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Method for the Automated Dimensioning of Gripper Systems

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Abstract

Industrial grippers play an important role within automated production and assembly processes. In most cases their selection and dimensioning is done experience-based. This article presents an approach to dimension grippers automatically based on the properties of the handling object, the handling environment, the handling device and the handling process. Special attention is paid to the adaption of the operational elements, which interact with the handling object, like suction cups or jaws.

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Keywords: handling; methodology; tooling

1. Introduction

Being the link between the workpiece and the handling device, grippers play an important role in automated production and assembly processes. To ensure the best possible handling performance, the selection of a feasible gripper and the adaption to the workpiece is crucial. This selection and dimensioning has so far been done manually based on experience and rudimentary methodologies [1]. To meet the requirements of future virtual production and assembly planning and to lower time and cost for the selection and dimensioning of gripper systems there is a need for an automated methodology to address this task [2].

To be able to automate the selection and dimensioning process a holistical examination of the system is required. There are five elements in the system “handling” (the system the gripper is embedded in): Environment, handling device, part, task and gripper. Earlier work analyzing the system showed that particularly the gripping point (“where does the gripper get in contact with the part”) and the gripping force have a tremendous impact on the behavior of the system [3]. Closely linked to these two topics is the dimensioning, which merges the requirements of gripping point and -force towards a feasible gripper.

This paper points out, how to address these topics against the background of an automated selection and dimensioning of gripper systems considering parallel, angular and vacuum grippers. Grippers again can be divided in a gripper body and the operational elements (jaws, suction cups) that interact with the part.

2. Automated search for gripping points

The gripping point is the major factor for the performance of a handling system and hence also for the selection and dimensioning of the gripper. It has a strong influence on a number of factors like, for instance, the gripping force. The gripping force again has a strong influence on which gripper to take and how to dimension the operational elements (jaws or suctions cups) that provide the contact with the part [3].

To automate the search for possible gripping points, means to define a program that extracts possible positions for different grippers based on the provided CAD data, ranks their fitness and processes them for the further selection and dimensioning process.

There are several approaches that address this task [4, 5, 6, 7, and 8]. Main drawback of all the methods is, that each of them only focuses on one kind of gripper, which makes the comparison of different solutions reaching across different

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gripper types difficult. The following approach shows possibilities to integrate different kinds of grippers in one process.

2.1. Definition of gripping positions

A gripping position is an umbrella term for a possible holding position of a specific gripper on a specific part. To be able to process the gripping positions further while addressing several gripper types the following classification is proposed:

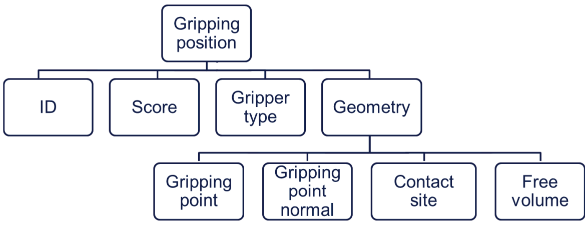

Fig. 1. Gripping position classification

ID: To address each position individually, each is assigned a distinct number

Score: As the program searches for any gripping position on a part there is a need to rank the positions. Ranking criteria are:

1. The distance of the position to the center of gravity
2. Size of the contact site
3. Curvature of the contact site
4. Free volume above the contact site

Grippertype: Applicable kind of gripper for the gripping position

Geometry: General information about the geometry of the gripping position, which consists of:

- The gripping point as origin of the gripping position
- The gripping point normal to describe the orientation of the gripping point
- The contact site which is a defined gathering of several gripping points with similar properties
- The free volume, which defines how much free volume is available for approaching the gripping position.

Central element of the gripping position is the contact site. It is the geometrical element that ensures a proper fixture between gripper and part. A vacuum gripper needs at least one contact site, a parallel or angular gripper at least two. There are three types of contact positions: Contact points, contact lines and contact areas. Vacuum grippers are due to their physical properties only applicable for contact areas.

2.2. Algorithm for the automated identification of gripping positions

In order to receive the data mentioned in section 2.1 the following steps have to be carried out by the algorithm.

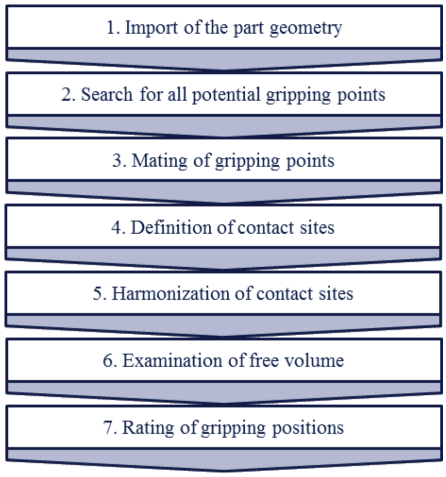

Fig. 2. Flow-chart of the gripping position search algorithm

First of all the CAD data has to be provided. Being widely-used STEP (Standard for the Exchange of Product Model Data) [9] is the preferred format.

In a second step, the algorithm searches for all theoretically possible gripping points. This is performed by rasterizing each surface of the part with a regular grid. This leads to a scatter-plot of the surface. For each intersection of the grid the normal vector of the surface is generated. The resolution of the grid has to be adapted manually based on the wanted accuracy.

In this step, the algorithm checks whether there are partners for the gripping points regarding parallel and angular grippers. This means that the normal vectors have the same orientation but face in the opposite direction. The user is able to define tolerances so that points which are not completely parallel to each other are also taken into consideration.

After the search for possible linked points the algorithm tries to calculate the maximal contact site symmetrically around each gripping point. Therefore the geometry around the point is further analyzed based on the original CAD data, which makes it possible to use the real shape of the contact site instead of the scatter-plot. If the algorithm is not able to build a contact area (but for example a contact point or a contact line) vacuum grippers are excluded from the further process.

For parallel and angular grippers, the algorithm then harmonizes the contact sites. This means it compares the sizes and geometries of the contact sites and tries to define contact sites that mate geometrically in the best possible way to ensure symmetrical jaws later during dimensioning.

In the sixth step, the free volume above the contact sites is determined to be able to dimension the grippers accordingly afterwards. Starting from the gripping points of the contact sites, the algorithm checks whether there is an obstacle. If there is an obstacle alongside the normal vector, the length of the normal vector is adjusted to this. If there is no obstacle, the program safes the orientation of the vector but sets the length equal 0.

The last step is to rank the gripping positions according to the criteria of 2.1.

All the gripping positions including the extra information are saved for further processing in the gripping force calculations and the linked dimensioning of the operational elements and grippers.

3. Gripping force calculation

Determining the appropriate gripping force is crucial for the design of a gripper. On the one hand, the force has to be large enough to secure contact with the workpiece during the whole handling process. On the other hand, if the force is too large it may cause damage to the workpiece or the gripper. To calculate a valid gripping force, it is essential to identify the forces acting on the workpiece during the handling and to model the forces applied by the gripper. Using equilibria on forces and moments, a condition for the minimum gripping force required can be obtained. The magnitudes of the moments that have to be compensated by the gripper depend on the distance of the gripping point from the point of load application, which is often the workpiece's center of gravity. To balance those moments, a large contact area is needed. Its size however, is restricted by obstacles surrounding the gripping point. Therefore the location of the gripping point has a strong influence on the required gripping force and the design of the gripper, especially on the operational elements.

3.1. Forces acting on the workpiece

The first step of the gripping force calculation is the analysis of the handling process, to determine the forces that are induced on the workpiece [10]. In the static case, only gravitation has to be considered. Linear or rotational movement will cause inertial forces and additional effects such as Euler Forces and Coriolis Forces. As accelerations are usually at their highest in emergency stop situations, those values should be used in the calculation. If no other information is available, Seegräber [11] proposes a value of 25m/s². Drag forces should be taken into account for the handling of workpieces with large surfaces [12]. Additional forces may occur due to the mating or processing of the workpiece [13]. All forces acting on the workpiece, both body forces (gravity, inertial forces, and rotational effects) and external forces (drag and process forces), can be summed up to a resultant force $\mathbf{F_{res}}$, which may vary in its magnitude and direction with time. As a simplification, a grip in the centre of mass is often considered first and the direction of the resultant force $\mathbf{F_{res}}$ assumed to be constant, parallel to the holding forces, such that moments can be neglected [10].

3.2. Vacuum grippers

In vacuum gripper applications, two main situations can be identified for the static case. When the cup is horizontal, the suction force has to equal the resultant force $\mathbf{F_{res}}$. For a vertical positon of the gripper, friction forces need to be considered in the calculation. The second situation is assumed to be the more critical one. According to Monkman [10], the necessary pressure difference in the cup Δp can be calculated with (1) for a resultant force $\mathbf{F_{res}}$ acting under an angle β to the normal of the suction plane, the efficiency η, the theoretical surface of the cup A and the friction coefficient μ. S_1 is a security factor against the workpiece falling off and S_2 is a security factor against the workpiece sliding off ($S_2 > S_1$). There are simple extension to this formula, taking moments into account [10,14].

$$\Delta p * A * \eta = F_{res} * (S_1 * \cos(\beta) + \frac{S_2 * \sin(\beta)}{\mu}) \qquad (1)$$

A model developed by Kaulins & Kaulinja [15] is able to represent the support reaction of the suction cup by considering a linearly distributed pressure along the sealing edge in addition to the suction force. The workpieces center of gravity is assumed to lie in the xz-plane and the movement to be either in the xy- or the xz-plane. Those restrictions have been eliminated in an extended model [16]. This model is also applicable to the handling of hollow workpieces [17]. For a stable grip, two conditions have to be fulfilled. Firstly, the pressure distribution has to be positive at every contact point, otherwise air could flow into the cup and dissolve the pressure difference. Secondly, the friction forces caused by the sealing load have to be large enough to counter any horizontal forces or moments. While the aforementioned models assume a rotation about the cups center in the case of failure, Mantriota [18] uses an unknown center of slip in the gripper plane. This method is used to calculate the minimum friction coefficient needed for a given pressure difference. The model can be applied to a gripper with multiple suction cups [19]. For those grippers, distances between the cups are assumed to be more important than the dimensions of a single cup. Hence, point loads at the center of every cup represents the sealing forces instead of pressure distributions.

3.3. Mechanical grippers

For mechanical grippers, friction forces and the resultant force $\mathbf{F_{res}}$ have to be brought into equilibrium. There is no evidence in literature on how the gripping force is calculated for a grip at angled surfaces. However, the calculations will differ from that of a grip at parallel surfaces, as the contact force will have a component in vertical direction [20]. Therefore, the vertical components of the normal force and the friction force have to be compared. The gripping force $\mathbf{F_G}$ can be calculated with (2), using a safety factor S and the angle between the gripping planes α (α=0 corresponds to parallel surfaces).

$$F_G = \frac{S * F_{res}}{2 * (\mu * \cos(\alpha) - \sin(\alpha))} \qquad (2)$$

There have been few attempts to include moments due to eccentric gripping of the workpiece. Monkman [10] shows that the reaction forces at the gripper jaws depend on the levers of the forces, without using those concepts for the gripping force calculation. The principle of virtual work is used by Chen [21] to derive the gripping forces for one eccentric grip configuration. Pedrazzoli et al. [22] calculate the gripping force as the sum of three parts. The first part is the force of a centric grip, the second part considers the moments due to eccentricities and the third part takes the moments into account that try to separate the gripper fingers. Some formulae have been introduced for V-shaped gripper jaws [10,13], though they neglect eccentric grips. Further research is required to set up a more general model for these jaw shapes. While all previous methods for mechanical grippers assume the gripping force to act as a point or line load, Barber et al. [23] use linearly distributed surface loads on the contact areas of a parallel gripper. They identify three different cases of failure. The workpiece may slide linearly, rotate or twist out of the grip. Their model uses an unknown center of slip, about which the workpiece has a tendency to rotate, on a plane parallel to the contact areas. Linear sliding is represented by a center of slip at infinity. An impending twist of the workpiece can be identified, when the value of the pressure is zero at any contact point. This method is used to evaluate gripping points, by calculating the minimum coefficient of friction needed to withstand the resultants of applied forces.

3.4. Automated method for gripping force calculation

There are two main criteria that have to be satisfied by a method for the gripping force calculation in an automated dimensioning. Firstly, the method has to be able to consider all possible orientations of the gripper and directions of the resultant force $\mathbf{F_{res}}$. Secondly, the effects of moments have to be taken into account, such that a valid gripping force can be calculated for different dimensions of the operational elements.

For a single suction cup, the model of Mantriota [18] can be used. The model is applicable to square suction cups [18], circular suction cups [24] and has to be extended to oval suction cups to cover the three main shapes. However, the method has to be changed in such a way, that the result is the necessary pressure difference at a certain gripping position for a given friction coefficient. Therefore, two pressure differences are determined independently. The first pressure difference is necessary to prevent the workpiece from falling off and the second pressure difference is necessary to prevent the workpiece from slipping in the gripping plane. The pressure differences are compared and the maximum between the two values is chosen to be the minimum pressure difference needed for a secure grip.

The method proposed by Mantriota [19] for multiple suction cups is limited to a gripper with four equally sized suction cups. As the dimensioning considers any number of suction cups, the method has to be automatically adapted to different layouts. In particular, this would include suction cups with different sizes and arbitrary positions. The only constraint is that all cups have to lie on the same gripping plane, as the tendency to rotate in case of failure is assumed to be planar [19].

In the enhanced method, the suction force at each cup will vary according to their respective size. This has to be taken into account for all force and moment balances. Arbitrary positions of the cup require a flexible definition of levers in the moment balances. Lastly, the stiffness condition of the gripper body has to be set up in a general way, such that the normal forces at each cup can be brought into relation with each other. This way, the necessary pressure difference can be determined for any layout of different suction cups. The positioning of the cups has to be automated in such a way, that the levers of the gripper's holding forces are increased and those of the resultant force $\mathbf{F_{res}}$ decreased. A possible approach is to maximize the area spanned by the center points of the cups. Further research should aim to verify this assumption. The validity of using normal forces to represent the contact should be certified, as an extended model using several distributed loads could prove to be more accurate.

A method for the gripping force calculation of mechanical grippers with parallel gripping planes can be based on the model of Barber et al. [23]. At the contact areas, a linearly distributed surface pressure is assumed, which has to be positive at every point. However, similar to the method for single suction cups, some alterations have to be made to this method such that the necessary gripping force can be calculated for a fixed value of the static friction coefficient.

With the aim to simplify the moment balances, all components $\mathbf{F_i^e}$ of the resultant force $\mathbf{F_{res}}$ and their respective moments $\mathbf{M_i^e}$ are transferred to a point called grip center, lying half way along the line connecting the centers of the contact sites (see Figure 3). While Barber et al. [23] integrate over polygons composed of triangles, the described method uses contact sites that are defined to be rectangular. Any other shapes have to be approximated by rectangles. Contact lines or points will be treated as rectangles with either or both infinitesimal length and height.

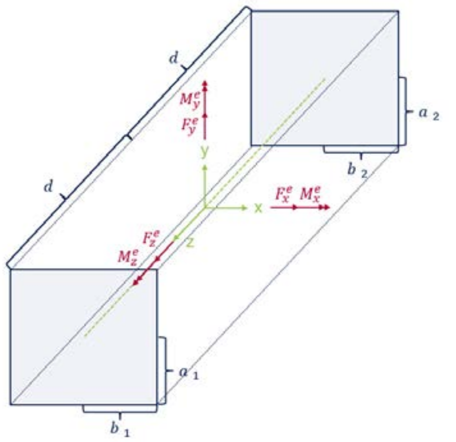

Fig. 3. Components of the resultant force $\mathbf{F_{res}}$ transferred into the grip center

For each contact area, a force is calculated by integrating the pressure. Under loading conditions, the two forces will often have different values (e.g. $\mathbf{F_z^e} \neq 0$) . Barber et al. [23] define the gripping force as the average of both forces. A result with a higher level of safety can be achieved by choosing the necessary gripping force to be the maximum between the two values, as described in equation (3). p_1 and p_2 are the pressures on the first and second contact area respectively

$$F_G = \max\left[\int_{-a_1}^{a_1}\int_{-b_1}^{b_1} p_1 dxdy; \int_{-a_2}^{a_2}\int_{-b_2}^{b_2} p_2 dxdy\right] \quad (3)$$

To be able to integrate over the friction forces and to consider their direction perpendicular to the center of slip, they are defined similarly to the tangential pressure distribution at a suction cup in the model of Mantriota [18]. Further extensions have to be made to this method to make it applicable to angular gripping planes and V-jaws. The contact pressure at an angular gripping plane has to be split into components in z- and y-direction. Additionally, the friction forces at such gripping sites have a component in z-direction. V-jaws require the consideration of four contact lines and corresponding friction forces instead of two contact areas. Those enhancements can be made after a method for plane parallel grippers has been established.

4. Dimensioning of the gripper system

The dimensioning can be seen as the gathering point for all information regarding environment, handling device, task and part. In an iterative process considering the gripping force and the acceptable forces/tensions for part and gripper the goal is to derive adapted operational element-gripper body combinations for a gripping position ensuring a safe grip. Final result of the dimensioning is a CAD model of the gripper body for vacuum grippers and CAD models for the jaws in case of a parallel or angular gripper. This data together with additional information like for instance the calculated gripping force for a parallel gripper and a ranking of the grippers, if several are applicable, allows the user to select the gripper that fits his needs the best possible way.

4.1. Algorithm for the automated dimensioning of parallel and angular gripper systems

1. Import of gripping positions from the gripping point search algorithm

2. Check on applicable jaw geometry

Based on the approach of Pedrazzoli [22], there are two possible basic jaw shapes: Flat shape and V-shape. For all plain contact sites, the algorithm chooses the flat shape, for curved or cylindrical surfaces the V-shaped jaw.

3. Calculation of the needed stroke

Dependent on the chosen jaw geometry the needed stroke is calculated by analyzing the distance between the two contact sites of the contact sites.

4. Definition of the jaw-dimensions

Knowing the needed stroke, the sizes of the contact sites and their curvature, it is possible to parametrize the jaws. The algorithm also takes into account possible restrictions due to obstacles (the information derives from the free volume examination in the gripping point analysis).

5. Calculation of the gripping forces and tensions

Taking into account the forces acting on the workpiece and the dimensions of the jaws it is possible to calculate the needed gripping force as well as the tension applied to the part.

6. Check on stability of jaw and part

Using an FEM tool or approximations due to the instant materials it is possible to check whether part and gripper withstand the acting forces.

7. Re-calculation of jaw-dimensions, if necessary

If the tensions exceed the tolerable range, the jaws are re-dimensioned. If this is not possible due to other restriction like for instance obstacles the operational element-gripper body combination is deleted.

8. Output of jaw as CAD model

4.2. Algorithm for the automated dimensioning of vacuum gripper systems

1. Import of gripping positions from the gripping point search algorithm

2. Ranking of the gripping points

The theoretical gripping force is added as a ranking criteria to the criteria coming from the gripping point algorithm.

3. Placement of suction cups on surface

Starting with the best ranked contact site, the algorithm places a suction cup on the surface. Applicable suction cup geometries are circle, rectangle and oval. Around each suction cup there is a tolerance zone avoiding the cup to be nearby a border of the contact site (like for instance an edge).

4. Calculation of the transferable gripping force

Based on the placed suction cup the algorithm calculates the actual realized gripping force for the chosen cup. If the force is not sufficient another cup is added.

5. If necessary increase of the number of suction cups

When there is a need to increase the number of suction cups, the algorithm takes into account several factors in order to place the next cup:

- Ranking of the contact site based on the potential gripping area size
- The stability and force division of the overall system (see also chapter 3)

6. Calculation of the actual gripping forces and tensions

Knowing the final number and position of the suction cups it is possible to calculate the final gripping forces and the tensions acting on the part.

7. Parametrization of the gripper body

Base of the gripper body parametrization is a structure alike figure 4, which is automatically designed dependent on the position and the kind of the suction cups, the forces to be transmitted and the connection to the handling device.

Fig. 4. 3-D printed vacuum gripper (robomotion)

8. Check on stability of part and gripper

Using an FEM tool or approximations due to the instant materials it is possible to check whether part and gripper withstand the acting forces.

9. Re-calculation of gripper body dimensions, if necessary

If the tensions within the body are too high, a re-calculation is applied. Main source for adjustments is the thickness of the structures walls.

10. Output of gripper body including number, position and kind of suction cups as CAD data.

5. Conclusion and perspective

The dimensioning of gripper systems is a challenging task. Automating this challenge could simplify the process while leading to more efficient grippers. Based on an algorithm for the gripping position search and a model to calculate occurring gripping forces an approach for the automated dimensioning of gripper systems is presented.

Future research should cover enhanced industrial testing of the proposed approaches. Once the approach is evaluated it should be extended to other kinds of gripping principles. Also the integration of the method into assembly- or other planning tools might be worth to investigate.

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