design automation approaches usually have a high provisioning time if the fingers have to be manufactured for each task. In addition, none of the described approaches provides for the simple integration of sensor technology into the gripper fingers to further increase the flexibility of the grippers.

3. Goal and Approach

As already mentioned, the design of the active elements of grippers is of particular importance in an industrial context. As a link between the product and the handling system, they ensure safe handling. Furthermore, in the course of changing boundary conditions with more individual products, more dynamic product life cycles and, as a result, smaller batch sizes, ways are needed to quickly design reliable gripper fingers that can be adapted to changing requirements in a short time and that can increase the flexibility of the grippers by integrating sensor technology. The goal is to have a method that fully automatically suggests gripper fingers suitable for the application based on the information provided by the user (see chapter 5). In practice, the result of the method should enable rapid design or adaptation of the gripper fingers to new requirements. In addition, the method should be suitable for mechatronic two-finger parallel grippers since two-finger parallel grippers are most frequently used in industry [2, 5] and mechatronic grippers offer the possibility of evaluating sensor technology and reacting to sensor signals due to their internal electronics. The following describes the areas that must be considered to implement the method:

1. Determination of the Requirements for Gripper Fingers

Since the design of gripper fingers is usually carried out manually by experts, only the requirements of the handling task at hand and the local boundary conditions (e.g. existing infrastructure) are usually considered in the design. However, in order to design gripper fingers in such a way that they are suitable for different handling tasks and can be used under different boundary conditions, cross-task or generally applicable requirements must be determined and considered during design.

2. Development of the Gripper Fingers

The required short provisioning time can be achieved by using prefabricated fingers or finger elements. This brings modular or reconfigurable design approaches into focus. As previously described, the design or adaptation of the reconfigurable gripper fingers is achieved by changing the joint angles or the position of cylindric pins. However, this restricts the customization options, e.g. with regard to finger projection. For this reason, a modular design approach is to be pursued here, which enables a methodical subdivision of the gripper fingers into modules and their combination via a standardized interface. In addition, concepts must be developed for transmitting the sensor signals from the moving fingers to the static gripper housing.

3. Determination of Gripping Points

Depending on the developed finger modules and the existing effective area of the fingertips, the gripping points for both fingers must be found on the objects to be gripped. Existing approaches for determining the gripping points can be used here, which must be adapted and validated for the modular fingers.

4. Configuration of Fingers

The last step is the actual support of the user in the design of the gripper fingers. The minimum number of modular gripper fingers configurations needed to perform the required tasks must be determined based on the objects to be gripped and the associated gripping points.

4. Procedure of Developing the Method

With regard to the first step, the determination of the generally valid requirements for gripper fingers, a systematic literature search is carried out according to the approach of Okoli and Schabram [27]. First, several literature databases are searched using a fixed search term, and the results are reduced by screening for selection criteria. The remaining sources are then searched for requirements or design guidance for gripper fingers. The raw requirements identified in this process can then be formalized and hierarchized by pairwise comparison.

Using common product development methods for modular product architectures, the formalized requirements can then be transferred into functions and clustered. Initial module definitions can be derived from the clusters. The minimal size of the finger cross-sections is determined by the space required for the mechanical and electrical interface. Therefore, based on the defined module types and the determined requirements, the methodical development of the interface between the modules and between the fingers and the gripper for selected gripper models is performed. Since the evaluation of the sensor technology takes place either in the gripper itself or outside the gripper, the sensor signals, as well as the voltage supply of the sensors, only have to be looped through the modules to the fingertip or the finger base. The sensors to be integrated into the fingertip are initially intended to record distances, slippage and forces. For this purpose, lines for common communication protocols such as CAN, SPI or I^2C are to be provided. For the mechanical interface, for example, quick-change systems are suitable so that the modules can be connected with as little backlash as possible and, if necessary, can be exchanged quickly and with little effort. Various concepts must be developed, validated and compared for this purpose.

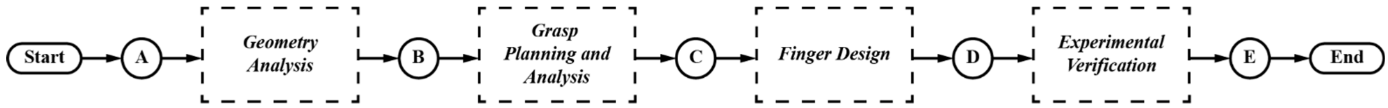

Fig. 2. Overview Flowchart of the Proposed Method (adapted from [1])

The goal of modular product architectures is to reduce internal diversity while maintaining a high degree of external diversity [28]. Therefore, the diversity of variants, e.g. with regard to the size gradations of the individual module types, must be reduced by applying methods of variant-oriented product design. An initial collection of modules for a gripper finger construction kit can then be defined from the variant-reduced module types with the previously defined interfaces.

The modules should later be combined to form fingers so that different workpieces can be gripped securely. It is, therefore, necessary to identify several pairs of gripping points for safe grasps per workpiece. Based on the 3D models of the objects to be gripped, these gripping point pairs (grasp sets) can be determined with the help of surface discretization and normal vectors and then evaluated with regard to grasp quality. The evaluation should be multi-criteria, including the possible overlap between the contact surface on the workpiece and the effective surface on the fingertip. For each workpiece, this results in evaluated grasp sets which can then be used for the configuration of the fingers. Input from the user is required to configure the fingers. For example, it must be defined which gripper is used or which workpieces are to be gripped. From gripping point determination, the gripping points are determined in $\mathbb{R}^3$. Based on the module definition, a kinematic chain can then be built from the selected gripper's base jaw to the desired gripping points. Due to the assumed small number of modules in the modular system, a limited number of combinations can be expected. Therefore, the determination of the theoretically possible finger configurations can be determined via a complete enumeration. The number of configurations can be reduced based on various conditions, such as avoiding collisions of the finger with the gripper. This then results in a number of possible configurations for all pairs of gripper points on a workpiece. The minimum number of finger configurations required to handle all previously defined workpieces can then be determined by comparing the configurations for the various workpieces.

5. Procedure of the Method

The method is designed for use in industrial production. It is intended to support the user in determining reliable gripper fingers from a modular system for changing conditions, such as new workpieces. Therefore, the method is divided into four main process steps that follow the generic steps of the Generic Optimized Finger Design (GOFD) procedures proposed by Honarpardaz et al. [29] (Fig. 2.). However, the design of the four steps differs somewhat from those of Honarpardaz et al. For example, the information obtained in the steps of Geometry Analysis and Grasp Planning and Analysis is used to design fingers from elements of a construction kit. The following describes the sub steps of the method in more detail:

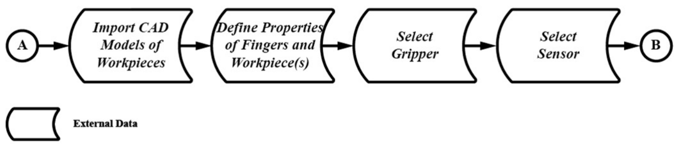

Fig. 3. Geometry Analysis

The starting point for the application of finger configuration is the geometry analysis step (Fig. 3). The user is guided through the configuration via a web-based application. First, the workpieces to be gripped are imported in the form of .stl files and the existing gripper is selected. Depending on the application, the user can select sensors that need to be integrated. This influences the selection of the fingertip and the possible finger configurations.

Based on the imported workpieces, the gripping points per workpiece can then be determined in the second step of grasp planning and analysis (Fig. 4). For this purpose, the surface is meshed and a point cloud of the objects is also created. With the help of the normal vectors in the respective points, point pairs with points on opposite sides of the object can be determined, whose normal vectors point in opposite directions.

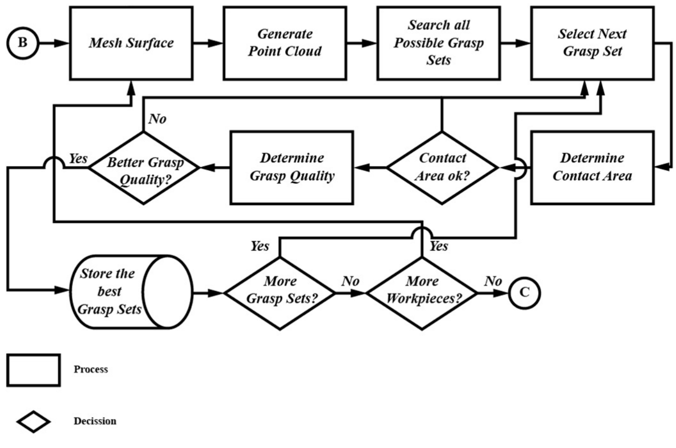

Fig. 4. Grasp Planning and Analysis

Smaller angular deviations are tolerated here in order to find gripping points even on surfaces that are not exactly parallel. Maximum possible deviation from parallelism is initially tolerated with smaller five degrees. A final limit is to be determined in tests. For each pair of grasping points, the size of the possible contact area around the respective gripping point is then determined. If this is sufficiently large, the quality of the grasp is determined using the grasp quality metric by Ferrari and Canny [30]. If this quality is better than that of the previously analyzed grasp set, the list of permissible grasp sets is updated. The objective is to identify the best grasp sets on different surfaces of the workpieces. The step is finished when all workpieces and all grasp sets have been analyzed.

The determined and evaluated grasp sets per workpiece can then be used to design the fingers (Fig. 5). For this purpose, gripper finger configurations are determined for all grasp sets by iteratively passing through the grasp sets. For each grasp set, the workpiece is oriented so that the pair of points lies on the grasping axis of the gripper. If surfaces of the workpiece cannot be used for handling, the user can orient the workpiece. All possible finger configurations for the current gripper set are then determined and evaluated. The result is a list of possible configurations with the associated quality evaluation. By comparing the finger configurations for all workpieces and all grasp sets, the minimum number of configurations required for the given workpieces can then be determined.

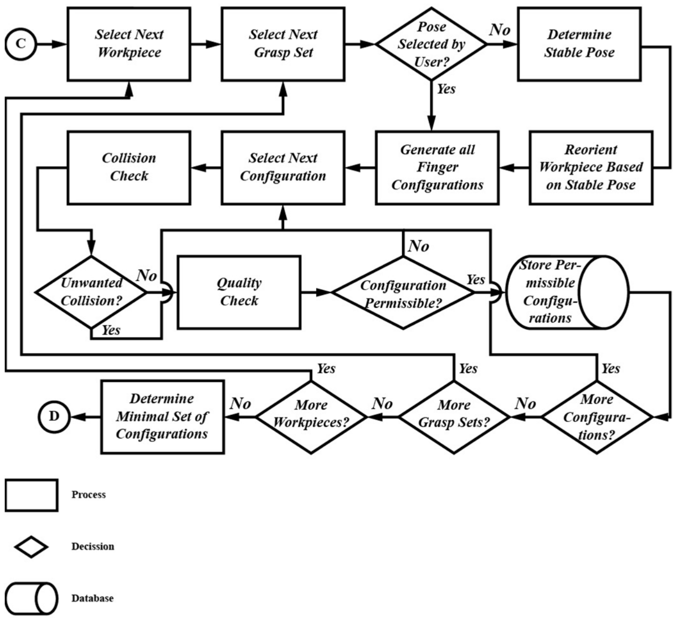

Fig. 5. Finger Design

Once the configuration is complete, an experimental review verifies and validates each finger design process (Fig. 6). This begins with the assembly of the modules to the determined finger configurations.

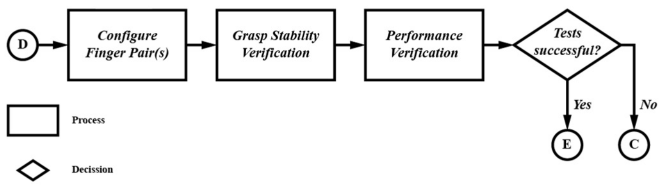

Fig. 6. Experimental Verification

The stability of the fingers is determined with force and torque tests. With successfully completed stability verification, the performance verification follows in two steps: In a pick-and-place experiment, the suitability of placing workpieces in predefined positions is determined, while in an assembly experiment, the suitability of the fingers for an assembly task is tested. The finger configuration process is completed with a successful experimental verification.

6. Conclusion and Perspective

The design of gripper fingers is a complex task that has been chiefly performed manually by experts. The use of software-supported methods to support or automate gripper finger design can simplify and accelerate this task. Existing approaches in design automation almost only consider individual gripper fingers, which, however, have a comparatively high provisioning time. In addition, none of the existing approaches to finger design takes the integration of sensors into account.

This creates the need for a new approach based on a modular finger concept. Compared to existing approaches e.g. in [1] and [23], the fingers do not consist of one piece. This brings considerable time advantages especially for the provision of new fingers. In addition, the commonality of the modules results in a lower space requirement for storing the finger modules instead of whole fingers. The integration of sensors also enables the direct acquisition of process and workpiece information and the consideration of this information in the handling process. An approach such as the one proposed in this paper can directly support the user in designing reliable gripper fingers for an existing gripper. This eliminates the need to select and procure a new gripper. Moreover, in view of advancing digitization and the increasing autonomy of production facilities, such an approach could enable the handling system to automatically determine the most suitable finger configuration for a workpiece and to switch to this configuration autonomously.

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