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Concept study on novel gripper concept for in-hand rotational manipulation of poultry products

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Abstract: Although automation is vastly applied in the food industry, challenges persist in the individual handling of poultry products due to the variation in products and complex manipulations in combination with high throughput. This study aims to provide a foundation for the development of an industrially suitable gripper for in-hand rotational manipulation of poultry products. Through a combination of a literature review and brainstorming, ten concepts were initially generated, from which concept "Belt driven manipulation" showed the most potential. In order to study the influence of design parameters on object rotation, a theoretical model was constructed and validated by experiments on a prototype. As concluded by the theoretical model, an increase in grip angle reduces the required tension force and theoretical belt strain. The prototype provided a proof of concept in which a rotation of 180 degrees was obtained within 260ms. Additionally, characteristics of poultry products, as flexibility and geometry were studied to ensure rotation was performed reliably. As a result, successful rotation was obtained for a configuration implementing a grip angle of 60 degrees and a maximum gap width of 8 millimeters.

Contents

1 Introduction

Marel Poultry, renowned leader in the field of food processing, covers full range solutions for poultry processing, from live stock handling to further processing (e.g. battered, breaded, or precooked) [1, 2]. Although automation is vastly applied to the poultry processing steps, some aspects of the automation process still pose a significant challenge [3]. One of these aspects is the individual handling of poultry products, with uncertainties and variation in combination with complex manipulation. These handling steps are present in mainly two categories, namely product loading (e.g. tray loading) and singulation (e.g. bulk picking) like presented in Appendix A. In order to manipulate products from and to their desired location and orientation, the product not only have to be translated, but also rotated. This is required for styling purposes, as a product can be more appealing from different viewpoints, and for singulation, since product originate from an unorganized distribution.

Initially, a literature review was conducted on gripper mechanisms for in-hand rotation of objects, as included in Appendix B. Several authors presented research on grippers for in-hand manipulation. The findings from the analysis of 26 articles can be thematically categorized in five concepts, these are presented in Table 1. The concepts were systematically analysed based on their construction and manipulation method, advantages and limitations were also of interest.

Starting with concept "Rotational motion" which implements object rotations by rotating each gripper jaw, due to a relative displacement of the contact points, causing object translation during the manipulation action. A method of achieving this manipulation is by utilizing a grasp-reposition-reorient type gripper and is comprised of a four-bar mechanism [4, 5]. However, this method presented a limited 90 degree rotation. Additionally, variable friction can be implemented to obtain continuous rotation through multiple manipulation steps [6]. This severely increases the required manipulation time. Experiments were conducted on rigid round and square profiles.

Next, concept "Opposing movement" allows for object rotation similar to the previous concept but with a linear motion of the gripper jaws. Various gripper constructions are mentioned and include: multi-modal [7], twisting and re-positioning [8–10], and adapted parallel grippers [11]. With this method a rotation of up to 180 degrees can be achieved and industrial testing of the twisting and re-positioning gripper demonstrated a manipulation time of about 0.6 seconds. However, in order to manipulate objects, the shape has to be slightly cylindrical.

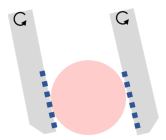
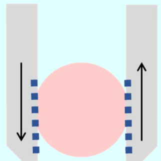
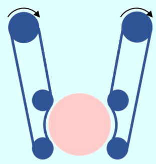
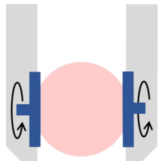
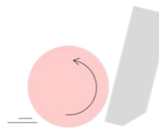
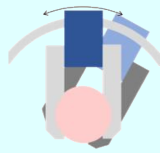
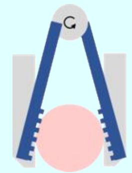
Another concept that applies relative displacement of the contact points is concept "Belt driven rotation". Some of the mentioned concepts utilizes a pliant closed belt to facilitate continuous rotation [18, 19], while others limit the motion of the belt [17, 21]. Due to the pliant belt, contact with the object is increased, improving the grip on the object. Notably, manipulation of heavier objects was limited due to friction.

In the concept "Fingertip re-orientation" a two-stage rotation method is mainly employed [23–25]. Initially, the object is grasped in an intermediate state, allow the object to rotate based on its inertia. In the second stage, the object is securely grasped. An additional concept provided actuated rotation and translation within the fingertip [26]. Due to the utilization of object inertia, control in terms of orientation is severely limited and the predefined orientation relies on the physical aspects of the object.

Finally, concept "Environment motion" utilizes the environment or end effector movement to obtain rotation. A range of manipulation action to enable rotation was mentioned in [27]. Action include rolling over a flat surface and re-grasping, and mentioned manipulation times of 0.2 seconds. Another study aimed to drop an object and regrasp from a different orientation [28]. Although these manipulations are expected to have high manipulation speeds, these concepts are dynamically complex and are influenced by the entire system.

While research has been conducted on in-hand rotational manipulation, solutions that are optimized in terms of operation speed, reliable manip-

Table 1: Set of concepts obtained through literature review (1-5) and brainstorming (6, 7), preliminary selection in cyan (2, 3, 6, and 7), and selected concept: Belt driven rotation (3).

Literature review					Additional	
1	2	3	4	5	6	7
Rotational motion	Opposing movement	Belt driven rotation	Fingertip re-orientation	Environment motion	External rotation	Eccentric motion
						
[4–6, 12, 13]	[7–11, 14–16]	[17–21]	[22–26]	[27, 28]		

ulations, and object variation are have not been developed. Since these aspects are essential to provide an industrially suitable gripper, future research should focus on further industrializing concepts and enhancing speed, reliability, and versatility.

The primary objective of this study is to set a foundation for the development of an industrially suitable gripper solution for the in-hand rotation of poultry products. This research emphasizes on two main aspects: first, providing a proof of concept for a belt driven manipulation gripper and second, gaining an understanding of the influence of the design parameters of the system on product rotation. Adapting the currently available RoboBatcher gripper to obtain a prototype capable of manipulating products, it is essential to explore the implications of the modification and to establish a proof of concept to aid the development of this concept. Therefore, the influence of parameters effecting the required actuating forces are investigated. Additionally, poultry products are considered with the aim to understand how variations in their shape, size, and flexibility impact the rotational behaviour of the mechanism.

Initially, the criteria regarding an industrially suitable gripper are presented and the concept selection based on these criteria is mentioned. Next, the RoboBatcher of Marel is explained and adapted to enable rotational manipulation. In order to gain an understanding of the impact of design parameters on the required motor torque, and thus gripper weight, a theoretical model is constructed and an experimental setup is made to validate the model. In addition to the effect on motor torque, the influence of manipulating poultry products is considered. Specifically, the change from a round object to an ellipsoidal product shape and product flexibility was examined. As a result, the findings of the theoretical model are mentioned. Furthermore, the experimental measurements are presented and compared to the data of the theoretical model to ensure the model is valid. To continue with the results, the information obtained on the influence of poultry products is presented. Finally, the gained understanding on the concept of belt driven rotation is concluded.

2 Method

2.1 Main criteria

Within the context of this concept study, the aim is to define a set of criteria to guide efforts in developing an industrially suitable gripper for in-hand manipulation.

Speed: prioritizing operation speed to provide high throughput is crucial, as it enhances customer value. Existing solutions are able to achieve a speed of 210 products per minute implementing three delta robots, requiring a cycle time of 0.86 seconds [29]. The goal of this criteria is to approach a similar speed, while considering the impact of additional features.

Versatility: given the inherent difference in poultry products, the ability to handle a variety in products is important. Variations are present in terms of geometry and size, which alter between breeds [1]. The gripper mechanism should be able to cope with these variations.

Secure grip: a reliable system is critical in an automated process. Due to the characteristics of poultry products, automation poses significant challenges, including the risk of losing grip [3]. Therefore, it is necessary to maintain a secure grasp while manipulating the product to obtain a reliable system.

Compactness: for the applications as singulation and product loading, products are grasped and placed in close proximity to one another. Unintentional interaction with products can cause inaccuracies or even failure. Therefore, optimizing the compactness of the mechanism is essential. Notably, for the scope of this study, compactness is of interest at the bottom of the mechanism where product interaction is present.

Contamination risk: due to the direct contact of the gripper with poultry products, risk of contamination is present. This risk can be mitigated by decreasing the amount of contact with the product and through improving the cleanability of the system.

2.2 Concept selection

In the process of concept generation, besides the obtained concepts in literature, additional concepts were obtained through brainstorming, experimenting, and creative thinking. The combination of these two sources of concepts lead to a list of ten concepts, as presented in Appendix C. To reduce the amount of concepts for further exploration a preliminary selection was performed based on the requirement that the gripper mechanism must be able to rotate products 180° over their longitudinal axis and the feasibility of the concept. The remaining four concepts are highlighted in Table 1. To gain an understanding of the concepts and provide information for the concept selection, the set of concepts were further explored, as mentioned in Appendix D. Next, a concept selection method was applied to select the concept with the most potential based on the main

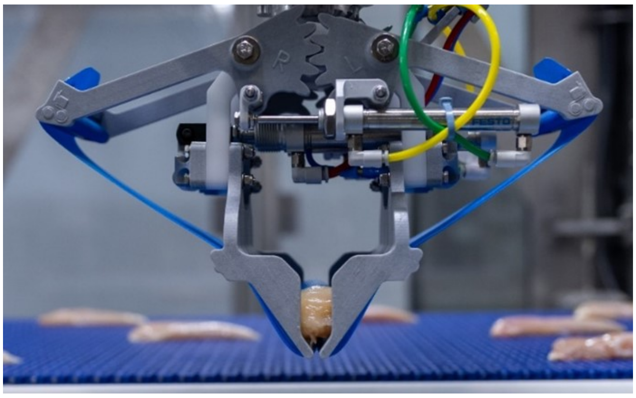


Figure 1: RoboBatcher Flex Breast Fillets of Marel [32]

criteria in Section 2.1. For this concept selection, the analytical hierarchy process was implemented since it allows for the inclusion of experience, instinct, and heuristic based decision making and provides a systematic mathematical comparison [17, 30, 31], the selection is included in Appendix E.

As a result, concept "Belt driven rotation" was selected. Due to the implementation of a pliant belt the concept is able to handle a variety of products and maintain a secure grip, as the forces are evenly distributed over the surface of the belt, which adapts to the shape of the product. Additionally, the amount product rotation is in direct relation to the displacement of the active surface and while considering friction, this should enable advancements towards high speed manipulation. Although contamination risk remains a concern, optimization of this criteria is not crucial at this stage of concept development. Furthermore, the concept performed moderate in terms of compactness and can be optimized once a definitive gripper is designed. Overall, the concept outperformed the other concepts in terms of the essential criteria namely, versatility, secure grip and compactness.

2.3 Adapted RoboBatcher gripper

Upon examining related solutions to the belt driven gripper concept, a clear link was made with the existing RoboBatcher Flex Breast Fillets, which is one of the systems that Marel provides. The gripper mechanism that is implemented in the

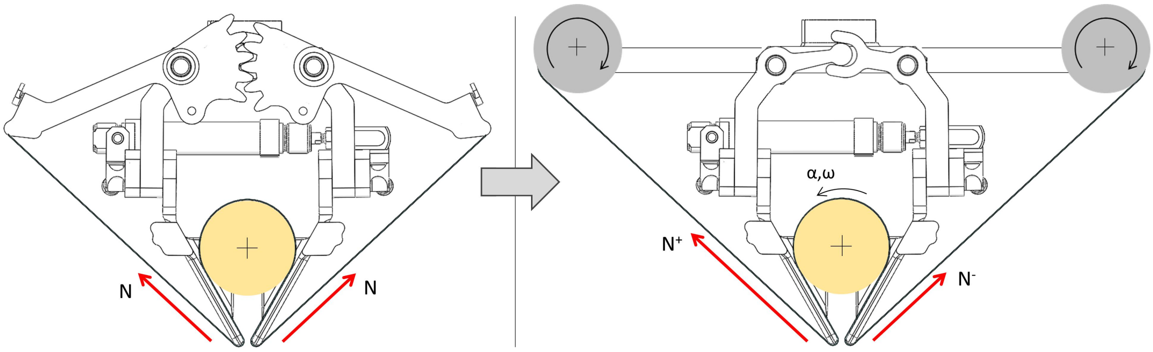


Figure 2: Schematic overview of the adaption of the RoboBatcher, current RoboBatcher gripper (left) and adapted RoboBatcher gripper(right). An indication of the belt tension is provided with the N vectors, where $N^+ > N^-$.

system is of interest in this case, this is shown in Figure 1. The RoboBatcher gripper consists of two pneumatic actuated mechanisms, one for opening en closing the gripper, the other for applying tension to both sides of the belt. The application of tension ensures that the product is compressed, facilitating efficient and space-saving tray loading. Although the mechanism is not capable of rotating products, it is proven to be an industrially suitable solution within the food industry.

Since the RoboBatcher provides a partial solution, the focus of this study is on the rotating aspect of the gripper. The existing RoboBatcher was adapted to enable in-hand rotation through a belt driven mechanism, as demonstrated in Figure 2. This adaptation involves the integration of two separately actuated drums that are rigidly connected to the base of the gripper. The both ends of the belt is attached to one of the drums. Moreover, the tension arms are removed as they are now redundant. Rotation of the drums in a similar direction causes the belt to translate. Since the product is enclosed and clamped by the belt, the product is rotated. Moreover, tension on the belt should be maintained during manipulation to ensure a uniform load acting on the product. This will ensure that the product is securely gripped. Notably, this adaptation offers several advantages, including enabling a rotation controlled by the rotation of the actuators and an increased range of rotation compared to the individual movement of the tension arms. Additionally, the rigid extension of the base allows for the placement of sensors (e.g. load cells) to measure forces acting on the belt. The implementation of sensors and actuators is further discussed in Section 2.5.

The addition of a rotating mechanism introduces a significant impact on the operation speed as it requires the implementation of rotary controlled actuators and an additional manipulation step. Moreover, a rotary controlled actuator (i.e. electric motor) provides additional weight in comparison to a pneumatic cylinder and increased end effector weight reduces acceleration. Thus, in order to maintain high operation speed, the motor weight has to be reduced. Therefore, the influence of design parameters on the required motor torque is studied. Furthermore, an important aspect of this research is the handling of variation in poultry products, in terms of product geometry and flexibility. This study aims to address the impact of an elliptical profile and product flexibility on rotational behaviour of the gripper mechanism.

2.4 Theoretical model

In order to gain an understanding of the impact of design parameters on the required motor torque, a theoretical model was constructed. As displayed in Figure 2, rotational motion can be obtained by translating the belt which causes a difference in tension forces on the belt due to friction in the system. Since motor torque and rotation speed are both dependent on the drum diameter, this model focuses on the required belt tension force on the primary drum. Beginning with a Free Body Diagram (FBD) of the product and considering the forces acting on the grippers, which are connected to a fixed base, provides a schematic overview of the forces within the system, as presented in Figure 3. Note that in order to reduce the number of variables, the vectors at the grippers originate from the tip instead of tangent to the gripper. The following step is to create a set of equations equal to the number of variables in the system. Then, the set of equations is solved and the influence of parameters on the tension force can be obtained by individually changing the variables.

Due to the rotational motion, this problem becomes dynamic and friction forces are introduced. There are two types of friction forces included in the model, namely contact friction between the belt and gripper and capstan forces acting around the tip of the gripper [33]. The contact condition between belt and product is assumed to be non-slip as the product will rotate with the movement of the belt. As a result, the belt is considered part of the product at contact and the presence of the belt is formulated by:

$$N_{ij} = -N_{ji} \tag{1}$$

with i and j as connection points of the belt. Furthermore, the grippers are assumed to be rigid to reduce parameters in the system that are not of interest at this stage. Therefore, through contact with both grippers, object translation is fixed. Acceleration of the system is neglected to reduce complexity.

In order to create the set of equation regarding the FBD of the product (Figure 3b), equations were formulated based on the principles of mechanics (e.g. Newton's laws of motion), and include the relations mentioned above. First, Newton's second law of motion is applied in the x- and y-direction, and the moment around the origin O. The forces in x- and y-direction are equal to zero since translation of the object is fixed. The sum of the forces in x-direction becomes:

$$N_{CDx}+N_{GFx}+F_{Cx}+F_{Gx}+F_{fCx}+F_{fGx} = 0 \tag{2}$$

and in the y-direction is written as:

$$N_{CDy}+N_{GFy}+F_{Cy}+F_{Gy}+F_{fCy}+F_{fGy} = 0 \tag{3}$$

The equilibrium of the moment around O can be defined as:

$$\sum -N_{ix}P_{iy} + N_{iy}P_{ix} - F_{ix}P_{iy} + F_{iy}P_{ix} - F_{fix}P_{iy} + F_{fiy}P_{ix} = I\alpha \tag{4}$$

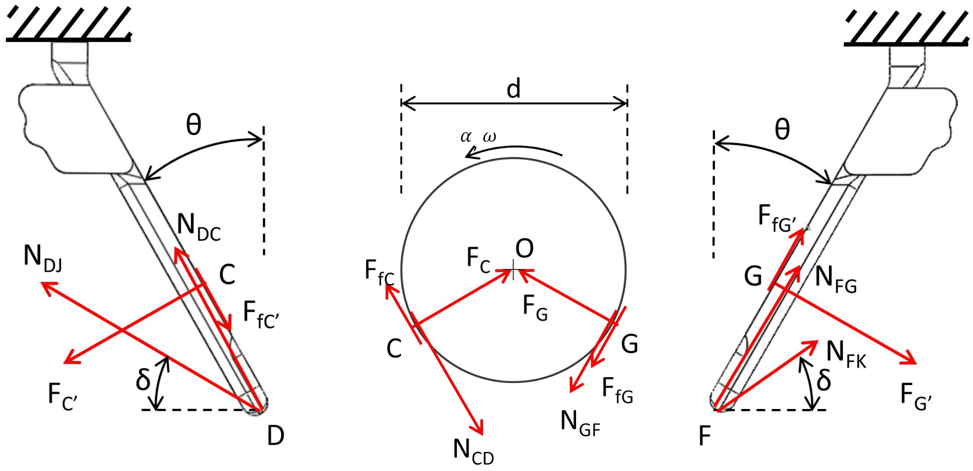
for i is C and G. Important to note that N_C represents N_{CD} and similar N_G is N_{GF}. The variable P_i defines the distance from the origin to the points C and G. The components in x- and y-direction of P_C and P_G can be written as $P_{Cx} = -dc_\theta/2$, $P_{Cy} = -ds_\theta/2$, $P_{Gx} = dc_\theta/2$, and $P_{Gy} = -ds_\theta/2$. Note that the sine and cosine of the angle theta are written as s_θ and c_θ respectively. Next, the relation and direction of normal forces and friction forces are defined as:

$$\begin{bmatrix} -\mu & 0 & 0 & 1 \\ 0 & \mu & 1 & 0 \\ c_\theta & s_\theta & 0 & 0 \end{bmatrix} \begin{bmatrix} F_{ix} \\ F_{iy} \\ F_{fix} \\ F_{fiy} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

for i is C and G, with friction coefficient μ for contact between the belt and gripper. Important to note is that c_θ is negative for i is C as both components are either positive or negative. Additionally, the direction of the direction of tension vector N_{CD} is tangent to the product and is defined as:

$$N_{CDx}c_\theta + N_{CDy}s_\theta = 0 \tag{6}$$

Finally, the capstan forces over the end of the gripper are considered, as presented in Figure 3a and 3c. In order to obtain the proper direction, a rotation matrix is included and Equation 1 is integrated to link the rigid grippers to the FBD of



(a) Rigid gripper left. (b) FBD product. (c) Rigid gripper right.

Figure 3: Forces acting on the system with: normal forces acting on the product F_C and F_G, friction forces F_{fC} and F_{fG}, and tension forces N_{DJ}, N_{DC}, N_{CD}, N_{GF}, N_{FG}, and N_{FK}. Reaction forces are indicated with an apostrophe. Parameters grip angle θ, belt angle δ, product diameter d, velocity ω, and acceleration α are included.

the product. As a result, the matrix for the left gripper can be written as:

$$\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ c_\varphi & -s_\varphi & -e^{-\mu\varphi} & 0 \\ s_\varphi & c_\varphi & 0 & -e^{-\mu\varphi} \end{bmatrix} \begin{bmatrix} N_{DCx} \\ N_{DCy} \\ N_{DJx} \\ N_{DJy} \end{bmatrix} = \begin{bmatrix} N_{CDx} \\ N_{CDy} \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

and the matrix for the right gripper as:

$$\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ c_\varphi & -s_\varphi & -e^{\mu\varphi} & 0 \\ s_\varphi & c_\varphi & 0 & -e^{\mu\varphi} \end{bmatrix} \begin{bmatrix} N_{FGx} \\ N_{FGy} \\ N_{FKx} \\ N_{FKy} \end{bmatrix} = \begin{bmatrix} N_{GFx} \\ N_{GFy} \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

note that the sine and cosine of φ are written as s_φ and c_φ respectively, where $\varphi = 1/2\pi + \delta + \theta$. The reaction forces acting on the gripper are not of interest as the gripper is assumed to be rigid. As a result, the set of equations defining the theoretical model is presented as a matrix in Appendix F.

Furthermore, to maintain constant tension forces N_{DJ} and N_{FK} during product rotation, the change in effective belt length l_e should be zero, a sketch is presented in Figure 4. Since the primary drum is winding the belt and the secondary drum is unwinding the belt, the drum diameter increases and decreases respectively. The change in belt length is defined as $\Delta l_e = x_p - x_s$, where x_p and x_s arise from the equation for the circumference of a circle times the number of rotations R, resulting in $x = \pi D R$. In this case, the diameter D is the sum of an initial diameter d and the component for the average change in diameter caused by (un)winding of the belt $\Delta d = \frac{2tR}{2}$. The equations for relative displacement of the belt are as follows:

$$x_p = \pi(dR_p + tR_p^2) \tag{9}$$

$$x_s = \pi(dR_s - tR_s^2) \tag{10}$$

where the secondary drum unwinds and therefore decreases in diameter. Considering a change in effective belt length equal to zero $x_p = x_s$, results in:

$$dR_p + tR_p^2 = dR_s - tR_s^2 \tag{11}$$

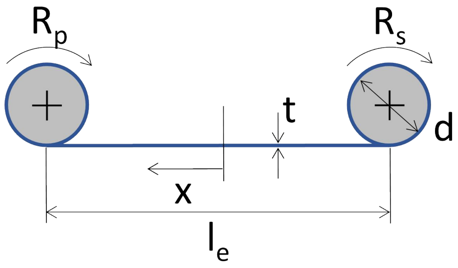


Figure 4: (Un)winding behaviour parameters: winding length x, number of rotations R, belt thickness t, initial drum diameter d, and effective belt length l_e. Primary and secondary drum are indicated with subscript p and s respectively.

which resembles the function of a circle going through the origin. Since the bottom half of the circular function is of interest, the equation for R_s can be written as a function of R_p like:

$$R_s = \frac{d - \sqrt{d^2 - 4dtR_p - 4t^2R_p}}{2t} \tag{12}$$

and can be utilized to compensate for the (un)winding behavior of the belt.

In conclusion, the required tension force on the belt are influenced by the geometric aspects of the theoretical model, friction, and pre-tension force. Therefore, the parameters that impact the system are product diameter, grip angle θ, belt angle δ, friction coefficient μ, and pre-tension force N_{FK}. The impact of these parameters is analysed in Section 3.1. Additionally, to maintain constant belt length and compensate for the (un)winding behavior, Equation 12 can be implemented.

2.5 Experimental setup

In order to validate the theoretical model, an experimental setup was designed and constructed, see Figure 5. Since the current RoboBatcher is unable to rotate a product the gripper mechanism was modified. By replacing the tension arms for two rigid elements, each with a drum attached, the belt could be moved in a direction by rotating both drums in similar direction. The drums were actuated using two NEMA 23 stepper motors (dark grey) with TB6600 drivers as stepper motors have high torque at relative low speeds and have a broad speed range. The rigid elements of the drum assembly was attached to the base by two YZC-133 20kg load cells (green) with HX711 load cell amplifiers to measure the force excited on the belt during rotation [34]. The system was controlled by an Arduino Uno. The added parts were printed using an FDM printer and were made out of ASA (light grey). Detailed drawings of the adapted RoboBatcher including parameters and dimensions are included in Appendix H.

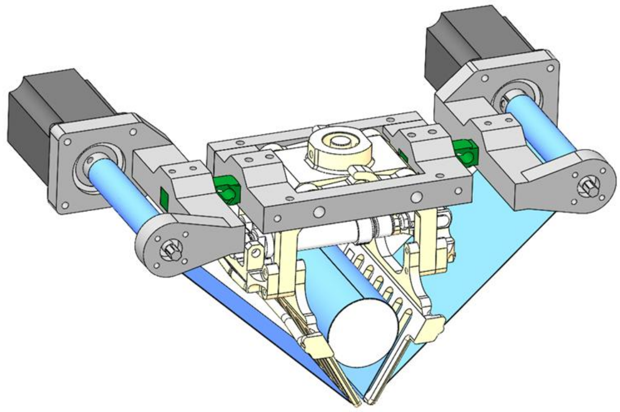


Figure 5: Adapted RoboBatcher gripper

To select a motor that is able to handle the required amount of torque, a theoretical model of the current RoboBatcher was constructed, as stated in Appendix G. Through analyzing the current model, the force acting directly on the product N_{CD} of 14.21N was obtained and implemented in the model of the adapted RoboBatcher at N_{GF}. This resulted in a tension force of 207.7N and with a drum diameter of 10mm, the minimum required torque is 1038.4Nmm. The NEMA 23 offers a sufficient holding torque of 1320Nmm.

The load cell in combination with the signal amplifier was able to perform measurements at 10Hz. Prior to starting a measurement, the load cell has to be calibrated, which was done by performing the calibration step within the HX711_ADC library. A calibration mass (m_{cal}) was used to set the calibration value and was validated with a second mass (m_{meas}). Moreover, the relative

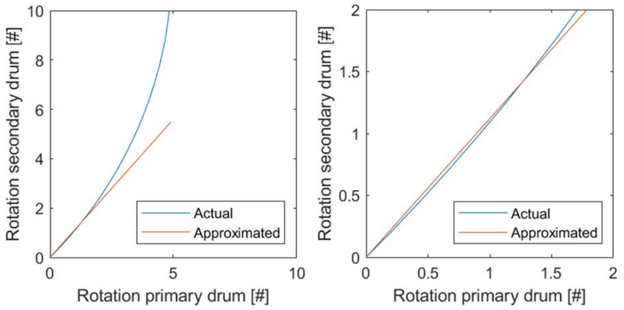


Figure 6: (un)winding behaviour, factor $f = 1.12$

measurement error ϵ was computed with $\epsilon = (m_{meas} - m_{cal})/m_{meas}$. Furthermore, from the measured mass, the force component in the direction of the belt can be obtained with the belt angle δ and the gravitational constant of 9.81m/s^2.

Due to limitations of the Arduino Uno the (un)winding behaviour is linearly approximated. Equation 12 derived in the previous section defines the rotation of the secondary drum as a function of the rotation of the primary drum, which is displayed in Figure 6 in blue, for a rotation larger than zero. This function is a half circle and increases more rapidly as the rotation of the primary drum increases. In order to approximate the slope of the function, the factor f is introduced, for which the function is displayed in red. Implementing a factor of $f = 1.12$ seems to give an accurate approximation of the function. The value for factor f is experimentally determined in Section 3.2.

2.6 Validation theoretical model

In order to validate the theoretical model, the tension forces acting on the belt were measured while rotating a product. By achieving a steady state rotation, the forces in the system are constant, thus reducing the impact of additional effects such as rotational acceleration on the system and ensuring more accurate results. To achieve this, a two step measurement procedure was formulated and implemented. First, tension is applied to the belt by winding both drums until they reached a specified load, measured at the load cells. Next, the object is rotated for two revolutions while measuring the loads on the load cells to obtain a steady state. Moreover, behaviour of (un)winding is compensated by the factor f, where $R_s = R_p f$. For the experiment, the initial of pre-tension of 1.3N was incrementally increased to 11.9N over the course of nine experiments, ensuring a theoretical force N_{GF} of up to 21N directly on the product. Each measurement was performed in clockwise and counterclockwise direction to account for deviations in the system.

Next, the measurement data was analyzed. The initial and last measurement steps were excluded to eliminate the initialization behaviour and rapid increase in force due to shortening of the effective belt length. The remaining data which resembles two constant forces, the primary tension force and the secondary pre-tension force. These measurements were plotted with "errorbar" function in Matlab to indicate the minima and maxima within the measurements and the average force.

Lastly, to validate the theoretical model, the measured secondary pre-tension force was converted to array using the "polyfit" function and was then used as input for the theoretical model. With this method, the resulting theoretical tension force could be compared to the measured tension force. Since the friction coefficient between gripper and belt was unknown, this parameter was utilized as a fitting variable to fit the theoretical model with the obtained data through experimentation.

2.7 Experiments for product variation

Although experiments are performed utilizing a rigid round object as a simplification to reduce complexity, poultry products exhibit significantly different characteristics. Specifically, they are flexible and tend to have an ellipsoidal shape, in contrary to rigid round objects in the initial experiments. To understand the implication of those differences, two experiments were carried out. Firstly, the impact of an ellipsoidal shape was investigated. Subsequently, the consequences of introducing flexibility in the product were examined. This approach ensures a distinctive relation between both factors could be obtained.

2.7.1 Ellipsoidal product shape

Since a product has the shape of an ellipse, the required belt length surrounding the product within the gripper changes as the product rotates. The difference in this length essential as it needs to be compensated for in order to maintain constant tension. An example displaying this effect is displayed in Figure 7. The perimeter surrounding the product within the gripper (blue and orange) consists out of a partial ellipse and two lines. To compute the arc length of an ellipse, the angle phi must be obtained.

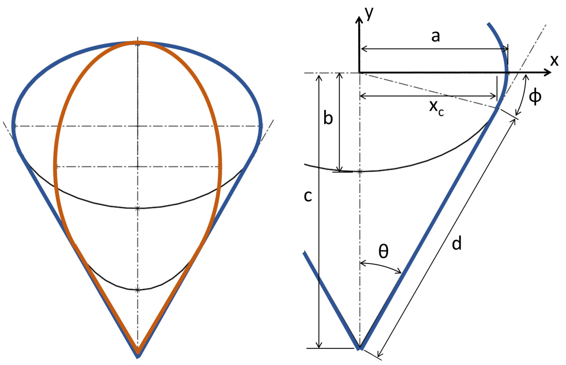


Figure 7: Belt length surrounding ellipse (left) and parameters (right)

The tangent line of an ellipse is defined as $y = sx - \sqrt{a^2s^2 + b^2}$ and the contact point is at $x_c = a^2s/\sqrt{a^2s^2 + b^2}$ [35], with s being the slope of the tangent line, in this case $s = 1/\tan(\theta)$. Since a linear equation can be written as $y = C_1x + C_2$, length $c = \sqrt{a^2s^2 + b^2}$. Next, angle phi can be obtained by $\phi = \tan^{-1}((c - d_y)/x_c)$, with $d_y = x_c/\tan(\theta)$. As a result, the equation for angle phi can be written as $\phi = \tan^{-1}(c/x_c - 1/\tan\theta)$. The parameters supporting these equations are shown in Figure 7.

A method of computing the arc length of an ellipse is mentioned in [36]. The arc length is computed as the difference of two elliptic integrals ranging from 0 to T, which is stated as $E(t, m) = \int_0^t \sqrt{1 - m\sin^2(t)}dt$, where $m = 1 - b^2/a^2$. Then the arc length can be obtained using $l_{arc} = aE(T_1 - \pi/2, m) - aE(T_0 - \pi/2, m)$. Note that the ellipse is horizontal for this calculation, therefore the value T has to be adjusted for a vertical ellipse. Thus, $T_0 = \arctan(a/b\tan(\phi)) + \delta$, with $\delta = 0$ for a horizontal ellipse and $\delta = -\pi/2$ for a vertical ellipse. The variable T_1 is calculated as $T_1 = \arctan(a/b\tan(-\phi)) + \delta$, with $\delta = -\pi$ for a horizontal ellipse and $\delta = -3\pi/2$ for a vertical ellipse.

Finally, the length of the ellipse is added to twice the length d in both cases and the strain can be obtained with $\varepsilon = \delta/L$. The influence of the variable grip angle theta can be examined and the ratio between a and b can be changed.

2.7.2 Product flexibility

To gain insight in the rotational behavior of flexible products within the gripper system, a systematic test was conducted. This experiment aimed to evaluate the system's ability to successfully rotate a product within the gripper and to determine which factors influence the performance. Gap width is considered a crucial parameter, since the product has the tendency to be forced through the gap between the grippers as it is compressed. Besides gap width, two additional parameters were varied to examine the influence on rotational behavior. First, the experiment was conducted separately for a grip angle of 30° and 60°, as this parameter is expected to be of significant influence. Second, two values for the initial pre-tension were applied to assess their influence on rotation success rate. Lastly, Additionally, to account for deviations in products, three distinct chicken drumsticks were utilized as test objects.

Experimental setup was constructed such that a fixed gap width in the range of 4 to 30mm could be obtained with incrementally adjustable steps of 1mm. Due to expectancy of the gap width having a critical range after which failure is certain, a limited number of experiments are continued beyond this range. Additionally, the experiment was conducted for both a grip angle of 30 and 60°, and for an initial pre-tension of 300 and 600 grams. Lastly, each of the variations was tested with the use of three chicken drumsticks ensure reliable and consistent results.

3 Results

3.1 Relations theoretical model

Since the forces acting in the system depend on only a few parameters, the influences of these parameters were examined. These parameters included grip angle, friction coefficient between belt and gripper, pre-tension, and belt angle, product diameter was excluded as this parameter is not determined by the design of the gripper. By individually changing these parameters while keeping the other values constant, the relation of various parameters on the required tension force was obtained. Baseline parameters are as follows, a grip angle of 30°, the friction coefficient was 0.2, a pre-tension of 5N, a belt angle of 42°, and the product diameter was set to 50.5mm.

As shown in Figure 8 the influence of the parameters on the required tension force are displayed. The tension force declines exponentially with an increasing grip angle. An exponential increase in tension force is obtained through increasing the friction coefficient. The pre-tension force and belt angle seem to have a linear effect on the tension force. Therefore, increasing the grip angle and decreasing the friction coefficient are most effective in reducing the required tension force.

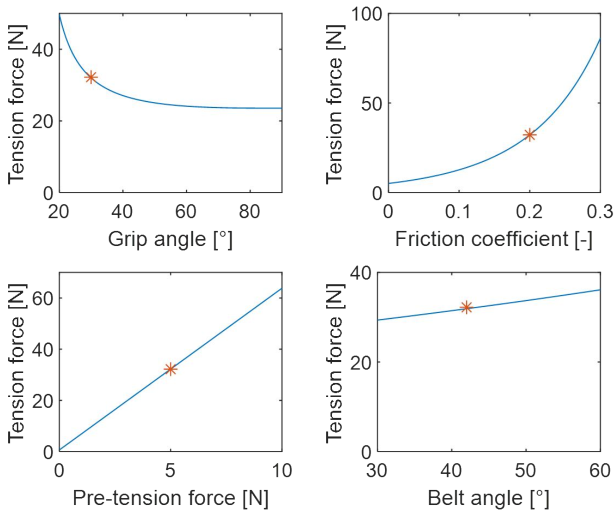


Figure 8: Tension force in relation to grip angle, friction coefficient, pre-tension, and belt angle sequentially. Baseline parameters are indicated as *.

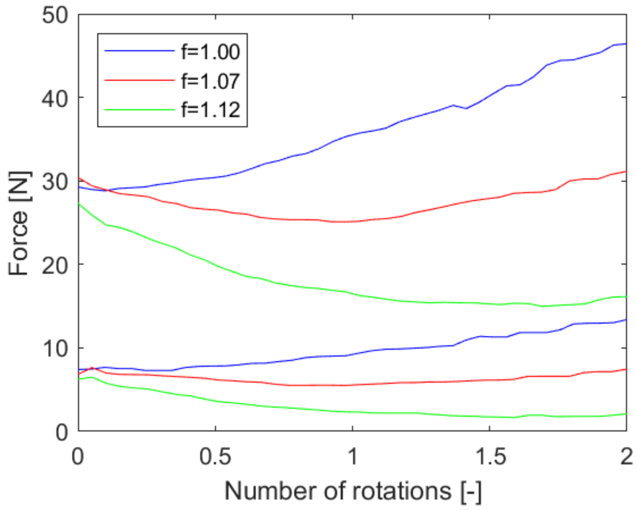
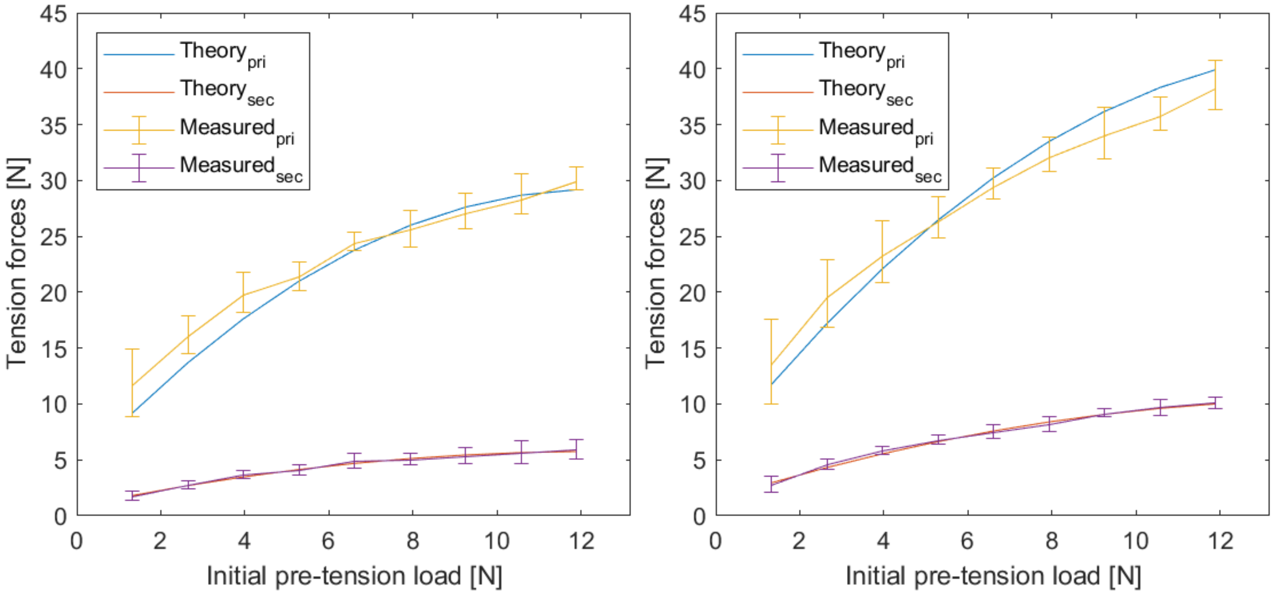


Figure 9: Measured primary (top) and secondary (bottom) tension forces for various factors f.

3.2 Validation theoretical model

In order to verify that the relations presented in Section 3.1 of the theoretical model hold, an experiment was conducted. In this experiment, tension forces on the belt were measured during the rotation of a test object. In regard to the theoretical model where the primary tension force can be obtained for a set of parameter, the goal of this experiment was to create a steady state rotation, such that the measured forces remained constant. This could be compared to the theoretical model to provide validation.

As mentioned in Section 2.5, a factor f was implemented to approximate the (un)winding behaviour of the secondary drum. As resulted from the theoretical computation, a factor of $f = 1.00$ would lead to negative change in effective belt length, subsequently increasing the tension forces throughout the measurement. Similar behaviour was measured in experiments, as seen in Figure 9, where the tension force increased throughout the measurement. Increasing the factor to $f = 1.12$ as indicated in the theoretical model, resulted in a decrease in tension forces. As a result, relative constant behaviour was obtained with a factor of $f = 1.07$. However, a slight dip was present throughout the measurement. This dip could be caused by the implemented linear approximation and by transient behaviour of the system.



(a) Grip angle of 30°.

(b) Grip angle of 60°.

Figure 10: Experimental measurement results and theoretical model with $\mu = 0.176$.

The experimental process began with the calibration of the load cells with the implementation of a test mass. The calibration lead to a maximum error of 0.36% which provides sufficient accuracy for this measurement, as stated in Appendix I. Subsequently, the product was placed into the gripper without tension on the belt. Next, the tension action was performed in which tension was applied to the belt up to a specified load. Finally, the rotation action was executed and tension forces acting on the belt were measured.

The measurement results are presented in Figure 10 where the tension forces are displayed in relation to increasing initial pre-tension. The experiment was conducted implementing a gripper with a grip angle of 30° in Figure 10a, and of 60° in Figure 10b. As a result, the measurement indicated an increase in both primary and secondary tension forces with an increase in initial pre-tension. Moreover, the minimum and maximum forces for each measurement are indicated within the plot and include the slight dip within the measurement as mentioned in the previous section and the difference in measurements in opposing direction. As concluded in Section 3.1, a larger grip angle of 60° demands less tension force when experiencing a similar pre-tension force compared to a grip angle of 30°, comparable behaviour was measured during experiments, as shown in Figure 10.

In order to validate the theoretical model, the theoretical model is compared to the experimental measurements, as presented in Figure 10. The required tension force was computed with the pre-tension as input equal to that of the measured data. In this case, the theoretical model was fitted utilizing the variable of friction coefficient as it was not precisely determined. As a result, the friction coefficient of 0.176 closely matched the practical data. The implementation of this value provided a satisfactory approximation for measurements of both grip angles, thus validating the theoretical model.

Additionally, the relation between the secondary pre-tension force and the primary tension force was analysed and displayed in Figure 11, revealing approximate linear behaviour. The analysis aligned closely to the theoretical model in which the friction coefficient of 0,176 was applied. This suggest the linear behaviour of the theoretical model mentioned in Section 3.1 to be valid.

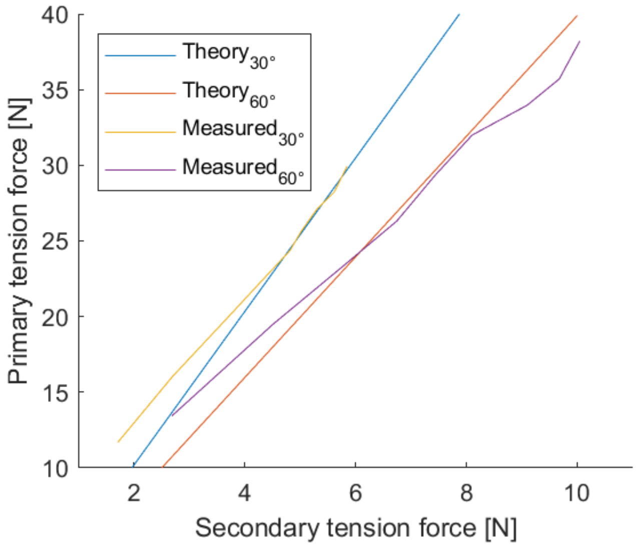


Figure 11: Primary tension force in relation to secondary tension force, displayed as theoretical model and measurements.

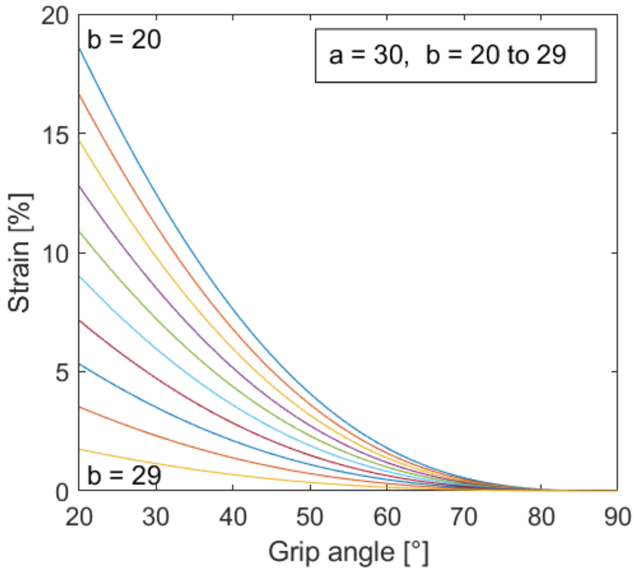


Figure 12: Belt strain as a function of grip angle

3.3 Object variation

In an effort to find the relation between grip angle and belt strain as an ellipsoidal object rotates, a theoretical model was constructed. In Figure 12 the impact on strain is displayed, as a result of change in grip angle and ratio in radii. A grip angle from 20 to 90° was presented, the radii of the ellipse was taken as a is 30mm and b was in ten steps increased from 20 to 29mm. As a result, an increase in grip angle revealed an exponential decrease in strain and increasing b, which lowers the ratio between radii, decreases the strain. The second is logical, as a round shape introduces no strain. When dealing with a decrease in grip angle, the difference position in z-direction during rotation is increased. This upward movement resulted in an increase in required strain of the belt.

To determine the critical value for the gap width of the gripper system, an experiment was performed to examine the success of object rotation within the gripper. Two additional parameters were incorporated into the experiment, namely grip angle and initial pre-tension. Furthermore, the test objects employed in this study were three chicken drumsticks. A table of all measurement results can be found in Appendix J.

Regarding the grip angle of 60°, it was observed that a gap width of 8mm or lower resulted in successful rotation, as shown in Figure 13. A successful rotation did not occur for a gap width larger than 13mm. However, when considering the grip angle of 30°, a successful rotation could not be guaranteed, with only a limited number of successful rotations at a gap width of 4 and 5mm.

Furthermore, the variation in test products resulted in the second product having a success rate of 29% regarding columns where variation was present. This is about 25% lower than for the other products and indicates that product variation can have an impact in rotational behavior. Moreover, regarding the grip angle of 60° the experiments performed with an initial pre-tension of 600 grams showed some slight improvement in performance as the data closely matches that of 300 grams. However, the initial pre-tension did not show a substantial difference throughout the entirety of the experiment, with a difference of 5%.

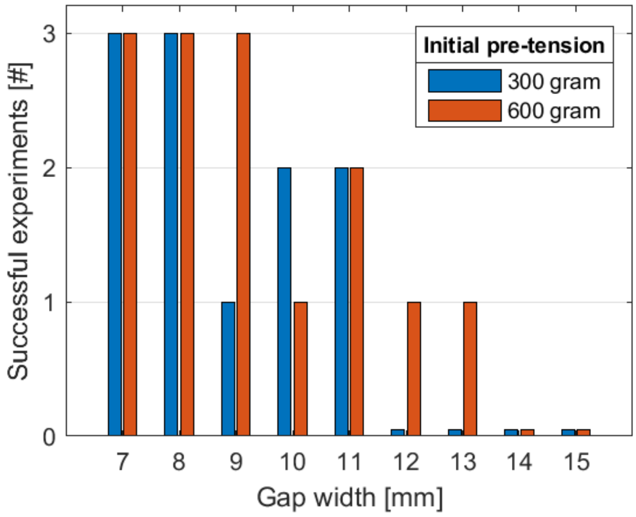


Figure 13: Measurement results on successfully rotating a chicken drumstick for a grip angle of 60° at varying gap widths

In summary, it can be said that a grip angle of 30° is insufficiently reliable for an industrial application. When considering the grip angle of 60°, the critical value for gap width is set at 8mm. Ultimately, this value could be utilized to determine the required stiffness of the gripper in a future design. Additionally, a quantitative study should be performed to determine the reliability with a large variation in products, as influence of product variation was experienced.

4 Discussion

Due to the implementation of the HX711 signal amplifier on the load cells, the maximum sample rate was 10Hz. Moreover, to allow readings of the load cell to be exported, the data was serially transmitted to the Arduino. This operation prevented mircostepping of the stepper motors for a brief interval. Although decreasing the rotation speed resolved these issues, measurements were limited in terms of rotational speed. Additionally, due to the winding behaviour of the primary drum, the rotational speed would increase during the experiment. However, as the rotation speed was already quite low, these effects are negligible.

Due to the limitation of the Arduino, the unwinding behaviour has to be compensated by means of a linear function. Although some deviation were observed in the measurements, caused by the slight dip, a clearly defined trend was outlined. Moreover, the result of a range of measurements was compared to the theoretical model this makes slight deviations insignificant in comparison to the general result.

Experiments were performed on chicken drumsticks and while examining ellipsoidal shape and flexibility, the curved shape along the rotation axis was not considered. Due to this flexibility and the applied tension on the belt, products were compressed into a cylindrical shape. Reducing the effect of the ellipsoidal shape and curvature of the product, allowing the majority of the product to be in contact with the belt.

As concluded, increasing the grip angle would be advantageous as it reduces the required tension force and reduces the amount of belt strain during manipulation. However, this increase limits the compactness as more material is present at the bottom of the gripper. An option to reduce this effect is to implement a slight curve into the gripper jaws.

5 Conclusion

With the primary aim of providing a proof of concept for in-hand rotational manipulation of poultry products, it can be concluded that a proof of concept regarding a belt driven rotation gripper is obtained. Since the required 180° of rotation was obtain in an instance of 260ms. Additionally, a configuration was constructed in which successful object rotation was demonstrated. The configuration implemented a grip angle of 60° and a gap width of maximum 8mm.

Furthermore, the analysis on the influence of design parameters shows that increasing the grip angle exponentially decreases the required tension force, as well as the theoretical belt strain. Moreover, an increase in friction coefficient exponentially increases the required tension force. Pretension force and belt angle both have a linear relation to the required tension force. These findings were validated by means of experiments for which a friction coefficient of about 0.18 seemed to fit the theoretical model to the experimental data.

The study on ellipsoidal product shape revealed an exponential decrease in belt strain with an increase in grip angle. As a result, the belt strain could be decreased from about 14% to 2% by changing the grip angle of 30° to 60°.

In regard to product flexibility, an experiment was performed analysing successful product rotation in relation to the gap width between the grippers. The experiment demonstrated successful rotational manipulation for a configuration with grip angle of 60° and a gap width of maximum 8mm. Moreover, in the range of 9 up to 13mm the outcome was variable and after 13mm failure was inevitable. Additionally, experiments performed with a grip angle of 30° proved unreliable as failure occurred more frequently than successful manipulations.

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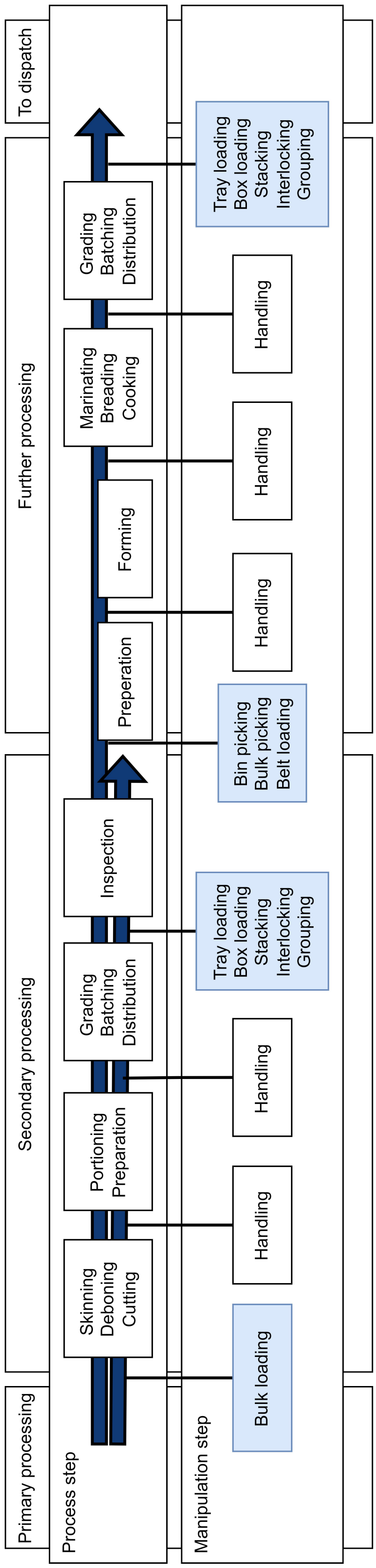
A Poultry processing steps



B Literature review

An overview on gripper mechanisms for in-hand rotation of objects

Abstract: Robotic manipulation is widely applied to reduce manual labor and increase throughput. However, robotic applications often lack in terms of dexterity and ability to cope with variation, which is required in the food industry. Pick and place systems are capable of handling a large range of objects, but in-hand manipulation during this operation is a challenge. In this review, a thematic approach is applied to categorize literature in terms of gripper manipulation mechanisms. This paper aims to provide an overview on the currently available in-hand manipulation grippers to assist researchers and engineers in selecting a suitable concept for further development in the field of robotic manipulation.

B.1 Introduction

The topic of robotic gripping technology has gained significant attention in the recent years due to the continuous effort to replace human labor with robotic solutions. Since the food industry requires the handleability of a variety of objects in geometry, size and stiffness, even within the same product group, the dexterity of a human is difficult to counteract with robots. Therefore, robotic solutions often remain mechanically unfeasible or lack speed [3, 37].

Despite the extensive reviews on robotic grippers, research in the field of robotic gripping technology is mainly performed in two directions. The first direction of research is human inspired gripping where the human motion and sensing capabilities are mimicked. The second direction are grippers for industrial purposes which focus on a specific task [38]. While surveys on industrially capable gripper solutions focus on the various types of gripping mechanisms, instead of on specific features [39, 40]. As certain key functionalities are determined by the end effector of the manipulator system, some of the recent challenges in the field of robotic gripping mechanisms are the in-hand manipulation and grasping capabilities [15]. Moreover, a review on in-hand rotation of objects was not presented, which this review aims to execute.

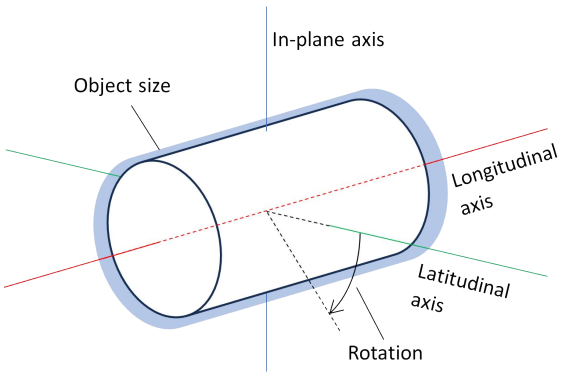


Figure 14: Manipulation parameters

The key goal of this review is to gain an understanding of how various concepts for in-hand rotation perform and in which aspects they are limited. Focusing on the industrial capabilities as manipulation speed, amount of rotation, and types of objects that are handled, a description is mentioned in Figure 14. Also, the construction of the manipulation mechanism is of interest. By presenting a literature review structured in types of manipulation concepts, the divergences of each of these concepts can be explored. As a result, a foundation is made to enable the selection of suitable solutions in future design challenges.

B.2 Method

The literature review process was carried out iteratively, with ongoing adjustments made based on the findings. Furthermore, the primary source for gathering relevant literature was Google Scholar. The search included search terms or synonyms of the terms, including those related to gripper design (e.g., compliant, underactuated, flexure), robotic manipulation (e.g., rotation, orienting, manipulation), object handling (e.g., object, in-hand, belt), and application (e.g., industry, dexterity, food). To ensure relevant and recent developments were incorporated, the time frame for inclusion of articles ranged from 2010 to 2023.

The criteria for inclusion and exclusion involved first examining the title, then reading the abstract, and subsequently analyzing the full text. Articles that did not provide a concept with an ability to in-hand manipulate objects were excluded. Additionally, anthropomorphic robotic grippers were also excluded, as they are complex and often lack in terms of speed, which is not suitable for high-speed industrial applications [38]. Furthermore, the information that was of most interest during data collection included the following aspects:

1. **Gripper configuration:** Details regarding the design and configuration of the gripper mechanism.
2. **Manipulation method:** Information on how the manipulation is performed.
3. **Object type:** The geometry and rigidness of objects that the gripper is able to handle.
4. **Amount of rotation:** The extent to which the gripper can rotate an object.
5. **Manipulation speed:** The time necessary to manipulate an object.

Subsequently, the collected information was systematically analyzed based on several key factors, including:

1. **Gripper construction:** A description on how the gripper mechanism was constructed, focusing on its mechanical and structural features regarding manipulation.
2. **Manipulation method:** An examination of the methods employed for the manipulation of objects.
3. **Gripper features/limitations:** The capabilities and limitations of the mechanisms are mentioned in terms of the following parameters.
    - Amount of rotation: The maximum amount of object rotation.
    - Manipulation time: The duration of the manipulation action.
    - Object type: The geometries the gripper can handle, including flexible items.
    - Object sizes: Suitable dimensions of objects that the gripper is able to manipulate.

The various concepts of gripper mechanisms identified in the reviewed literature were organized thematically. Based on the type of rotational manipulation, relevant information was grouped. This thematic organization allowed for a systematic overview, ensuring an understanding of each concept type. Next, an overview of the reviewed literature was created, which summarizes the obtained data of the different types of concepts. Lastly, the findings were synthesised and discussed. Advantages and limitations could be considered to gain knowledge on gripper manipulation options for future problem solving.

B.3 Results

Within this segment, the results of the 26 examined articles are presented. These sources are examined based on crucial aspects as gripper construction, manipulation methods, and various gripper features and parameters. In order to establish a clear overview of the topic, a thematic approach was used to systematically classify each source. This offered valuable insight in degree of rotation, manipulation duration, object geometry of each category of gripper.

B.3.1 Rotational motion

In this section, several gripper concepts regarding object re-orientation by means of rotating gripper jaws are discussed, as presented in Figure 15. Due to the relative difference in displacements of the contact point, rotation of the object is achieved. The explored concepts include commonly referred mechanisms as: four-bar mechanisms, variable friction grippers, and grasp-reposition-reorient (GR2) gripper designs as shown in Figure. Furthermore, certain concepts in the context are influenced by human finger thumb manipulation, aiming to replicate dexterous rotational movements in robotic grippers [12].

Figure 15: Rotational motion concepts found in literature [4–6, 13].

The first approach consists of a 2-degree-of-freedom (DOF) four-bar mechanism which is a typical GR2 gripper design [4]. This type of gripper has a locked and unlocked state, and is underactuated in the unlocked state. Planar rotation of objects is possible for a maximum angle up to 28.6 degrees, while the center point of the rotational axis shifts during manipulation. Experiments were conducted on rigid square and round profiles with a size of 20 to 45 millimeters in width. Notably, square objects would transition from edge to side contact and were not capable of returning to the initial state. Furthermore, the no-slip condition was difficult to maintain with square objects. Two options for the gripper were proposed in this research, one with solid links connecting to the pivot point and one with flexible links. Unlocking central link in the solid link configuration allows for the ability to go from side contact to edge contact with a cube, resulting in large increase of rotational motion. Similarly, the maximum angle of rotation was increased when using flexible links. The research was limited in terms of speed, which helped maintain grasp stability.

Another concept that was presented is a human inspired 2-DOF gripper where the rotation action is obtained through variable friction [12]. By varying the friction between the finger and the object on one side translation and rotation were achieved. Experiments showcased the capability of a full rotation though stepwise manipulation on a square profile having a width of 25.4 millimeters, other shapes were also used. A limitation was reached for cylindrical objects as the rotation was decreased due to rolling behavior.

A variation of the GR2 gripper was explored in two variations, namely an intermediate and coalesced GR2 gripper, with the design being based on brute force search computation [5]. The coalesced GR2 gripper has a locked and unlocked configuration. Moreover, the simulations showed better performance for the unlocked coalesced GR2 gripper. In-hand reorientation of approximately ninety degrees was achieved for the original GR2 gripper and was increased towards the optimized coalesced GR2 gripper. Various circular and square profile objects of 20 to 63 millimeters across were tested. Seemingly, object rotation peaked at a specific object size and decreased with increasing size.

The next gripper focusses on the ability to measure rotation and position, which is done by including a new type of TacTip sensor to the GR2 gripper [13]. In this case cylindrical objects with a diameter of 20 to 35 millimeters were analyzed. Measurements were performed for rotations of 42 to 67 degrees, with an error no larger than five degrees. Furthermore, misaligned cylinders were investigated and had a rapidly increasing error of 20 degrees for 3 millimeters of translation.

A review was presented on multi-fingered grippers, including some two fingered gripper designs [6]. Moreover, some dexterity based orientation principles were mentioned as well as different manipulation strategies. Focusing on the two fingered gripper, rotation of a cube was achieved by moving while switching to active friction. This operation was limited in terms of speed with an average execution time of 40,8 seconds. The gripper also lacked in terms of manipulation as some objects or states were limited, causing inaccuracies and slippage.

In summary, various concepts were explored with the ability to in-hand rotate rigid objects. Experiments were conducted on round or square profile objects of sizes ranging from 20 to 63 millimeters. Since the concepts implemented rotating jaws to establish difference in contact point to obtain manipulation, the amount of rotation was limited in most cases. Notably, there was no focus on achieving high-speed manipulation, as maintaining a stable grasp was considered crucial.

B.3.2 Linear opposing movement

Next, the implementation of opposing movement to enable rotation is presented below. Solutions range from single sided linear motion to both gripper jaws being operated simultaneously. Moreover, the frequently proposed gripper types Multi-Modal (M2) and Twisting and re-Positioning (TP) are included. Also, adaptations to the basic parallel gripper are made, like presented in Figure 16. In some cases computational software was implemented to gain understanding of the gripper, while other sources experimented with sensors. An overview of the various concepts for linear opposing movement is shown in Figure 16.

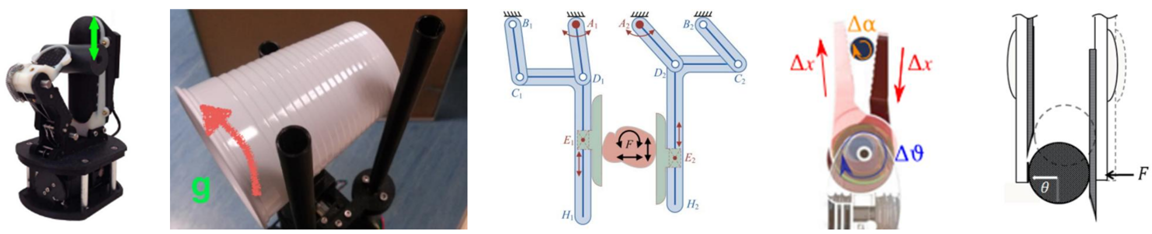


Figure 16: Linear opposing movement concepts found in literature [7–9, 15, 16, 38].

In order to obtain feedback on object positioning within a M2 gripper, tactile sensing is integrated [7]. The rotation manipulation is performed through linear displacement of the object while maintaining contact with a flat surface with tactile sensors. Experiments were performed with cylindrical objects, featuring diameters of 20, 25, and 30 mm. Specific data regarding angular displacement was not detailed as the displacement distance was obtained. An approximation of the angle was deduced using the available data on object perimeter and distance, revealing a rotational angle of around 90 degrees.

A dexterous 16 DOF gripper is proposed in [14], however, a more industrially suitable gripper is also mentioned, decreasing the number of DOF's to 5. This gripper consists of three shafts that can individually rotate around their axis, one axis is able to extend and retract, while the other two can move back and forth simultaneously. Therefore, the gripper is able to rotate a foam ball around two axis of rotation, a plastic cup also rotated. Additionally, a simulation of the 16 DOF gripper in MSC ADAMS shows a rotation of 90° within 10 seconds [38]. Lastly, the advantage of dexterity on any given plane is mentioned.

In the next study, another adaptation towards the parallel gripper is made, the two jaws are modified to enable the grasping with small or large fingers [11]. Moreover, switching between fingers is done by means of a rack and pinion mechanism. One actuator is used for each jaw, and one for the open and closing action. Furthermore, various experiments were conducted, including the in-hand rotation of a ratchet wrench with a cylindrical handle. As a result, the wrench could be rotated 180 degrees. Earlier measurements showed that switching between modes, which is necessary for the rotation manipulation, has a duration of one second precisely.

A novel parallel gripper design implementing two fingers, both with an added translational DOF was mentioned in [15]. The parallelogram was implemented to increase the reliability and robustness of the system, in combination with improved motion capabilities in comparison to the base size. Notably, the focus of this work was on industrial integration of the gripper. Numerical computations were performed on a cylinder with a diameter of 35 millimeters. In addition, a rotation of forty degrees was achieved while also re-positioning the object.

In this paper a standard laparoscopic tool is adapted to gain the ability of in-hand rotation [16]. Due to the surgical application, gripper size is relatively small, but a 2:1 scale replica was developed for experiments utilizing a round needle as object. The gripper's open and close action is done by rotating around a central axis. Furthermore, the opposing movement is implemented through turning a central cam shaft which ensures gripper motion in opposite directions. Hence, the object experiences in-hand orientation. As a result, re-orientation of the needle was possible in a range of +/- ninety degrees.

Lastly, the TP type gripper is mentioned which is a combination of re-orientation through rotational opposing movement, together with linear opposing movement [8–10]. This gripper is constructed as two linear actuated fingers with a rotational motion of the fingers by two rotational actuators. The rotational motion can be determined by both the inner and outer actuators. In this research rotation of various rigid objects was demonstrated which include a straight cylinder, a straight prism, and an irregular object with a size of 10.5 to 17 [mm] in diameter. These objects were gripped at the center of mass which enhanced successful twisting around their longitudinal axis. Rotation was achieved within a safe region for the parameters R and α, which represent the cross section diameter and the gripping angle respectively. During high speed and acceleration testing industrial potential was shown as the twisting action could be accomplished in less than 0.6 seconds. Thus, this type of gripper demonstrates simplicity while realizing dexterous manipulation, as shown in experiments.

To synthesize, a variety of concepts were explored, each of which implemented the simple concept of opposing movement in a different manor. Ranging from a complex multi DOF system to a more plain cam actuated mechanism. Among these concepts, manipulation of only cylindrical objects mentioned, as well as other basic shapes and irregular rigid objects, most of which within 10 to 35 millimeters of size. However, in order to rotate objects, the shape has to be somewhat cylindrical. As a result, object rotation of around 90 to 180 degrees was regularly achieved, with the shortest manipulation time being under 0.6 seconds. Besides rotation, some grippers are able to perform a pull-in action to enhance grip or improve reach.

B.3.3 Belt driven rotation

Continuing with belt driven manipulation, these concepts implement a moving surface in order to rotate an object, as shown in Figure 17. The majority of the concepts mentioned utilize a conveyor belt to ensure continuous rotation, while others keep the motion of the belt limited. Additionally, a diverse range of geometries were tested, including flexible objects. Lastly, a variety of manipulation actions and applications were presented.

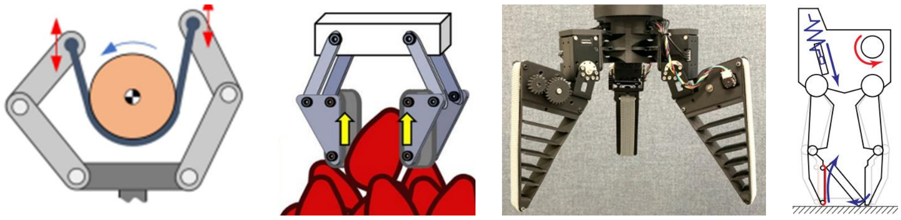


Figure 17: Belt driven rotation concepts found in literature [17–19, 21].

In this research in-hand manipulation was performed by implementing vibration into a gripper with a flexible belt surrounding the object [17]. This type of manipulation was inspired by the art of diabolo juggling, where short stroke fluctuating actuation ensure continuous rotation of an object. Therefore, belt movement is limited while maintaining flexibility to grasp various objects. As a result, the gripper was able to steadily hold and rotate objects of different shapes, sizes and masses. In terms of objects, multiple experiments were performed on cylindrical objects with a diameter of ten up to fifty millimeters. Furthermore, some arbitrary shapes were tested, all objects were rigid in this research. As for the cylinder, a rotation of one hundred degrees could be obtained in one second. The findings indicate that higher frequencies lead to an increase in rotational speed. Likewise, smaller diameter objects yield a rise in rotational speed.

The following concept proposes the combination of a conveyor belt and a parallel gripper [18]. Each of the two surfaces used for the grasping and manipulation operation can be displaced, enabling rotation as well as translation of the object. Thus, allowing for the ability to grasp and pull objects from a pile. Experiments were performed on various objects to determine robustness under different conditions. In addition, actual food in the form of strawberries were tested. On the contrary, results on rotation angle and speed were not included. However, potential on the manipulation of object with varying hardness and geometry was mentioned.

Next, an addition of conveyor belts is made towards the fin ray type grippers in [19]. Introducing multiple flexure aspect, not only in the fin ray gripper, but also in the connection between gripper and base. This allows for the ability to grasp various objects while maintaining contact with the active surface for manipulation. A range of various objects were employed for experiments, including spherical and cylindrical objects, along with a more flexible object. As a result, the wide applicability of this gripper was demonstrated, including two operational modes for grasping. On the contrary, the gripper provided limitations in terms of the rotation for relative long or flat objects. Furthermore, it was noted that the weight of an object would impact the energy efficiency, since the friction between gripper and belt increases for heavier objects.

In [20] an underactuated gripper design is fabricated and experiments are carried out to test the validity. The mechanism consists of a parallel gripper with added belt, and is able to grasp and pull objects. However, the mechanism was not designed to accomplice rotational manipulation, as the active surfaces are not able to move in opposite directions. The manipulation actions can be obtained through the actuation of a single motor and a planetary gear mechanism. Experiments are conducted on various items, a rigid mug, flexible foil, and a paper cup were grasped and pull-in with multiple grasping methods. As a result, the validity of the concept was demonstrated.

An underactuated parallel gripper with actuated surface is proposed in [21] to lift thin objects from a flat surface. In this design, the grasping action and manipulation step are tendon-driven by a pulley, tension is provided with linear spring attached to the belt. Due to the design, three grasping modes are passively executed, parallel grasping, pull-in, and power grasp sequentially. Various objects were subjected to experimentation, including a flexible rubber sheet, a softcover book, and a cylindrical item. This design showed potential in grasping soft and high friction object, but is less suitable for slippery items. Rotation was limited to a maximum of 90 degrees for thin objects grasped from a flat surface.

Since the concepts that include either a continuous rotation or a high frequent reoccurring step, rotation is continuous. To clarify, angle of rotation is not limited and initial grasp configuration is therefore identical in each situation. Due to the flexible active surface of a belt, contact with objects is increased, especially for more complex shapes, this improves grasp reliability. Furthermore, the belt allows for manipulation of flexible objects, increasing the variety of objects that can be handled. Also, as the belt is flexible, grasp force is more evenly distributed, which makes grasping of delicate products possible. Objects were in a broad spectrum of shapes and sizes, as cylindrical objects with a diameter of 10 millimeters, to as large as a mug and a softcover book. Rotational speed was only mentioned in [17] of 100 degrees in one second. Furthermore, limitations were caused by friction between the belt and gripper decreasing efficiency with heavier objects.

B.3.4 Fingertip re-orientation

Within this segment, rotation around the end of a jaw is discussed, like displayed in Figure 18. The majority of the proposed concepts implement two-stage rotation, where in the first stage an object is grasped while under constraining the allowable motion of the object. The goal of this step is to manipulate the object towards a known orientation. The second stage is fully grasping the object and constraining all motion of the object. On the contrary, also an actuated gripper with adjustable orientation is presented. Since orientation goes from uncertain to known, applications such as grasping objects with undefined orientation and precise object placement are regularly considered.

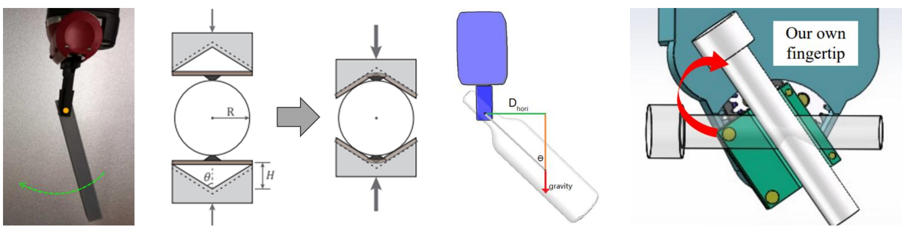


Figure 18: Fingertip re-orientation concepts found in literature [22, 23, 25, 26].

The following concept utilizes the inertia of the grasped object [22]. The manipulation process is facilitated by altering the friction force applied during this interaction, allowing for control over the rotation of the object. It is important to note that the extent of rotational motion using this approach is influenced by several factors, including the size and mass of the object. Rotation angle is modelled and verified, friction coefficients were altered throughout the experiment. A desired angle could be reached with a multi-step method, where unsuccessful manipulation attempts were in a 5-degree range of the target orientation.

In contrast to the previous concept, this two phase gripper design allows for rotation due to gravity instead of inertia [23]. Firstly, the object is slightly grasped, pivoting the object. Secondly, the object is precisely secured in a V-groove to enhance precision for cylindrical objects. Furthermore, for achieving a 90-degree rotation, picking up cylindrical objects from a horizontal surface has proven to be a successful strategy. Altering the concept was suggested to fit various shapes, which could be further explored in future research.

A similar gripper design is presented in [24], however, rotation is facilitated by a pneumatic breaking mechanism. Additionally, the mechanism includes a sensor for angular displacement. The working principle was demonstrated by grasping a glass test-tube of a horizontal surface and performing a 90-degree rotation to align the tube with the gravitational direction. Experiments were performed on various rigid objects, all of which could be re-oriented without the need for tuning, the objects were relatively long in comparison to their widths. There was no mention of operational speed, but experiments showed a duration of approximately 4 seconds for the free phase step, including pivoting and placement. As a result, the mechanism offers advantages over similar designs as the mechanism is independent of grasping force.

Likewise, in [25] object manipulation is executed by pivoting. Unlike other methods, pivoting is only present due to slip between object and contact point, while the basic gripper design is unaltered. Various objects are manipulated with multi-stage operations, object mass and absolute friction are altered throughout the experiment. The pivoting strategy highly impacts the rate at which objects are successfully rotated, reducing the slippage as suggested in this article has a positive effect on success rate.

In order to handle randomly placed screws for assembly purposes the fingertips of a parallel gripper are modified in [26]. Moreover, the fingertip is able to rotate parallel to the jaws, enabling in-hand rotation of grasped objects. Additionally, a friction wheel is positioned off center at the contact point and covered at the top. This allows the screw to be translated within the gripper. Screws were picked from a pile and placed into slots for assembly, implementing a vision system for correct placement. Furthermore, the fingertips are able to continuously rotate back and forth, provided that the object did not interfere with the gripper. As a result, the gripper was able to successfully grasp and place screws from flat and angled surfaces into the assembly.

To summarize, the two-stage grippers rely on gravity or object inertia to enable rotation, this limits the rotation to 180 degrees. However, since experiments focused on grasping from flat or incline surfaces, rotation was not more than 90 degrees. Moreover, the studies implemented pivoting or friction alteration to allow rotational motion and secured their grasp in the second stage. On the other hand, the actuated manipulation in [26] was continuous. Objects ranged from small fasteners, to wine bottles. Notably, rotations in the mentioned studies were performed along the latitudinal axis of the objects. There was no mention on details of operational speed of the various mechanisms.

B.3.5 Environmental based rotation

Besides the concepts presented in the section above, the grippers discussed in this section utilize the environment or end-effector motion to obtain rotation, like shown in Figure 19. A range of optional manipulation strategies are described and a complex dynamic manipulation is mentioned. In order to achieve these types of manipulation, a combination of end-effector movement and in-hand gripper manipulation is required.

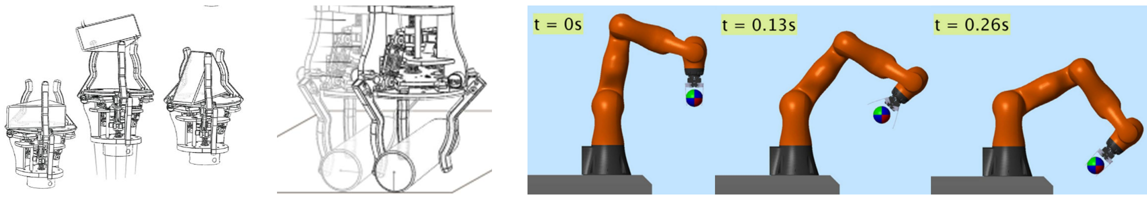


Figure 19: Environmental based rotation concepts found in literature [27, 28].

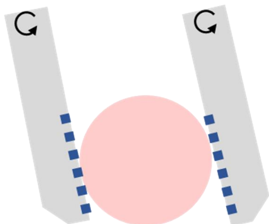
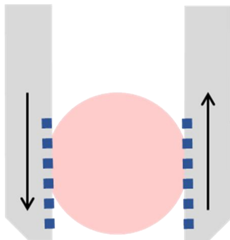
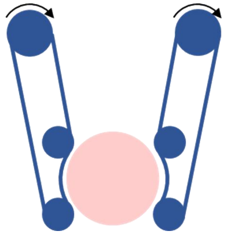
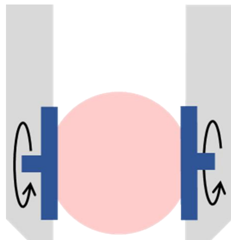
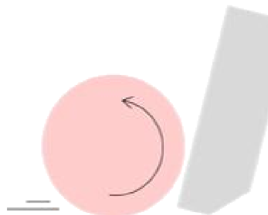
In the next article multiple methods for object in-hand manipulation are discussed, including options to rotate an object [27]. Manipulation is performed with the utilization of arm motion, object inertia, gravity, and external contacts. Object rotation was obtained with various actions, including rolling over a flat surface and rolling to fingertip. Additionally, various regrasp methods can be combined to achieve a required orientation. Experiments done on a prism exhibited success on most of the twelve regrasp methods, roll-to-ground and throw-and-flip included 18 to 32 percent failure of the trails. Furthermore, the throw-to-palm was planned to be executed in 0.2 seconds. It was discussed that this type of manipulation offers a drastic reduction in complexity in regard to dexterous hands. However, variation in objects is limited in this research and should be studied as manipulation is object dependent.

In [28] the complex manipulation of dynamic regrasping is studied, by releasing an object into midair and regrasping it, the object can be rotated. Moreover, the robotic arm's dynamics are utilized to obtain object rotation, the gripper attached to the robotic arm is rather basic. In this case, the gripper changes in angle relative to the object instead of the opposite. Simulation showed an angular displacement of 80 degrees within 0.3 seconds. Since experiments were performed on an incline air-hockey table, the effect of gravity is reduced. As a result, a regrasp angle of 25 degrees is obtained within 1.5 seconds. Notably, simulations were performed on a spherical object and experiments are done on a cylindrical object.

Ultimately, manipulation by combining the dynamic aspects of the entire system introduces complexity. However, results show failure on a slight part of the manipulation options. As a result of simulations, manipulation time is expected to be less than 0,3 seconds, but experiments are not optimized for speed. The operation is limited in terms of versatility, as the manipulation has to be adjusted for different objects. Amount of rotation is dependent on multiple factors, under which the manipulation strategy.

To synthesize, the obtained data on gripper features and limitations were summarized in Table 2, in which concept properties as range of motion, manipulation time, object types, and object sizes are mentioned. Note that the data available in the overview is determined by the obtained information in literature. As some aspects were barely mentioned within a concept type. Similarly, some outliers were excluded from the overview.

Table 2: Overview of obtained data on manipulation gripper concepts

Gripper type	Rotating jaw gripper 	Opposing movement 	Belt driven rotation 	Fingertip rotation 	Environment based motion 
Maximum range of motion [°]	<90	90 – 180	Continuous	90 – 180	∼90
Manipulation time	Measured duration not applicable	90° rotation in 0.34s	100° rotation in 1s (diabolo concept)	Pivot and placement in 4s	Single manipulation action in 0.2s – 0.3s
Object types	Cylinder, cube	Cylinder	Cylinder, cube, irregular	Relatively long cylinder, cuboid	Sphere, cylinder, prism
Approximate object sizes	20 – 63 mm in width	10 – 35 mm in diameter	10 – 60 mm in width	20 – 300 mm in length, 4 – 30 mm in width	15 – 70 mm in width

B.4 Discussion

The literature review presented above provides valuable insights into various concepts and approaches for achieving in-hand rotation of objects using robotic grippers. The discussion of these concepts clarifies their strengths, limitations, and potential applications in the field of industrial gripper manipulation.

Rotating jaw gripper

The first category of gripper concepts discussed in the review focuses on rotational motion achieved through mechanisms such as four-bar linkages, variable friction, and GR2 designs. These concepts primarily aim to manipulate rigid objects, often of cylindrical or square shape, within a limited range of rotation. The use of flexible links and variable friction in some designs enhances their adaptability to manipulate objects.

A notable limitation that was presented is the relative slow manipulation speed. Since experiments focused on obtaining a stable grasp and accurate manipulation, speed was not optimized. This would make them less suitable for high-speed applications. Therefore, research on improving operation speed is of interest. Furthermore, due to the construction of the grippers, a rotation exceeding 90 degrees is difficult and should be considered when selecting this type of concept.

Opposing movement

The second category explores concepts that apply opposing movement to enable object rotation. These concepts include designs like M2, TP, and adapted parallel grippers, The concepts demonstrate the ability to rotate cylindrical shaped objects (typically 90 to 180 degrees). Additionally, the pull-in function was integrated to improve grasp strength.

Experiments in this category show that the concept is capable of high-speed operations. The range of motion is increased relative to the "rotating jaw gripper" concept, due to the change in contact points during the manipulation. However, the limitation lies in the object geometry which requires to be somewhat cylindrical as the object rolls within the gripper.

Belt driven rotation

The third category, depending on the design, can offer continuous rotation by means of belt driven mechanisms. These concepts typically involve a flexible belt or conveyor system. Moreover, this offers advantages in terms of adaptability to a variety of object shapes, including flexible objects.

The belt driven concepts are well suitable for applications within the food industry, as they can handle a range of object geometries. Another advantage is the fact that the concept is able to continuously rotate objects. However, the friction between belt and gripper can impart efficiency, particularly with heavier items. Also, the mention on operation speed was limited which should be researched in the future.

Fingertip rotation

The fourth category emphasises on manipulation at the fingertips of a gripper. These concepts often involve two-stage operations where the object is lightly grasped and re-orientated towards a predefined position, after which the object is securely grasped. This manipulation action rotates by allowing pivoting and utilizing the inertia of an object.

The application of this type of concept is object specific, as the geometry and grasp position determine the rotation. Thus, parameters must be adjusted for deviating objects, which limits the variability.

As a result, this concept is suitable for applications with repetitive tasks. Notably, these types of concepts ensure a rotation over the latitudinal axis of the object, in contrary to the other concepts mentioned which mostly rotate objects over their longitudinal axis.

Environmental based motion

The final category addresses concepts which implement the environment to achieve a rotational motion, either by performing a series of in-hand re-grasping maneuvers or through releasing and re-grasping the object from a different angle. Manipulation operations are not only determined by the gripper, but the entire system influences object rotation, which adds complexity.

Due to the dynamic complexity of the operations, versatility is limited. However, experiments demonstrate repeatability with limited occurrences of failure for operations on a single object. Apart from rolling motion on a surface, object rotation is limited and would require multiple steps achieve a larger rotation. Though these steps can be performed at a relatively high speed.

B.5 Conclusion

This literature review highlights a range of approaches and mechanisms to achieve in-hand rotation. In order to select a suitable concept, multiple factors need to considered, such as application, type of object, manipulation speed, amount of rotation, and grasp stability. It was found that with regard to the manipulation of food items, the belt driven rotation concepts were valid options, as they provide an extensional amount of contact with the object and are able to cope with object variation and flexibility.

Future research in this field could focus on further industrializing the concepts and improving the operation speed and efficiency. Additionally, as numerous studies focus on integrating sensors and advanced algorithms, these aspects could be combined to achieve a high level of adaptability and control over these robotic systems.

In conclusion, this review provides an overview of currently available robotic gripping technologies for in-hand rotation of objects. This overview offers a basis for future work of researchers and engineers in development of robotic manipulation systems.

C Concept generation

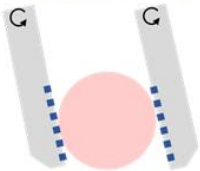
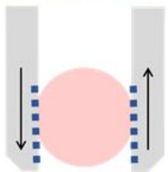
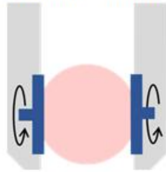
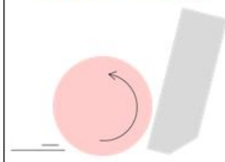
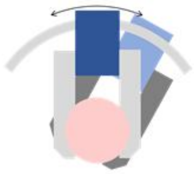
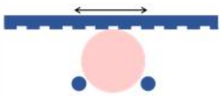
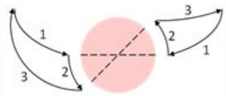
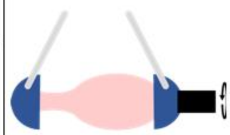
This section presents an overview of concept generation, acquiring knowledge from both obtained literature and through brainstorm sessions, a list of these concepts is presented in Table 3. By synthesizing the gathered information from the literature review and defining concepts based on generated ideas a range of concepts were explored. A preliminary evaluation was performed, leading to exclusion of concepts that were unable to meet the requirements or proved unfeasible.

In the process of concept generation, two primary sources were explored, namely literature review and brainstorming sessions. The literature review yielded insight into further developed concepts for in-hand object rotation. However, concepts were limited in terms of industrial suitability and operating speed. The concepts "opposing movement" and "belt driven rotation" were considered valid options, while dismissing "rotating jaw gripper" due to the limited rotation angle. Furthermore, "fingertip rotation" was excluded as the concept focuses on rotation over the latitudinal axis of an object and mostly achieves a similar end orientation for each object, preventing adjustability. Lastly, "environmental based motion" was deemed outside of scope for this project.

Brainstorming and creative thinking lead to additional concepts, namely "external rotation" were two identical grippers rotate over a similar axis of rotation as the product. To ensure rotation, the grippers alternately grasp and rotate the product in a continuous manor. Concept "rack and pinion" grips the product with roller-like jaws, such that the product can act as pinion, while the rack provides force to enable rotation. Furthermore, concept "cycloidal rotation" is a mechanism inspired by a cycloidal drive, which utilizes a slight difference in gear ratio to drive a shaft through an eccentric motion. In this case the eccentric shaft is located above the product. Next, "pattern movement" relies on a pattern to introduce a slight rotational step, which is repeated to enable continuous rotation. Finally, "in-line rotation" grasps the product in-line with the axis of rotation, minimizing the complexity of moving parts.

The considered concept "rack and pinion" is excluded, since the amount of force transferred to the product is applied in a small region. Moreover, products deviate in geometry and size, are flexible and are processed in a humid environment. As a result, it is expected that contact is difficult to maintain and slippage will occur, obstructing product rotation. Another concept is eliminated, namely "in-line rotation" which grasps products in-line with the rotational axis. Stiffness is required to securely grasp products in-line and while containing bone, the product is still largely flexible and unpredictable in terms of geometry. Additionally, for the application of product loading, products are placed parallel inside of narrow containers limiting operating space in-line with the product. In conclusion, both aspects decrease the potential for a suitable solution. As a result, the list of concepts was reduced to the four remaining concepts which were explored in the next section.

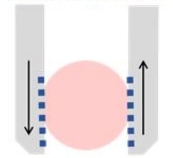
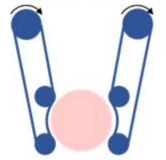
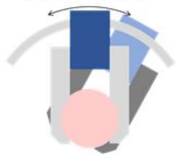
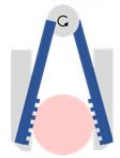
Table 3: List of concepts

Literature review				
1 Rotating jaw gripper 	2 Opposing movement 	3 Belt driven rotation 	4 Fingertip rotation 	5 Environmental motion 
Brainstorm				
6 External rotation 	7 Rack and pinion 	8 Eccentric 	9 Pattern 	10 In-line 

D Concept exploration

The concepts resulting from the concept generation section were further explored to gain insight in the feasibility and acquire factual data where possible. Technical aspects of these concepts are mentioned to allow for a rational comparison. Since concepts "opposing movement" and "belt driven rotation" are proposed in literature, an informational background is already available. Despite the relative complex timing of the concept "external rotation", the general idea is straightforward and can be accomplished through many variations. On the contrary, the concepts "cycloidal rotation" and "pattern movement" are integrated into a single solution. The final set of concepts is displayed in Table 4.

Table 4: Final set of concepts

Concepts			
1 Opposing movement	2 Belt driven rotation	3 External rotation	4 Eccentric
			

D.1 Main criteria

Several key aspects should be considered during the exploration and selection of concepts for in-hand manipulation of poultry products. Due to the application of manipulating poultry products, criteria must be optimized in order to ensure an industrially suitable solution.

1. **Speed:** high throughput is always a goal as it adds value for the customer. Existing solutions offer a throughput of up to 210 products per minute implementing three delta robots. Therefore, achieving similar speed would require a cycle time of 0,86 seconds [29]. Although a similar speed might not be possible with the added features, it remains the goal. Since actual manipulation speed is defined by many variables (i.e. actuator, friction, moving mass, etc.) a score will be obtained by estimating the efficiency between the actuator output and amount of rotation.

2. **Versatility:** as poultry products are never identical, the ability to cope with variation is important. Differences can occur in terms of geometry or size, which alter between breeds. Aspects that are impacted by product variation are of interest, including the error in rotation angle, impact on grip forces, and ability to rotate. The presence of a possible risk includes a score of 0-33%, otherwise a score of 33% added.

3. **Secure grip:** the system should be reliable, as failure causes downtime. Therefore, the products should be securely grasped, also during manipulation. Aspects that are considered to decrease reliability are limited contact between the gripper and product, need for re-grasping during manipulation, and variation in clamping forces for performing the manipulation action. The applied scores are obtained similar as for "Versatility".

4. **Compactness:** for singulation and product loading, products are grasped and placed close to each other. Unintended interaction between products can lead to failure, therefore compactness has to be optimized. Since product interaction is only present at the bottom of the mechanism, compactness above objects is not taken into consideration at this stage. As shown in Figure 20, the compactness of the various concepts can be measured for a value w of the green rectangle,

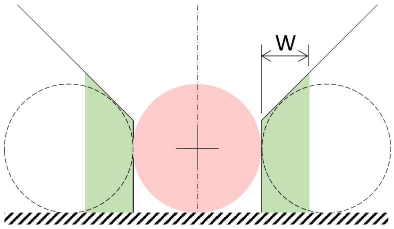


Figure 20: Required footprint

which is fitted to the size of a gripper present in that area.

5. **Contamination risk:** since the end effector is in direct contact with poultry products, risk of contamination is present and the cleanability of the system is essential. Factors that can increase contamination risk or limit cleanability include shadow faces (faces blocked by part of the gripper), overlapping surfaces, cavities, and extensive contact range for manipulation. In order to obtain a score, the amount of risks are simply counted.

D.2 Opposing movement

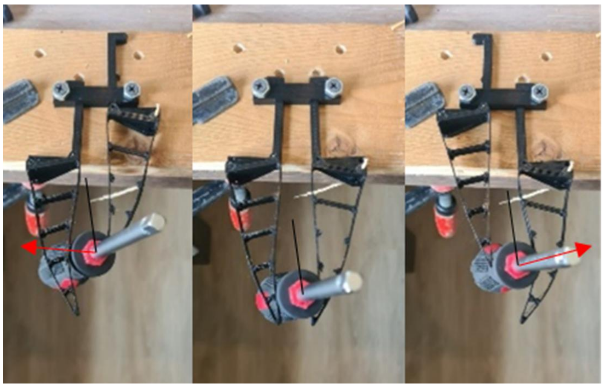


Figure 21: Initial prototype implementing adaptive grippers.

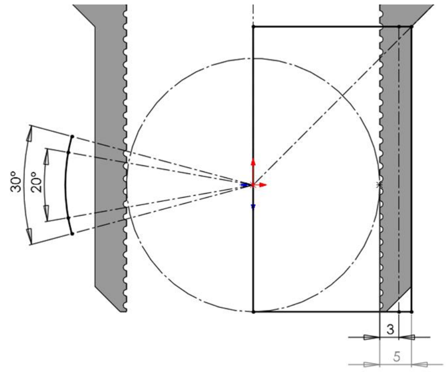


Figure 22: Geometric data opposing movement.

The ”opposing movement” concept excels in terms of simplicity, there is no interaction between mechanism and the product, which in turn increases compactness, motion is straightforward and operation speed is high as mentioned in literature review in Appendix B. However, the issues arise in reliably manipulating poultry products. Research is primarily conducted on the manipulation of rigid round profiles, which largely differ from poultry products. This concept relies on friction, which is a problem when dealing with slippery and compliant objects.

Another issue that needs to be solved is the rotation angle. In theory a rotation angle of 180° can be obtained by starting in the -90° position before grasping and manipulating to the +90° position for placement. However, this would cause interference between the jaw and surface when the jaw is extended beyond the product. The addition of a pull-in mechanism could provide a solution for grasping, but does not eliminate the problem.

Table 5: External rotation concept score based on the criteria.

Criteria	Description	Score
Speed (efficiency)	Actuator motion can be directly transferred to the product, a margin is included to account for slip between actuator and product.	80-100%
Versatility	For an opposing motion with linear movement the grip and rotation are not severely impacted. However, when implementing a rotation to obtain opposing motion the contact angle will change, and rotation is affected. The error is impacted, as the angle of rotation depends on the circumference of the product.	0-100%
Secure grip	Due to the opposing motion, contact is limited and only applied at two points. Clamping forces may vary slightly, but not significantly to be accounted for. Re-grasping is not implemented in this concept.	66-100%
Compactness	The value for “w” is currently at 5mm but could be decreased to improve compactness. The “w” value is only required to implement stiffness in the model.	3mm
Contamination risk	Present risk: extensive contact range. However, due to the decreased angle of rotation the range is limited.	0-1

D.3 Belt driven rotation

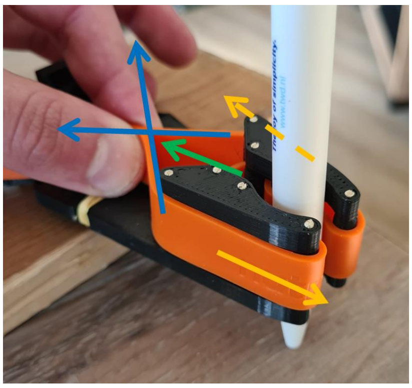


Figure 23: Belt driven manipulation options.

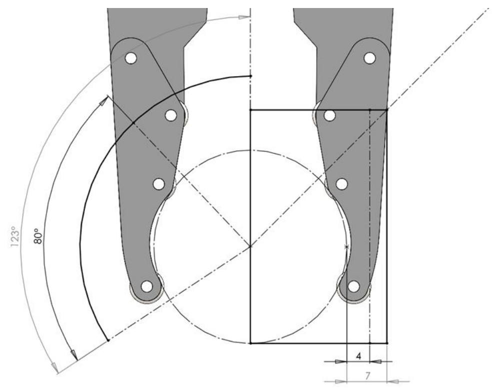


Figure 24: Geometric data belt driven rotation.

Belt driven rotation is similar to the previous concept, but utilizes a flexible belt which increases contact surface area and distributes forces more evenly. This allows for advantages in terms reliable grasping and handling product variation, which was also mentioned in literature. Conversely, inefficiency was mentioned due to friction between belt and gripper, which should be considered during future development. Since the belt is guided by rollers, moving parts are located around the product, this increases contamination risk and decreases compactness. Furthermore, the addition of the belt introduces a moving surface at the sides of the gripper, having the potential to interfere with neighbouring products.

In addition, prototyping highlighted certain options to obtain actuation through belt manipulation. As shown in Figure 23, rotational motion can be achieved by moving the belt in a single direction (yellow). Additionally, by tensioning the belt in the center, the force applied closes the gripper (blue).

Lastly, through applying force on the belt bridging the gab between the grippers, a pull-in operation is obtained.

Table 6: External rotation concept score based on the criteria.

Criteria	Description	Score
Speed (efficiency)	Actuator motion can be directly transferred to the product, a margin is included to account for slip between actuator or product and belt.	80-100%
Versatility	In terms of grip, the width between the fingers changes and the angle will change slightly. The belts will ensure contact even with different sized objects. The moving surface over the whole grip area will maintain the ability to rotate, this is also presented in literature [source].The error is impacted, as the angle of rotation depends on the circumference of the product.	66-100%
Secure grip	Roughly half the product is in contact with the gripper which is considered high. The clamping forces stay more or less constant while gripping and rotating due to the consistency of using a belt. Re-grasping is not implemented in this concept.	100%
Compactness	The value for "w" is currently at 7 [mm] but could be decreased to improve compactness. This is limited due to the presence of the belt.	4mm
Contamination risk	Present risks: shadow faces, overlapping surfaces, and extensive contact range.	3

D.4 External rotation

Figure 25: Demonstration of external rotation.

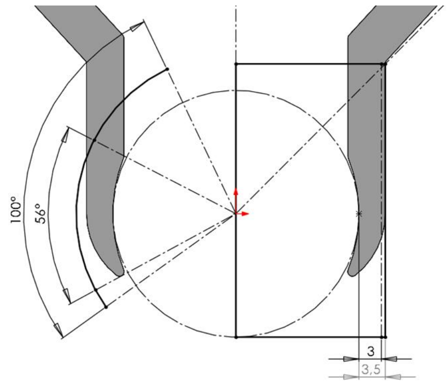


Figure 26: Geometric data exteranal rotation.

The main principle of concept "External rotation" is introducing a partial rotation and alternating grasp to enable a step-wise rotational motion. This can be achieved with two grippers that are able to rotate individually or alternately around the rotational axis of the product. In terms of constructing such a gripper, numerous industrially suitable grippers are available to obtain the grasping action. Similarly, solutions are available for rotational guidance (e.g. curved rails or flexures). In order to match the current solution in terms of speed, the two grippers need to move rapidly and a large rotational step is mandatory to reduce the number of cycles. As a result, the focus on developing this concept should be on reducing weight of the individual grippers to reduce actuation forces, and ensure a reliable re-grasping method within a split-second.

Table 7: External rotation concept score based on the criteria.

Criteria	**Description**	**Score**
Speed (efficiency)	For one step the motion is directly proportional to the rotation. However, between steps the gripper needs to re-grasp and release which is considered to reduce the speed by a factor of two.	40-60%
Versatility	Gripping the product initially only changes the grip width, but re-grasping during manipulation will introduce uncertainty with every step. Rotation angle is less effected as the rotation does not depend on product size, the same holds for rotation error.	66-100%
Secure grip	When improved roughly half the product is in contact with the gripper which is considered high. Re-grasping is present and will change grip position. This will introduce a change of forces each time when re-grasping.	33-100%
Compactness	The value for “w” is currently at 3,5mm but could be slightly decreased to improve compactness. The “w” value is only required to implement stiffness in the model.	3mm
Contamination risk	Present risks: shadow faces and overlapping surfaces. However, both could be prevented by increasing space between parts and opposing position during cleaning.	0-2

D.5 Eccentric rotation

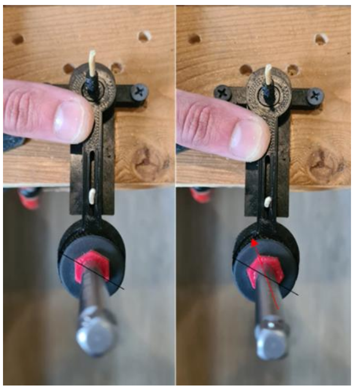


Figure 27: Cycloidal rotation.

Figure 28: Pattern movement.

Figure 29: Prototype eccentric rotation.

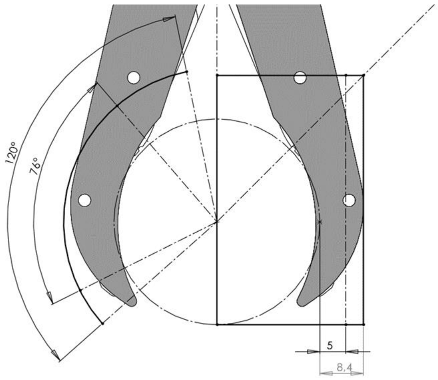


Figure 30: Geometric data eccentric rotation.

As mentioned, the concept "cycloidal rotation" utilizes a camshaft to manipulate two identical jaws as a slider crank mechanism, see Figure 27. While actuating the camshaft, the effective diameter within the gripper is smaller than the diameter of jaws, ensuring a displacement relative to the contact points at the jaws. Each rotation of the crankshaft allows for a slight rotation of the product, which is influenced by parameters including the difference in diameter and dimensions of the slider crank mechanism.

Similar to the concept "cycloidal rotation", the concept "Pattern movement" in Figure 28 implements a slider crank mechanism, but the mechanism is attached to each of the two jaws. Therefore maintaining contact with the product during roughly half the rotation of the shaft, introducing a slight rotation. Due to the crank, motion is the opposite direction is performed without making contact, ensuring the rotation step can be repeated.

Since concept "cycloidal rotation" had issues reliably holding objects, and the concept "pattern movement" included a mechanism close to the product, these concepts were combined into a single working solution, as shown in Figure 29. Having a repeating motion with two secondary grippers actuated by a single camshaft (blue) over which the primary grippers also rotate (red). This configuration ensure that a product can be securely grasped with the primary grippers and be manipulated with the secondary grippers. Although actuation is above the product, the mechanism operates in contact with the product, limiting compactness and cleanability which could be improved by reducing thickness and avoiding contact between moving parts respectively.

Table 8: External rotation concept score based on the criteria.

Criteria	**Description**	**Score**
Speed (efficiency)	During roughly half of the rotation the eccentric motion contributes towards rotation, and it might be possible to be increased.	40-60%
Versatility	The gripping angle is changed slightly but will not impact grip as it can adjust the grip width. This grip angle might change rotation error slightly, but ability to rotate will be maintained. The angle of rotation depends on the circumference of the product. Both influence the rotation error.	66-100%
Secure grip	Roughly half the product is in contact with the gripper which is considered high. Although re-grasping is present, due to the primary and secondary fingers the gripping force on the product does not vary a significant amount.	66-100%
Compactness	The value for "w" is currently at 8,4mm but could be decreased to improve compactness. However, there still needs to be space available for the mechanism.	5mm
Contamination risk	Present risks: shadow faces, overlapping surfaces, and cavities. There are some improvement options, namely increasing space between parts eliminating overlapping surfaces and cavities can be placed above the product reducing the risk.	1-3

E Concept selection

E.1 Selection method

In order to choose a valid concept selection method, the literature review presented in [41] was employed. This review provides a description of concept selection methods and analyses them based on aspects including the number of concepts and complexity to perform the analysis. By including methods for the selection of up to five concepts, and eliminating methods that were complex to use, four selection methods remained. These methods include Pugh's evaluation matrix, Quality Function Deployment (QFD), Analytical Hierarchy Process (AHP), and Pahl and Beitz's Utility theory. Since the concepts are selected based on the independent criteria, coupled decision making is not applied, which excludes QFD and Pahl and Beitz's Utility theory. Pugh's and AHP both introduce pairwise comparison, however Pugh's remains a simple method. AHP implements pairwise comparison to first obtain weight factors, and then to compare concepts. The method AHP is preferred as it as it combines multiple aspects of complex decision making, namely experience, instinct, and heuristic-based and implements a systematic mathematical way of providing a detailed comparison [17, 30, 31].

The AHP implements a structure defining the goal, criteria, and alternatives (concepts) as shown in Figure 31. Comparison is performed in two stages which are similar in terms of computation. The first stage compares the various criteria against each other. The second stage compares the alternatives for each of the criteria. In this case there are five criteria and four concepts, which results in ten comparisons for the criteria and a total of thirty for the alternatives. Additionally, each comparison generates a normalized priority vector (PV) that indicates relative score and consistency ratio (CR) that suggests if the comparison is consistent. After comparison, an overall priority score for each of the concepts is obtained.

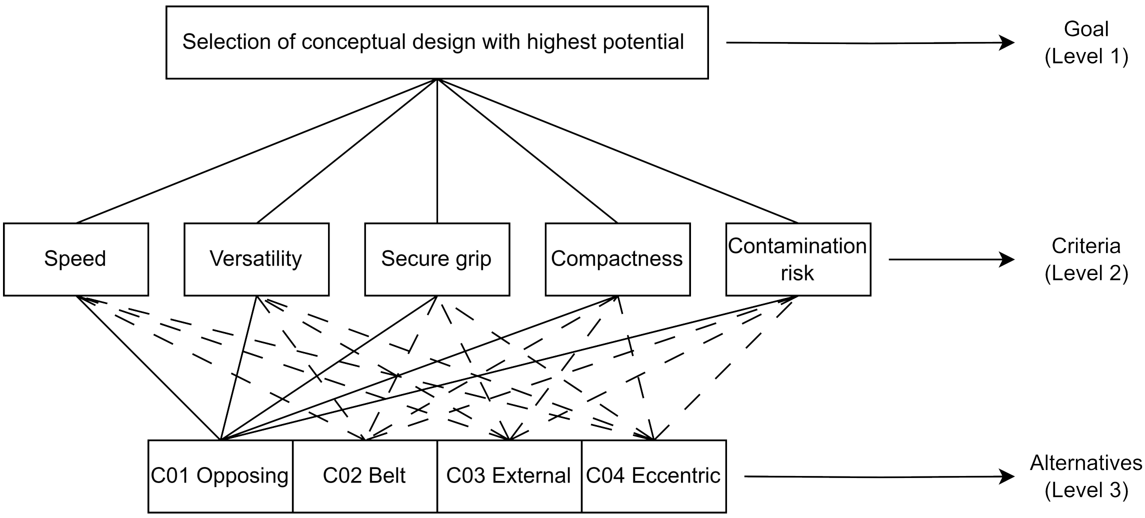


Figure 31: AHP comparison structure

The pairwise comparison matrix a_{ij} is defined as a $n \times n$ matrix, with n being the number of items, either five for criteria or four for alternatives. A value from one to nine is given to define the weightage intensity, from and identical score to an enormously strong score respectively, which is further explained in Figure 9. Thus, comparing the same item results in a one. Furthermore, if a comparison is inverse, a reciprocal is used. For example, comparing speed against versatility $a_{12} = \frac{1}{3}$, meaning versatility has a marginal extra score with regard to speed. After comparison, the PV W is computed with Equation

13. Next, the CR is computed by $CR = CI/RI$, where $CI = (\lambda_{max} - n)/(n-1)$ and $\lambda_{max} = a_i W/w_i$. Random Index (RI) is 0.9 and 1.12 for n is equal to four and five respectively. Moreover, a CR lower than 0.1 is considered to be consistent. The overall priority is the dot product of the PV for the criteria with the PV of an alternative.

$$W_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_i^n a_{ij}}, \quad i,j = 1,2,...,n \tag{13}$$

In an effort to increase the credibility of the comparison, the first stage of comparing the criteria is executed by an expert panel as they have experience in the field of food applications and robotics, and are in direct relation to application of this development. A session was planned with the expert panel, consisting of a Mechanical Design Engineer, the Technical Lead Robotics, and a System Architect, where each comparison of the criteria was discussed. To reduce the dependence on human-based decision making, the second stage is compared based on a scoring system for the concepts on the criteria, where for example a score of 0 to 100% is proportional to a weightage intensity of nine to one. Comparing two score is obtained through the (inverse) difference plus one, ensuring a range from one to nine is achieved. Since the second stage is performed in an exact manor, the CRs are equal or close to zero, meaning consistent.

E.2 Concept selection results

In this section, the AHP is performed for the four alternatives and five criteria described in Figure 31. First, the scores are described in Table 9, where the general score is mentioned for the scoring of the alternatives. Next, the scoring of the alternatives is included and converted to a general score, as displayed in Table 10. Furthermore, the comparison is executed with an expert panel for the comparison of the criteria, and the comparison of the alternatives is performed by comparing the general scores. Lastly, the summary of the results is displayed in Table 11.

Table 9: Score applied to pairwise relations and method of obtaining general score for comparison of the alternatives

Measure of pairwise relation			**General score**		
Weightage intensity	Outline	Description	0-100%	0-8mm	0-4
1	Identical score	Two factors are of equal score	100	0	0
3	Marginally extra score	Situation where marginally prefer one over another	75	2	1
5	Strong score	Situation where strong prefer one condition over another	50	4	2
7	Very strong score	Situation where very strong preferred and its superiority is showed in practice	25	6	3
9	Enormously strong score	The proof of preferring one over another is of the utmost possible order of confirmation	0	8	4
2, 4, 6, 8	In-between scores among two adjacent choice	Situation where settlement is required			
Reciprocals	Reciprocals for inverse comparison				

Table 10: Scoring of the alternatives in terms of actual score (top) and general score (bottom)

Scoring of the alternatives - Specific

	Speed (%)	Versatility (%)	Secure grip (%)	Compactness (mm)	Contamination risk (#)
C01	80-100	0-100	66-100	3	0-1
C02	60-80	66-100	100	4	3
C03	40-60	66-100	33-100	3	0-2
C04	40-60	66-100	66-100	5	1-3
Scoring of the alternatives - Generalized					
C01	2	5	2	4	2
C02	3	2	1	5	7
C03	5	2	4	4	3
C04	5	2	2	6	5

Pairwise comparison - Criteria

Citeria	Speed	Versatility	Secure grip	Compactness	Contamination risk	W	λmax
Speed	1	1/3	1/5	1/5	4	0,095	5,160
Versatility	3	1	2	1	5	0,306	5,457
Secure grip	5	1/2	1	2	5	0,295	5,654
Compactness	5	1	1/2	1	5	0,257	5,513
Contamination risk	1/4	1/5	1/5	1/5	1	0,046	5,247
Σ	14,250	3,033	3,900	4,400	20,000		

CI	0,102	
CR	0,091	consistent

Pairwise comparison - Alternatives w.r.t. criteria

Speed

	C01	C02	C03	C04	W	λmax		
C01	1	2	4	4	0,484	4,042	CI	0,007
C02	1/2	1	3	3	0,297	4,023	CR	0,008
C03	1/4	1/3	1	1	0,110	4,009		consistent
C04	1/4	1/3	1	1	0,110	4,009		

Versatility

	C01	C02	C03	C04	W	λmax		
C01	1	1/4	1/4	1/4	0,077	4,000	CI	0,000
C02	4	1	1	1	0,308	4,000	CR	0,000
C03	4	1	1	1	0,308	4,000		consistent
C04	4	1	1	1	0,308	4,000		

Secure grip

	C01	C02	C03	C04	W	λmax		
C01	1	1/2	3	1	0,239	4,021	CI	0,007
C02	2	1	4	2	0,433	4,032	CR	0,008
C03	1/3	1/4	1	1/3	0,089	4,008		consistent
C04	1	1/2	3	1	0,239	4,021		

Compactness

	C01	C02	C03	C04	W	λmax		
C01	1	2	1	3	0,351	4,014	CI	0,003
C02	1/2	1	1/2	2	0,189	4,009	CR	0,004
C03	1	2	1	3	0,351	4,014		consistent
C04	1/3	1/2	1/3	1	0,109	4,004		

Contamination risk

	C01	C02	C03	C04	W	λmax		
C01	1	6	2	4	0,492	4,128	CI	0,027
C02	1/6	1	1/5	1/3	0,063	4,025	CR	0,029
C03	1/2	5	1	3	0,309	4,127		consistent
C04	1/4	3	1/3	1	0,136	4,038		

Table 11: Concept selection results

Criteria	Speed	Versatility	Secure grip	Compactness	Contamination risk		
PV criteria	0,095	0,306	0,295	0,257	0,046		
Alternatives						Overall priority	
C01 Opposing	0,484	0,077	0,239	0,351	0,492	0,253	25%
C02 Belt	0,297	0,308	0,433	0,189	0,063	0,302	30%
C03 External	0,110	0,308	0,089	0,351	0,309	0,235	24%
C04 Eccentric	0,110	0,308	0,239	0,109	0,136	0,210	21%

As a result of the pairwise comparison of the criteria performed by the expert panel, it is clear that the criteria speed and contamination risk have is significantly lower priority than the other criteria. The argument for a low priority on speed, is the option to stack multiple systems, for instance in series where two delta robots handle double the amount of product. The contamination risk is an aspect that is considered less important in the early stages of concept development. Moreover, there are many options to provide cleaning and although some might not be ideal (i.e. disassembly or replacement) and impact the usability, the performance with not be severely restricted. The criteria of versatility and secure grip scored relatively high as they directly impact the reliability of the system. On the contrary, compactness influences the functionality of the gripper, which was considered relevant.

In comparing the alternatives, note that concept "opposing movement" lacks in terms of versatility, which was also concluded in the literature review. In terms of compactness, concept "belt" and "eccentric" scored lower than the other concepts, which is logical as components of the mechanism used for rotation are located close to the product. Disregarding speed and contamination risk, concept "belt driven rotation" scores highest in two out of three criteria, and the score in compactness has less influence than the other criteria.

While maintaining focus on compactness and contamination risk, concept "belt driven rotation" will be selected as concept for further development. Since the concept utilizes a pliant belt, product variation in aspects as shape, size, and flexibility can be resolved and forces remain evenly distributed. This offers potential in terms of versatility and secure grip. The expectation is confirmed by the data from the AHP, where the highest score is assigned to the concept as well. The combination of findings in literature, prototyping, estimations on criteria, and engineering insight, provided a solid foundation for the choice of concept "belt driven rotation".

F Set of equations theoretical model

Set of equations regarding FBD product:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ -P_{Cy} & P_{Cx} & -P_{Gy} & P_{Gx} & -P_{Cy} & P_{Cx} & -P_{Gy} & P_{Gx} & -P_{Cy} & P_{Cx} & -P_{Gy} & P_{Gx} \\ 0 & 0 & 0 & 0 & -\mu & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\mu & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mu & 0 & 0 & 1 & 0 \\ c_\theta & s_\theta & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s_\theta & -c_\theta & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & s_\theta & c_\theta & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} N_{CDx} \\ N_{CDy} \\ N_{GFx} \\ N_{GFy} \\ F_{Cx} \\ F_{Cy} \\ F_{Gx} \\ F_{Gy} \\ F_{fCx} \\ F_{fCy} \\ F_{fGx} \\ F_{fGy} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ I\alpha \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ N_{px} \\ N_{py} \end{bmatrix}$$

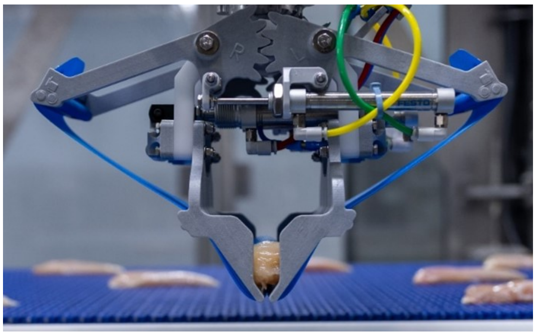
Set of equations regarding rigid gripper left:

$$\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ c_\varphi & -s_\varphi & -e^{-\mu\varphi} & 0 \\ s_\varphi & c_\varphi & 0 & -e^{-\mu\varphi} \end{bmatrix} \begin{bmatrix} N_{DCx} \\ N_{DCy} \\ N_{DJx} \\ N_{DJy} \end{bmatrix} = \begin{bmatrix} N_{CDx} \\ N_{CDy} \\ 0 \\ 0 \end{bmatrix}$$

Set of equations regarding rigid gripper right:

$$\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ c_\varphi & -s_\varphi & -e^{\mu\varphi} & 0 \\ s_\varphi & c_\varphi & 0 & -e^{\mu\varphi} \end{bmatrix} \begin{bmatrix} N_{FGx} \\ N_{FGy} \\ N_{FKx} \\ N_{FKy} \end{bmatrix} = \begin{bmatrix} N_{GFx} \\ N_{GFy} \\ 0 \\ 0 \end{bmatrix}$$

G Analysis current RoboBatcher

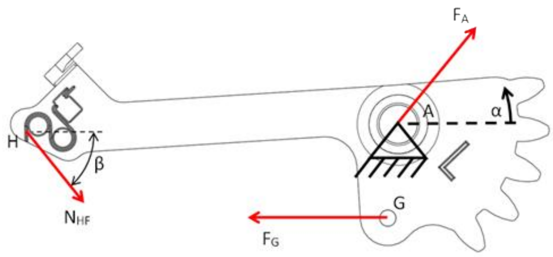


Assumptions

- Problem is static.
- Product is a rigid cylinder.
- Gripper is symmetric over the x-direction.
- Tension forces around a circumference attach at the same point.
- Vectors in matrix are initially positive, this does not match the FBDs.
- The belt flexes around a circumference ensuring maximum contact.
- Friction coefficient is assumed to be 0.20 from data sheet.
- Gravity is neglected.

Tension arm

FBD - tension arm



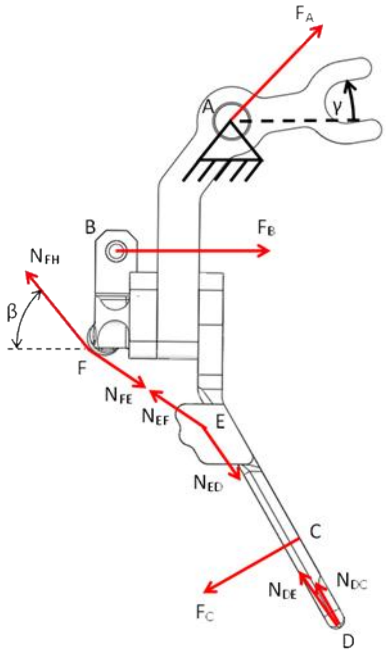
Equilibrium equations - tension arm

- Force and moment equilibrium: $\sum F = 0$, $\sum M = 0$ (3)
- Tension force in belt direction: $N_{HFy} = N_{HFx} \tan\beta$ (1)
- Cylinder force at point G: $F_G = F_{C1}$ (1)

$$\begin{bmatrix} 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & AGy & AHy & AHx \\ 0 & 0 & 0 & -tan(\beta) & 1 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} F_{Ax} \\ F_{Ay} \\ F_G \\ N_{HFx} \\ N_{HFy} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ F_{C1} \end{bmatrix}$$

Gripper

FBD - gripper



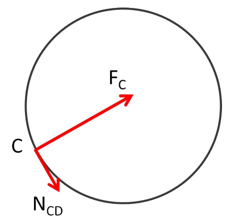
Equilibrium equations - gripper

- Force and moment equilibrium: $\sum F = 0$, $\sum M = 0$ (6)
- Tension forces are opposing: $N_{ij} = -N_{ji}$ (12)
- Capstan forces over circumference: $N_{ij} = [R_{\pi+\alpha_i}] \, N_{ik}/e^{\mu\alpha_i}$ (12)
- Product equilibrium in y-direction: $F_{Cy} = -N_{DCy}$ (2)
- Normal force perpendicular to gripper: $F_{Cx} = F_{Cy}/\tan\delta$ (2)

$$
\begin{bmatrix}
1 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 0 & By & Fy & -Fx & Fy & -Fx & Ey & -Ex & Ey & -Ex & Dy & Dx & Dy & Dx & Cy & Cx \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \mathrm{c}(\pi+\alpha_F) & -\mathrm{s}(\pi+\alpha_F) & -e^{\mu\alpha_F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \mathrm{s}(\pi+\alpha_F) & \mathrm{c}(\pi+\alpha_F) & 0 & -e^{\mu\alpha_F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{c}(\pi+\alpha_E) & -\mathrm{s}(\pi+\alpha_E) & -e^{\mu\alpha_E} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{s}(\pi+\alpha_E) & \mathrm{c}(\pi+\alpha_E) & 0 & -e^{\mu\alpha_E} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{c}(\pi+\alpha_D) & -\mathrm{s}(\pi+\alpha_D) & -e^{\mu\alpha_D} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{s}(\pi+\alpha_D) & \mathrm{c}(\pi+\alpha_D) & 0 & -e^{\mu\alpha_D} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\tan\delta & 1
\end{bmatrix}
\begin{bmatrix}
F_{Ax} \\ F_{Ay} \\ F_B \\ N_{FHx} \\ N_{FHy} \\ N_{FEx} \\ N_{FEy} \\ N_{EFx} \\ N_{EFy} \\ N_{EDx} \\ N_{EDy} \\ N_{DEx} \\ N_{DEy} \\ N_{DCx} \\ N_{DCy} \\ F_{cx} \\ F_{cy}
\end{bmatrix}
=
\begin{bmatrix}
0 \\ 0 \\ 0 \\ -N_{HEx} \\ -N_{HEy} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{bmatrix}
$$

Product

FBD - product

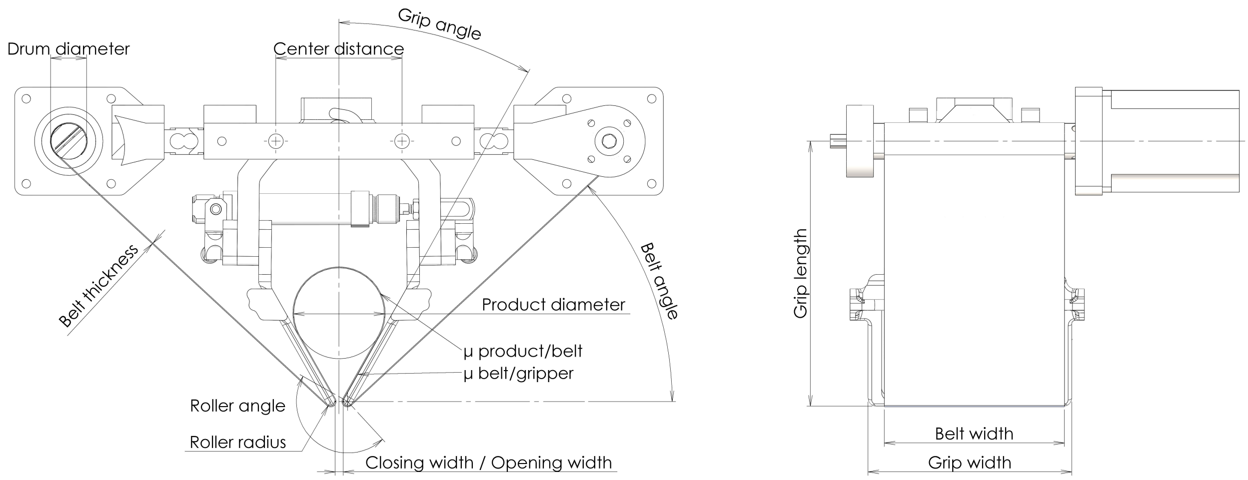


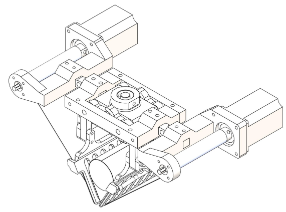
Equilibrium equations - product

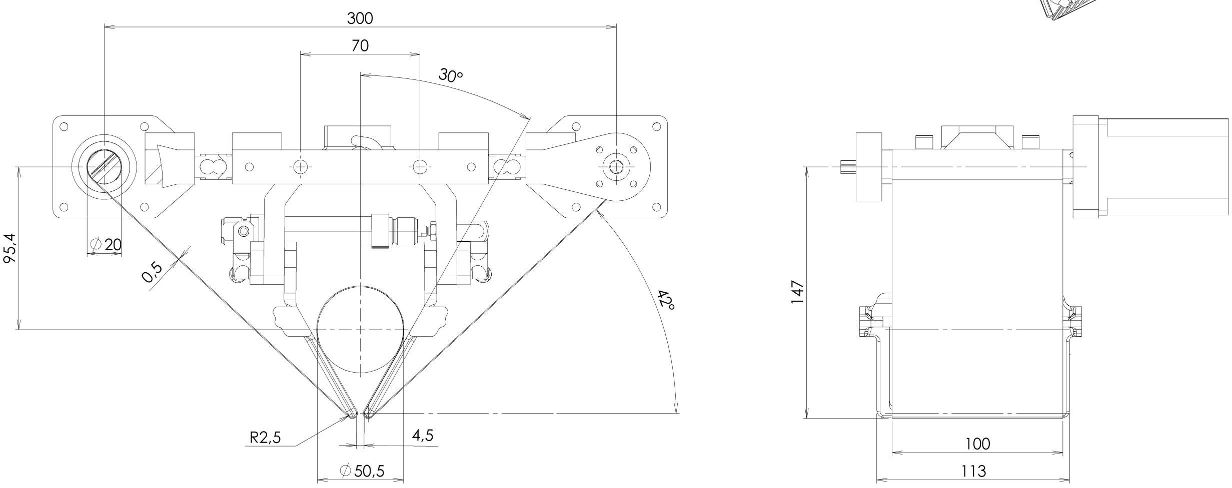
- Force equilibrium: $\sum F_y = 0$ (1)
- Tension forces are opposing: $N_{ij} = -N_{ji}$ (2)
- Normal force perpendicular to gripper: $F_{Cx} = F_{Cy}/\tan\delta$ (1)

$$
\begin{bmatrix}
0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -\tan\delta & 1
\end{bmatrix}
\begin{bmatrix}
N_{CDx} \\ N_{CDy} \\ F_{Cx} \\ F_{Cy}
\end{bmatrix}
=
\begin{bmatrix}
0 \\ -N_{DCx} \\ -N_{DCy} \\ 0
\end{bmatrix}
$$

H Prototype parameters and dimensions







Dimensions in mm

I Measurement calibration

Calibration of measurements for validation theoretical model (01-08-2023)

LoadCell L			**LoadCell R**		
Calibration mass	781.7	g	Calibration mass	781.7	g
Calibration value	99.05		Calibration value	100.83	
Test mass	256.2	g	Test mass	256.2	g
Measurement test mass	255.4	g	Measurement test mass	255.27	g
Error ϵ	-0.31	%	Error ϵ	-0.36	%

Calibration of measurements on the influence of the gap width (23-10-2023)

LoadCell L			**LoadCell R**		
Calibration mass	788.8	g	Calibration mass	788.8	g
Calibration value	98.77		Calibration value	101.04	
Test mass	263.4	g	Test mass	263.4	g
Measurement test mass	263.2	g	Measurement test mass	263.7	g
Error ϵ	-0.08	%	Error ϵ	0.11	%

J Experiment on the influence of the gap width

Experimental measurements for a grip angle of 30°.

Initial pre-tension [g]	Product [#]	Gap width [mm]					
		4	5	6	7	8	9
300	1	✓	✓	×	×	×	×
300	2	✓	×	×	×	×	×
300	3	×	✓	×	×	×	×
600	1	×	✓	×	×	×	×
600	2	×	×	×	×	×	×
600	3	×	✓	×	×	×	×

Experimental measurements for a grip angle of 60°.

Initial pre-tension [g]	Product [#]	Gap width [mm]											
		4	5	6	7	8	9	10	11	12	13	14	15
300	1	✓	✓	✓	✓	✓	×	×	✓	×	×	×	×
300	2	✓	✓	✓	✓	✓	×	✓	×	×	×	×	×
300	3	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×
600	1	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	×
600	2	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×
600	3	✓	✓	✓	✓	✓	✓	×	✓	×	×	×	×

Influence of initial pre-tension and different products on experiment success, excluding all successful or all failure columns.

	Successful experiments	
Initial pre-tension [g]	[#]	[%]
300	9	43
600	10	48
Product [#]	[#]	[%]
1	8	57
2	4	29
3	7	50