Designing a Flexible Grasp Tool and Associated Grasping Strategies for Handling Multiple Meat Products in an Industrial Setting

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***Abstract*—In this paper, we present a suction cup based gripper tool for grasping different cuts of meat. The tool is attached to a 6DOF robot arm in order to test different grasp strategies. The task of grasping pork bellies is difficult since the objects are highly flexible. Due to the deformations, an airtight connection can form between the meat and the object below it. During the lift, this can lead to a vacuum which sometimes causes the grasp to fail. Thus it is important that the tool and the grasp strategy is able to minimize the effects of this vacuum in order to generate a stable grasp. Furthermore, there is a high variation in the meat products and the initial placement of the products. Thus the tool has to be sufficiently flexible to handle the different cases robustly.**

***Index Terms*—Gripper design, Grasp strategies, Deformable object manipulation**

I. Introduction

Moving meat pieces is a necessary task in slaughterhouses and meat packing facilities. Most of the transportation can be handled by conveyor belts, but in some cases, more advanced motions are required. Some difficult cases occur when moving meat pieces from specialized equipment onto a conveyor belt, or when packing meat pieces from a conveyor belt into boxes. In this paper, we focus on a currently manual task at a "Danish Crown" slaughterhouse[1], where meat pieces are moved from a box onto a conveyor belt, the task is illustrated in Fig. 1. When the meat pieces arrive, they are stacked in the box and the automation solution has to pick the pieces one at a time, starting with the topmost piece. We refer to this task as "bin picking of meat".

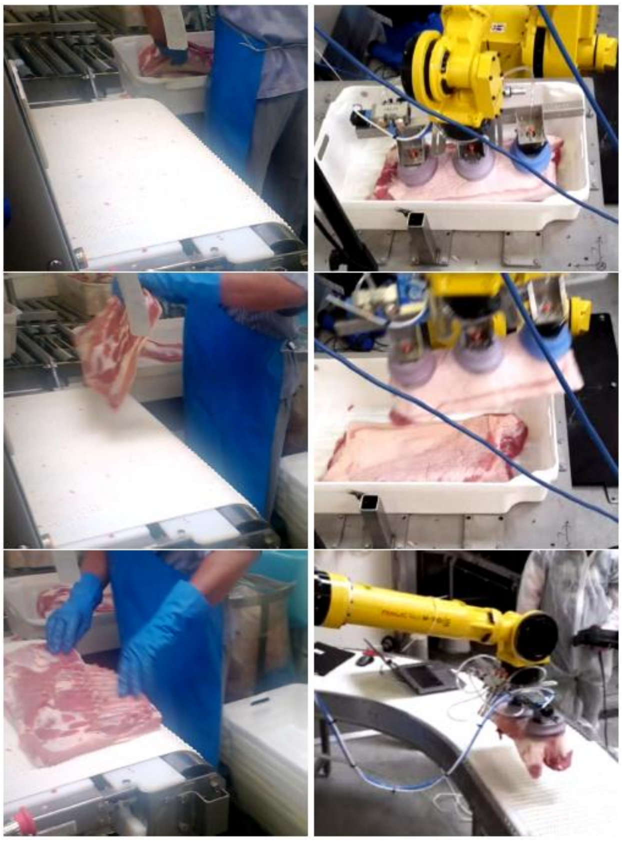

Figure 1. The task. left) A human executing the task. right) An automatic setup executing the same task.

There are many challenges in this task compared to more conventional handling operations. First of all, there are many different cuts of meat that has to be handled by the same production equipment. Therefore the hardware

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should be adaptable so that it can be adjusted to the different meat cuts. A second challenge is that there is a significant variation within the same product categories. This means that even after the automation solution is tuned to a particular case, it should still be able to cope with some variation in the shape and size of the meat cuts. The last challenge is that the meat pieces are deformable. This means that the initial placement of the meat has a higher variation compared to rigid objects.

To cope with these challenges, a 6-axis robot arm with an attached gripper tool is used to lift the meat pieces. The 6-axis robot is a flexible automation solution, which enables a high level of control over the pose of the gripper tool. The gripper tool itself is also designed to be adaptable and flexible, such that it can be adjusted to individual meat categories and also be flexible enough to cope with the variation within each meat category. The design process for the gripper tool is discussed in detail in section 3.

Besides designing the tool, we also investigated grasp strategies for how the robot should lift the meat pieces out of the box. To solve this task, two different grasp strategies were developed, as described in section 4. After the tool and the grasp strategies were designed, they were tested in a physical prototype at a Danish slaughterhouse, as described in section 5. Lastly, the work is concluded in section 6. This paper is an extension of a conference paper [1].

II. Related Work

In this paper, we present a grasping tool for meat and associated grasp strategies. A wide range of grasp tools has been designed for handling deformable objects and meat products[2-6]. These grippers use different mechanical techniques to attach the object that is to be moved. One method is to use granular jamming [1], where a deformable ball is moved to the object that is to be grasped. After the deformable ball is wrapped around the object, the air is removed from the ball, which makes it stiff and creates a firm contact with the object to be moved. Another approach is to use a two finger gripper. An example where such a gripper is used to manipulate deformable objects is presented in [3].

When manipulating deformable sacks more specialized tools are often used. An example of this is inflatable needles [4], where a needle is pushed into the bag and then an air chamber in the needle is expanded to ensure the needle cannot get out of the bag when pulled. Another tool for grasping sacks is a roller based tool, where the sack material is squeezed between rollers to create a firm grasp [5]. Lastly, several grasp tools are presented in [6] including mechanical caging grippers, where the gripper encage the object with fork-like fingers. In the proposed task it is difficult to place something below the meat pieces, which makes it complex to utilize the grippers mentioned. Furthermore, the grippers for sacks are unsuitable since they would damage the meat.

Thus we investigated grippers that can attach to the surface of the meat. An example is cryo grippers [7], where a metal plate is placed on the object and then frozen to create a strong contact to the object that is to be lifted. Another example is needle grippers [8], where needles are pushed into the object to create a contact. Lastly, we investigated suction cups [6], where a vacuum is used to create the contact force. Due to contamination constraints, needle grippers were infeasible and to the best of our knowledge, there are no commercial large scale cryo grippers available. Thus we focus on a vacuum based grasp tool in this work.

There are several ways to generate a lifting force based on under-pressure. Some of the common methods are to rely on the Bernoulli effect, the Coanda effect or to simply connect and under-pressure to the suction cups. Bernoulli grippers work by blowing air out at a high velocity parallel to the contact surface [3]. Thus creating an under-pressure, which in return produce a lifting force. The main advantage of this technique is that it is contact-less and thus there is no contamination risk. However, the lifting force produced is too small for the meat products handled in the use case of this paper. The Coanda gripper uses a slightly different principle, but again it is based on airflow and produce a relatively low lifting force [3]. Thus in this paper, we focus on the last technique where an under-pressure is connected directly to the suction cups. This produces a larger lifting force, but it also requires an airtight connection between the suction cups and the meat piece, which poses a higher requirement for the suction cup design. Ejectors are used to generate the under-pressure [3].

Besides designing a grasp tool, it is also necessary to design a grasp strategy for lifting the meat pieces. The research in grasp strategies for suction cups is limited, but work has been done to determine the suction cup placement, which minimizes the vacuum level required for a stable manipulation of a rigid object [11]. Furthermore, researchers investigated how to avoid placing suction cups on window frames for a wall climbing robot [12]. Both methods are highly specialized and cannot be directly applied to the problem presented in our paper.

In terms of grasping deformable objects, such as the meat pieces handled in this paper, more research has been conducted. However, most of this is focused on mechanical grippers, such as multi-finger grippers. Some of the same ideas can be used when designing strategies for suction based grasping. For instance, Foresti et al. [3] proposed that to grasp cloth or fur, the cloth should be segmented, and based on this segmentation appropriate grasp points should be determined. A similar technique was used in [3]. This is also the basic approach used in this paper. However, the technique is developed for using suction cups to lift meat pieces and thus the implementation is quite different.

III. Gripper Design

In this section, we describe the gripper in detail and discuss the most relevant design choices. A CAD Model of the developed gripper is shown in Fig. 4, and the real gripper is shown in Fig. 5. The gripper was designed in an iterative process along with the grasp strategy in order to enable robust grasps of flat and flexible meat pieces. The main difficulty that arises in the task is that the meat is deformable and thus the grasp surface changes substantially between every grasp. Therefore, the tool has to be flexible to cope with this variation.

Examples of the cases the gripper has to grasp are presented in Fig. 2. Here it can be seen that the pork bellies (Fig. 2b) are much wider than the loins (Fig. 2c), and the bellies are also substantially thinner. The pork backs (Fig. 2d) are somewhere in-between, however they are heavier than all the other cases. Besides the difference in size and shape, it can also be seen that the deformed state of the meat pieces in the box varies substantially. Furthermore, the rigidity of the objects vary a lot, and especially the bellies with skin (Fig. 2a) are more rigid than the other products. This illustrates well the types of variation the gripper should be robust towards.

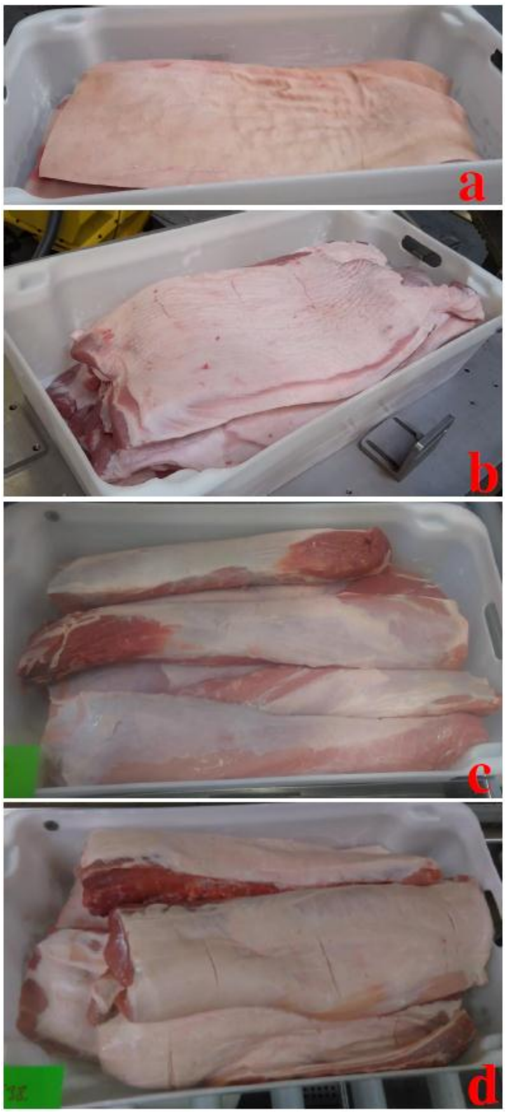

Figure 2. Meat pieces the gripper should handle. a) Pork bellies with skin, b) pork bellies without skin, c) pork loins and d) pork backs.

During the development of the gripper, four different gripper designs were tested. The first three are illustrated in Fig. 3, these all had practical limitations which lead to the final design illustrated in Fig. 5. The first gripper (Fig. 3a) relied on an array of 8 relatively small suction cups. However, when the tool was tested in practice one or more of the suction cups often released the meat. Furthermore, placing the individual suction cups on highly curved meat surfaces became time-consuming, since the robot has to move the suction cup array to several different positions, and establish a vacuum at each of these positions.

The second gripper (Fig. 3b) relied on two larger elliptical suction cups, in an attempt to reduce the chance that the meat was dropped, and increase the simplicity of the tool. However, this allowed larger deformations of the meat between the suction cups, which again increased the chance that the meat was dropped.

The third gripper (Fig. 3c) relied on three larger suction cups. This produced a more stable grasp. However, the three suction cups still had to be placed individually to grasp meat pieces with a highly curved surface. This lead to the final gripper (Fig. 5), where air pistons were added to make the tool more compliant. These air pistons were used as passive components and acted much like 1-dimensional springs. This allowed all three suction cups to be placed simultaneously on the meat.

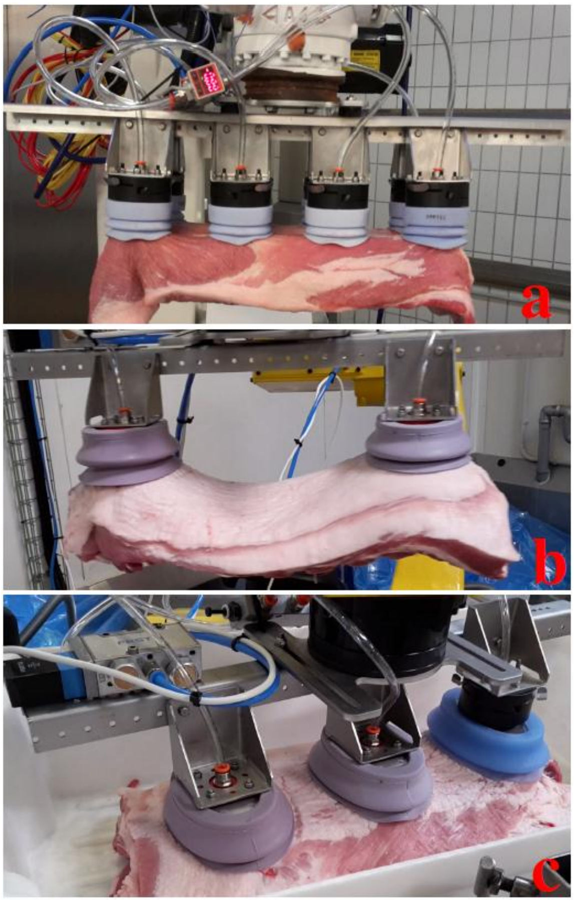

Figure 3. Initial gripper designs. a) The gripper relies on a suction cup array with 8 suction cups. b) The gripper uses two large elliptical suction cups placed far apart. c) An extra suction cup was added to the gripper to make the grasp more stable.

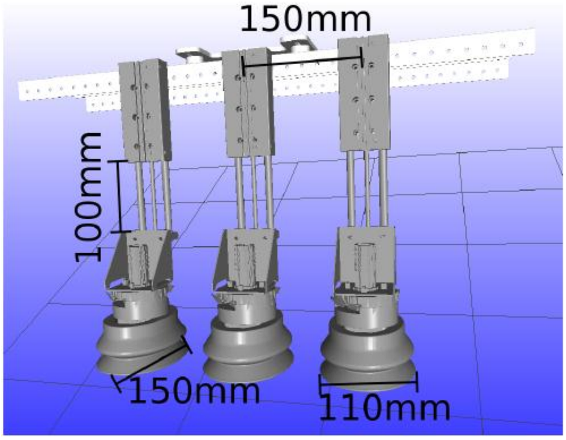

Figure 4. CAD model of the gripper tool.

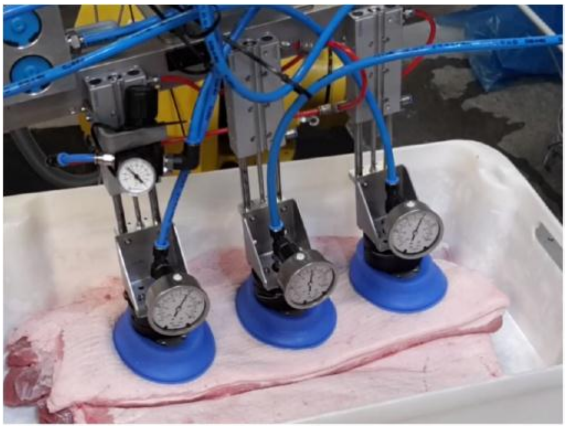

Figure 5. The real gripper tool.

The suction cups used had to adapt to the local surface variation. Therefore, soft and flexible suction cups were desirable. The three suction cups used in the final gripper are commercial products with a shore of A-20 and a stroke of 30mm [15]. The material properties ensured that the suction cups are strong enough to lift the meat while being soft and flexible. The suction cups are elliptical and have a semi-major axis of 150mm and a semi-minor axis of 110mm (Figure 4). This ensured a large contact area, which results in a high vacuum force and a larger part of the meat being directly controlled.

Besides handling the local surface variation, the tool relied on air pistons to compensate for more global surface variation. The air cylinders have a 100mm stroke and an air pressure of roughly 1.15 bar. The air pressure ensures the suction cups are pushed towards the meat surface, improving the chance of an air-tight connection. The main reason for using air cylinders instead of springs is that the stiffness can be controlled by adjusting the air pressure. By trial and error, we determined that 1.15 bar was a reasonable level. This pressure is high enough to create an airtight connection in most cases and low enough such that the meat was not squished too hard during the lift. If the meat is squeezed too hard, it increases the chance of a vacuum forming below the meat, as illustrated in Figure 6. Such a vacuum can make the meat piece stick to the surface below, which make the grasp fail, either because the gripper drops the meat or because the robot lift both the meat and the object below. To further reduce the chance that this vacuum form, two different grasp strategies were developed where one was designed specifically to reduce this effect, as discussed in section 4.

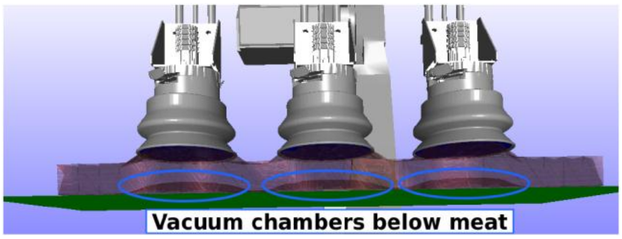

Figure 6. Exaggerated illustration of how a vacuum chamber can form below the meat piece during a vertical lift. The meat model is transparent such that the bulges below the meat can be seen.

Lastly, the air cylinders were placed on a rod such that they can be moved further apart. This makes the tool more flexible since it can be adapted to meat pieces of different sizes. By trial and error, we found that 150mm apart was a good match for the pork bellies we lifted in the experiments.

IV. Grasp Strategies

In this section, the two tested grasp strategies are described. Both strategies rely on a segmented point cloud of the meat surface to determine the grasp motion. This point cloud is obtained through a vision system, which is beyond the scope of this paper.

A. *The Flat Grasp*

The first grasp strategy is the “flat grasp”. This strategy works by determining a grasp frame, which captures how the gripper should be aligned with the surface of the meat during the grasp. During the actual lift, the robot moves the gripper to a fixed height above the grasp frame, next it moves the gripper down such that it is aligned with the grasp frame. Then the suction cups are activated, and finally the meat piece is moved to the conveyor belt. The strategy for determining where to grasp is illustrated in Figure 7, and the full robot motion is shown in Figure 8.

To determine the grasp frame, the first step is to do a PCA analysis of the segmented point cloud representing the meat piece. Then the suction cups are simulated to match the PCA frame and it is analyzed how far the suction cups should be moved down to be in contact with the meat piece. This is done by projecting the point cloud onto the suction cup surfaces. For all points that lie inside the 2D suction cup surface, the projection distance is determined. The grasp frame is then lowered 40mm more than the maximum projection distance. This is done to ensure a tight contact between the meat piece and the suction cups.

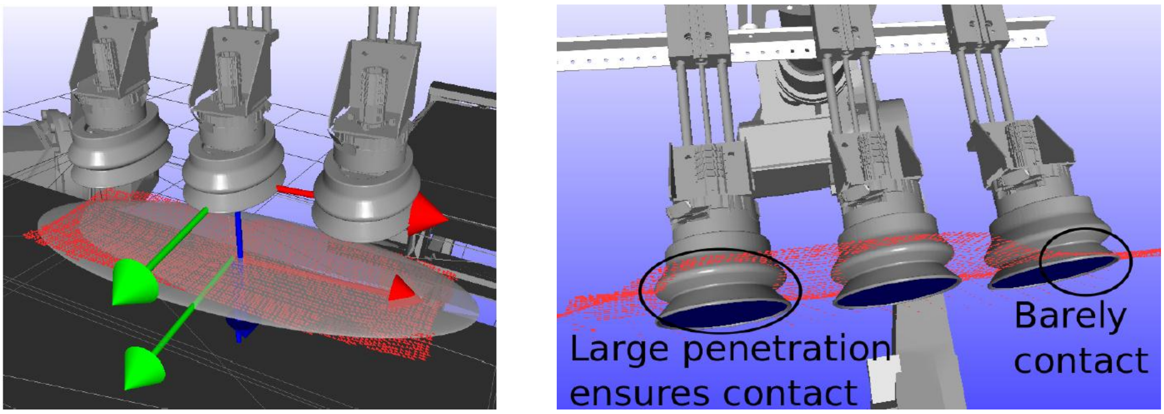

Figure 7. Flat grasp. Top) a PCA analysis is used to determine the graspframe based on the red point cloud. The ellipsoid illustrates the Eigenvectors and Eigenvalues of the PCA analysis. Bottom) the final grasp frame is determined to ensure the suction cups move through all points, even for highly uneven surfaces. The actual final frame is moved 40mm further down to make the contact more reliable in practice.

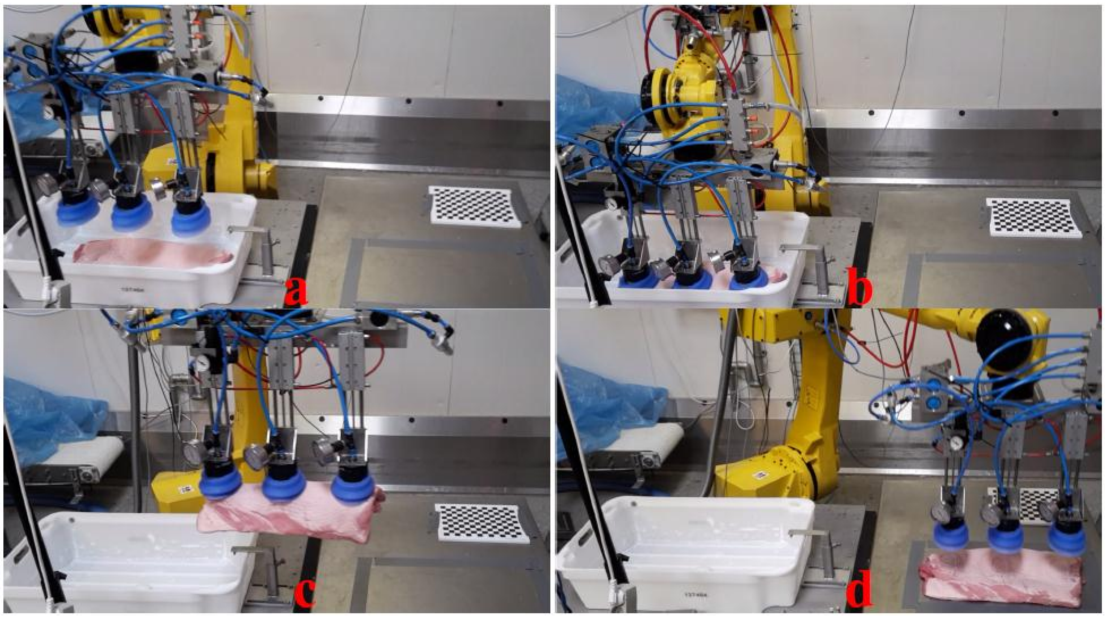

Figure 8. Robot motion for the flat grasp. a) The suction cups are placed above the meat. b) the suction cups are moved down to the meat. c) the meat is moved toward the table where it is to be delivered. d) the meat is placed on the table.

B. *The Rolling Lift*

As discussed in section 3, a vacuum can form between the meat piece and the surface below. The purpose of the rolling lift, was to develop a grasp strategy that reduce the chance of this vacuum forming. The strategy is illustrated in Figure 9 and 10. In this strategy, the point cloud is analyzed to determine a suction cup placement, which ensures the suction cups are close to the edge of the meat piece (Figure 9). After the suction cups are placed and activated, the meat is lifted in a rolling motion to minimize the amount of meat lifted before air can flow below the meat to remove potential vacuum chambers (Figure 10). After the lift, the meat piece is moved to the conveyor belt similarly to the flat grasp.

To determine the where the suction cups should be placed, the first step is to determine an edge-model of the meat piece such that the suction cups can be placed close to this edge. This edge-model is achieved by using a PCA on the point cloud of the meat to determine a rough estimate of the surface plane of the meat piece (Figure 9a). Afterwards, the point cloud is projected onto the x,y-plane of the PCA frame (Figure 9b). Then the edge-model is defined as a concave hull of the projected 2D point cloud. The PCL concave hull algorithm [16] is used to determine the concave hull. After the edge is determined, it is re-sampled to a resolution of 10mm (Figure 9c).

After a model of the meat edge is determined, the next step is to place the suction cups close to this meat edge. This is achieved by posing the problem as a minimization problem where a regret score is minimized. The regret score is based on how close the suction cups are to the edge and it is minimized by moving the suction cups around on the 2D-plane of the edge-model of the meat. The process of minimizing the regret score is illustrated in Figure 9, where the suction cup placement before minimization is illustrated in Figure 9c and the suction cup placement after minimization is illustrated in Figure 9d.

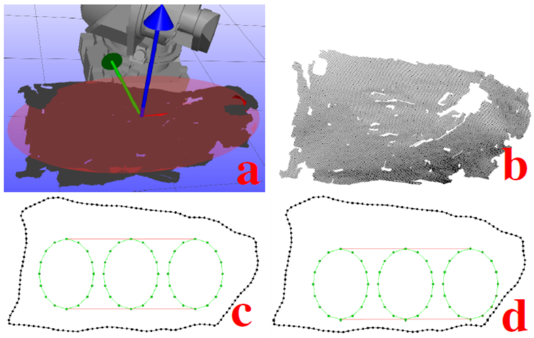

Figure 9. Placing the suction cups. a) A PCA is applied to the point cloud of the meat. The red ellipsoid illustrate the Eigenvectors and Eigenvalues and the frame is the PCA frame. b) The point cloud is projected onto the x,y-plane of the PCA frame. c) The edge of the meat piece is determined as a concave hull of the 2D point cloud. Furthermore the initial placement of the suction cups are illustrated as green dots. d) The suction cup placement is determined by minimizing a regret score.

The regret score consists of two parts; $\boldsymbol{R_{cups}}$ which ensures each suction cup is placed close to the edge of the meat and $\boldsymbol{R_{meat}}$ which ensures that a large part of the edge-model is close to the suction cups. When both these measures are low it is more likely that air can flow below the meat piece during the lift.

If one of the suction cups moves outside the meat, air can flow into it which make it unable to produce a vacuum and lift the meat. This is undesirable and to avoid it a large penalty is introduced in the regret score if one of the suction cups is placed outside the meat edge. The regret score and the two subcomponents are defined in (1), (2) and (3).

$$R_{\text{cups}} = \begin{cases} \frac{1}{N}\sum_{i=1}^{N}(\|\mathbf{s}_i - \mathbf{p}_{ci}\| - 0.02)^2, & \mathbf{s}_i \text{ inside meat} \\ 1.0, & \text{otherwise} \end{cases} \tag{1}$$

$$R_{\text{meat}} = \begin{cases} \frac{1}{M}\sum_{j=1}^{M}\sqrt{|\|\mathbf{p}_j - \mathbf{s}_{cj}\| - 0.02|}, & \mathbf{p}_j \text{ outside the suction cups} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$R = R_{\text{cups}} + R_{\text{meat}}^4 \tag{3}$$

$\boldsymbol{R_{cups}}$ represent the distance from the suction cup points to the point cloud edge representing the meat. $\boldsymbol{s_i}$ is a point on the edge of the suction cups and $\boldsymbol{p_{ci}}$ is the meat edge point which is closest to $\boldsymbol{s_i}$. The margin of 0.02m is subtracted from the distance to reduce the chance that the suction cups are placed outside the meat piece. $\boldsymbol{N}$ is the total number of suction cup points, which is 16 per suction cup. If a suction cup point is outside of the meat edge, this will result in the suction cup being unable to produce a vacuum. Therefore this scenario is heavily penalized, by giving it a value of 1.0, which is high since everything is measured in meters.

$\boldsymbol{R_{meat}}$ represent the distance from the meat edge points to the suction cup points. The score is computed as the square-mean-root estimate, to ensure that outliers do not dominate the score since some edge points will be far away from the suction cups at the ideal position, e.g. see Fig. 5 a and b where the blue points represent good suction cup positions and the black dots represent the meat edge. In the equation $\boldsymbol{p_j}$ is a meat edge point and $\boldsymbol{s_{cj}}$ is the suction cup point which is closest to $\boldsymbol{p_j}$. Again a margin of 0.02m is used to reduce the chance that the suction cups are placed outside the meat. $\boldsymbol{M}$ is the total number of meat edge points.

$\boldsymbol{R}$ represents the penalty score that is to be minimized. The $\boldsymbol{R_{cups}}$ score is raised to the power of 4 to ensure both parameters have the same units and are of a similar scale. Furthermore, the tradeoff between the two scores were estimated by trial and error, to ensure that the suction cups are placed in the desired manner on a test set of 15 real world cases. A 1:1 tradeoff turned out to give satisfactory results.

To determine a good grasp based on the regret score, the numeric minimization algorithm coordinate descent [17] is used to move the suction cup array around in order to minimize the regret. The parameters that are optimized are the x and y-coordinate of the suction cup array. The orientation of the suction cup array is not optimized since this is already satisfactory based on the PCA analysis. The translated suction cups are illustrated as blue points in Figure 10a.

After the suction cup placement is determined in 2D, it is projected back into 3D to determine the “grasp frame”. This is done by aligning the gripper tool with the PCA frame and then translating it according to the optimal translation found in 2D. Afterwards, the suction cup tool is moved in the z-direction to ensure full contact with the point cloud. This is done similarly to the flat grasp. The full 3D mapping is illustrated in Fig. 10b and 10c.

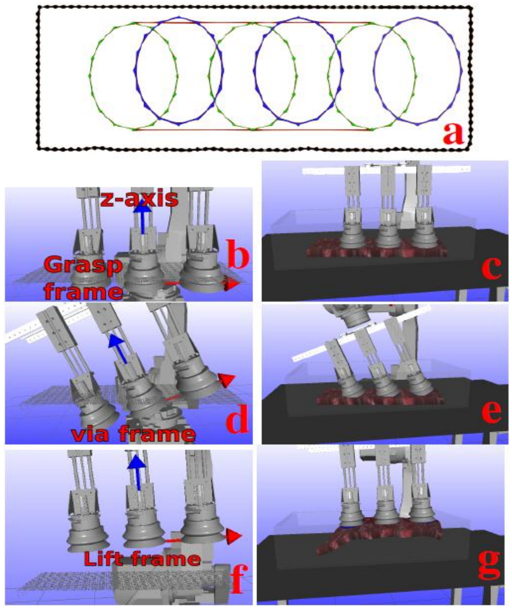

Figure 10. Rolling lift - planning and simulation. a) The grasp frame is determined in 2D by optimization. The green dots represents the initial suction cup placement and the blue dots represents the optimized placement. c, d) The grasp frame is mapped to 3D, and the gripper is placed accordingly. e, f, g, h) A rolling motion is used to lift the meat. Notice the air cylinders are used as passive components, so they are always stretched during planning, but in simulation (as in the real world) they are pushed back by the meat, this can be seen most clearly in e) and f).

After the grasp frame is defined in 3D, the next step is to determine the rolling motion to lift the meat from the box onto the conveyor belt. This is achieved by introducing two more frames to define the overall motion. These frames are a “via frame” and a “lift frame”, which is used to describe the rolling lift and subsequent realignment to ensure a flat tool alignment before moving the meat to the conveyor belt. First, the tool is moved to the “via frame”, which is defined as the “grasp frame” rotated 25 °around the y-axis. Then the tool is moved to the “lift frame” which is defined to be the “grasp frame” translated 150mm in the z-direction. This is illustrated in Figure 8d, 8e, 8f and 8g. After the tool reaches the “lift frame”, it is moved to the conveyor belt where the meat piece is placed.

V. Results

To evaluate the two grasp strategies, we tested them on a physical prototype at a Danish slaughterhouse. The scenario was a fairly difficult case, where thin and highly flexible pork bellies were grasped. For both strategies we did 54 grasps. To improve the analysis of the grasps they were videotaped and the vacuum levels of all suction cups were measured. The vacuum measurements were conducted using vacuum sensors attached to the suction cups (Figure 11). Furthermore, we stored the generated point clouds, to ensure the vision system didn't negatively affect the grasps. Grasps that failed due to the vision system were discarded since the interest of this paper was the mechanical system. The test setup can be seen in Figure 11.

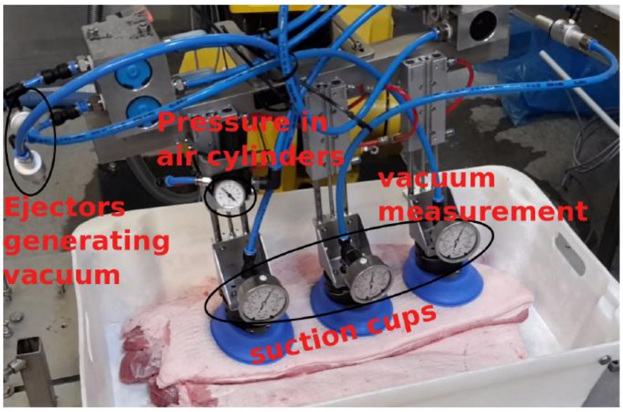

Figure 11. Test setup including sensors used to analyze the grasps, the camera used to capture the image is the same used to film the grasps for later analysis.

Based on the manual analysis of the grasps, they were classified into 4 groups; Success (S). Failure due to vacuum loss during the lift (FL). Failure due to vacuum loss during motion towards the conveyor belt (FM). Failure due to the meat piece sticking to the meat or the box below it, such that multiple objects are lifted during the grasp (FML). Examples of the error cases can be seen in Fig. 12.

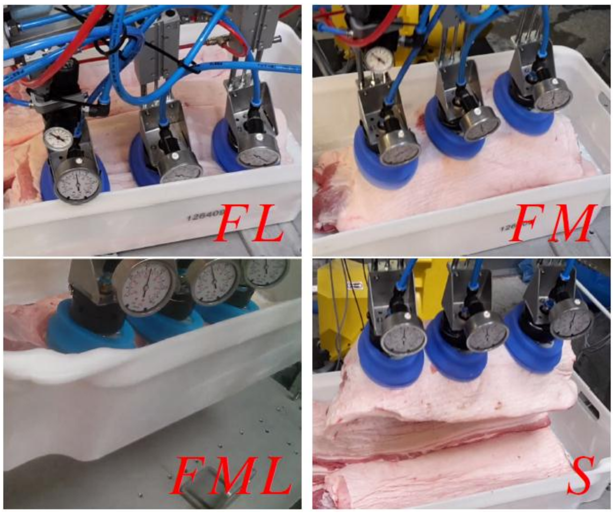

Figure 12. Grasp categories. FL) Notice the vacuum gauges, vacuum is never established due to the large ridges in the meat. FM) During the motion the left suction cup drops the meat, notice the needle in the vacuum gauge is much lower than the others. FML) The box is lifted along with the meat. S) success, the meat is lifted and all suction cups are at full vacuum.

The manual classification of the grasps resulted in the failure rates presented in Table 1. Here it can be seen that the flat grasp strategy has a worse performance in terms of achieving a proper grasp during the initial lifting. This is seen both in the FL and FML failure rates, it is only the flat grasp that lifts two meat pieces at once and it also fails more often in the beginning of the lift. The reason for this is twofold. First of all, the rolling motion helps reduce the impact of potential vacuum chambers forming below the meat piece during the lift. The second reason is that the rolling motion wiggles around more, and thus the chance of an air-tight connection forming between the suction cups and the meat piece is improved.

Besides testing the gripper on the difficult test case, we also evaluated it on a simpler case, where the meat pieces still had skin. The skin makes the meat thicker and more rigid. In this case we did 20 trials with the rolling grasp since this strategy showed the most promise.

Both grasp strategies have a similar performance when moving the meat piece to the conveyor belt, which was expected since the motion after the grasp is similar. Overall the rolling grasp had the best performance, and for the pork bellies with skin it grasped all pieces successfully.

TABLE I. Failure Rates for Lifting Pork Bellies

Strategy	Total failure rate	FL failure rate	FM failure rate	FML failure rate
Flat grasp	30.8%	23.1%	5.8%	1.9%
Rolling grasp	14.5%	7.3%	7.3%	0.0%
Rolling grasp - with skin	0.0%	0.0%	0.0%	0.0%

VI. Conclusion and Future Work

In this paper, we presented a flexible gripper tool for handling large meat pieces. The tool can be manually stretched and contracted to fit the size of the meat pieces, and thus it can be applied to multiple cases. Furthermore, the tool is designed to cope with the high surface variation of grasp scenario, which arises partly due to variation in the meat product, but also due to the initial placement and deformation state of the meat.

Furthermore, we presented two grasp strategies, a flat grasp and a rolling grasp. The rolling grasp had the best performance, partly since it allows air to flow beneath the meat piece during the lift, but also because it wiggles the suction cups around more, which improve the chance of an airtight connection being established.

In future work, we intend to investigate different re-grasping strategies to improve the success rate even for the difficult cases. This could be implemented by measuring if all suction cups establish a vacuum and otherwise drop the meat and re-grasp it. Furthermore, we intend to test the gripper on a larger range of products and determine how adaptable it is.

To further improve the gripper a more advanced vacuum system should be implemented. Partly to establish vacuum faster, but more importantly to get a faster and more controlled release of the meat pieces, which is necessary for a fast and reliable placement strategy.

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