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An End Effector Based on the Bernoulli Principle for Handling Sliced Fruit and Vegetables

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ABSTRACT

This paper describes the design and testing of a gripper developed for the handling of delicate sliced fruit and vegetable products commonly found in the food industry. The device operates on the Bernoulli principle whereby air flow over the surface of an object generates a lift. The gripper allows objects to be lifted with minimal contact thereby reducing the chances of damaging or contaminating the object. The paper will describe the mathematical basis of the gripper operation followed by tests showing the nature of the grasp.

As a secondary benefit it will be shown that the flow of air over the object can also be used to remove surface moisture produced during slicing. This drying effect is a feature particularly useful in some areas of food production.

The paper will show a test manufacturing cell demonstrating the placement of slices of tomatoes and cucumber on to sandwiches.

KEYWORDS: End-effector, Gripper, Non-contact, Bernoulli effect, Food, Tomato, Cucumber.

1 INTRODUCTION

Food and drink manufacturing forms one of the largest global industry sectors. In the EU alone the industry has a turnover of €600bn and employs 2.5million people [1]. It has for over a decade been identified as a major growth area for the application of automation systems with the aims of [1]:

- improving production efficiency
- enhancing hygiene standards
- improving working conditions
- impacting on yield margins and profitability
- conforming to existing and future legislation pertaining to food production.

Yet inspite of these driving influences only a small number of companies make significant use of automation for raw and in-progress product handling.

Although limited use of automation is certainly a reflection of conservative investment policy in a low margin industry, in many instances the use of labour intensive manual techniques is a deliberate policy. This is due to the flexibility provided by the human worker and the perceived in-abilities of current automation systems, particularly the capacity to handle and manipulate food products.

This need for flexibility and scepticism with regard to automated handling is strongly influenced by the nature of the food product which is in many instances non rigid, often delicate and/or perishable and variable in texture, colour, shape and sizes. The consequence is that the food product inherently deforms significantly during handling.

Clearly the nature of many food products means that the handling, characteristics cannot be adequately described in a conventional geometry based manner since their geometry is often a function of time and the forces applied to the object. Any systems developed to handle food therefore need to react accordingly to this deformation. Humans handle these complexities with ease by combining dextrous handling capabilities (human hand) and behavioural models of the product accumulated with experience.

In this paper one of the most difficult situations is approached, this is the handling of freshly sliced fruit and vegetable products specifically tomato and cucumber. The paper describes the development of a Bernoulli based end-effector for the handling of soft flexible foodstuffs. It begins by examining grippers developed for handling non-rigid food products. This is followed by a study of how such products, particularly tomato and cucumber slices, are currently handled. Section 4 describes the development of a Bernoulli principle gripper and this is followed by a section that compares experimental results with modelled performance. The gripper has the secondary benefit of being able to dry the object it is handling and this is explored in section 6. Section 7 demonstrates the effectiveness of the gripper through the development of a robot cell. Section 8 highlights the benefits of the gripper developed and finally conclusions are presented.

2 GRIPPERS FOR NON-RIGID FOOD PRODUCTS

The majority of food products are non-rigid and vary enormously in size, shape, texture and colour. As a result it is often not possible to handle food products using traditional techniques and this has led to the development of a number of novel approaches. Taylor [2] classifies the main techniques for gripping non-rigid material into three classes.

Mechanical Surface **-** here the material is clamped or pinched between gripper fingers to give high frictional holding. Items such as fish and poultry can be handled using a clamping type gripper with the gripper surface being angled to mechanically lock slippery items in place. A compliant interface rubber or foam may be added to the gripper to prevent bruising when grasping fruits and vegetables.

Intrusive **-** here pins are fed into the surface or body of the material and moved to lock it into place. This type of gripper is generally unsuitable for food products as it would cause unacceptable damage.

Surface Attraction – this includes the use of adhesives or vacuum. Vacuum grippers which employ suction cups can be used to grip food items. However, not all food items can be handled with such grippers as the vacuum nozzle can become clogged with dirt or scraps of materials and this can be a source of bacterial contamination or cross product contamination. This type of gripper is commonly used in the harvesting of fruits where the surface being gripped is relatively hard and yet easily bruised.

The highly variable nature of food products means that there have also been a number of other approaches which broadly fit into the three classes outlined above.

Stephen and Seliger [3] developed a ‘freezing gripper’ where grip is attained by rapidly freezing water vapours that have been distributed on the gripping spot. The freezing element (Peltier Heatpump) can, it is claimed, produce a grip surface temperature of -10°C within one second of contact. To release the material, the frozen vapour is liquefied by slightly warmed air. Although this gripper was developed for the textile industry it may have great potential in the food industry especially for example in the packaging of frozen food items.

Electrostatic grippers using a high voltage field to create an adhesive effect have also been developed to handle textiles and leather. Although the grip forces are small it is possible that this method could be applied to handling of thin delicate strip materials eg smoked salmon.

Erzincanli *et al.* [4] developed a non-contact robotic handling system for non-rigid materials. This was a surface attraction technique based on air out-flow not suction. The end-effector consists of radial air flow nozzles that generate high speed air flow between the nozzle head and the material surface, thereby creating a vacuum which lifts the product. The clearance gap of the nozzle must be very small compared with the diameter of the central supply tube for an attractive force to be generated. The high outflow rates from the nozzle mean that this method is not suited to handling of delicate products that would be destroyed by the air flow.

Further detail of the handling of non-rigid materials can be found in the work of Saadat and Nan [5] which presented an overall picture of recent research into the automatic manipulation of flexible materials.

3 TOMATO AND CUCUMBER HANDLING

Within the food manufacturing and assembly industry the placement of freshly sliced products, particularly vegetables, is common. Within the UK sandwich industry, which has an annual turnover of over £4bn, tomatoes and cucumbers are the most common ingredient. However, they are notoriously difficult to handle and as a result their placement during sandwich assembly is always performed manually.

Typically fresh vegetables such as tomatoes and cucumbers are washed and sliced in a secondary part of a factory using large scale slicing machines capable of processing many kilos per minute. Once sliced the product is deposited into trays, Figure 1, for delivery to the lines.

The high water content of most vegetables and the nature of the cutting means that slices have a high residual moisture on their surfaces and cannot be placed directly onto sandwiches without making the bread soggy. This reduces the appeal to the customer although it has no significant environmental issues. To reduce this “sogginess” and improve shelf life the sliced vegetable trays are left to drain, for at least two hours, before being used. The effectiveness of this method is highly variable, with the upper layers of ingredients draining more thoroughly than those towards the middle or bottom of the tray.

After draining the trays are delivered to the assembly lines where operators pick individual slices from the trays and place them on the sandwiches, Figure 2. It is extremely difficult to do this without further damaging the slices and as a result it is not uncommon for the centre of tomatoes to become detached. Furthermore the moisture causes the slices to stick together and the operators have to separate them, slowing the overall process. For this reason a line working at 50 sandwiches per minute can typically have 4 operators just placing tomato slices.

Investigation of this process suggested that automation of the existing process is extremely difficult, requiring identification and selection of an individual slice.

The solution proposed here involves cutting slices on the actual assembly line for immediate use. A slice would only be cut when required and thus the need to pick an individual slice from a tray is removed.

Although the basic concept of slicing at the assembly line is simple two fundamental problems arise:
i). The handling of delicate slices particularly tomatoes is not possible using conventional grippers.

ii). The slices must have the excess moisture removed before placement on the bread base.

A new form of gripper was therefore required.

4 BERNOULLI GRIPPER

Grippers that use the Bernoulli effect are well known but typically they have only been used to handle rigid materials such as silicon wafers. However, Erzincanli et al [4] applied the technique to the handling of sliced meats and jelly blocks and Ozcelik et al [6] used a similar device in the textile industry. These devices are not suited to the handling of particularly delicate objects as the impact of air could damage the material.

4.1 Principle of operation

In conventional Bernoulli gripper operations compressed air is supplied to the gripper through a central channel with circular cross section as can be seen in Figure 3. The air flows down this channel until it impacts with the object to be gripped. This generates a repulsive force on the object, F_{jet}, which pushes it away from the gripper. At the same time, the air, which is now unable to continue to travel away from the channel is deflected to flow in a lateral direction, Figure 3(a). Due to the circular nature of the gripper the air radiates in all directions away from the central channel. This causes the air to travel across the upper surface of the grasped object and inline with Bernoulli's principle produce a reduction in the air pressure above the object. The resultant pressure differential between the upper and lower surfaces of the object generates an attractive force between the gripper and the object, F_{lift}.

As the gripper is brought closer to the upper surface of the object to be lifted the gap between it and the gripper is reduced. To enable the same volumetric flow of air to exit the gripper the air must travel faster and therefore the closer the gripper is brought to the object the higher the air velocity across its upper surface becomes. This increase in velocity results in an increase in the lift force F_{lift}. At a threshold distance from the object the lifting force F_{lift} will become larger than the sum of the force repelling the object F_{jet} and the gravity effect on the object. At this point the gripper lifts the object and pulls it towards the surface of the gripper. As the object continues to get closer so the attractive force further increases, however, as this happens the repulsive force F_{jet} also increases. Eventually the object will reach an equilibrium point where the three forces acting on it are balanced and it is securely grasped without making any contact with the gripper.

In this form the gripper is not capable of handling very delicate materials such as tomato slices. The reason for this is that the three forces acting on the object are not distributed evenly across its surface. The pressure generated by the gripper at a distance r from its centre can be calculated as follows, Figure 5:

$$\frac{P}{r} = -const\left[\left(\frac{r_O}{r}\right)^2 - 1\right] \qquad (1)$$

where ρ is the density of air and r_O is the radius of the object being held.

It can be seen that as the air travels away from the centre of the object the pressure differential and therefore grasping force becomes less. Similarly the effect of F_{jet} is confined to the centre of the object across the area of the input channel. The result is that although the overall force on the object is a lifting force the centre of the object is in fact forced away from the gripper. For solid materials this does not present a problem but more delicate objects can become damaged as the centre section can become detached from the remainder of the object. If this happens the gripper is no longer able to operate as the air passes through the hole produced in the object. This means it is not deflected by the object and so does not flow across its surface and therefore no lifting force is produced.

To overcome this problem the gripper developed within this project does not rely on the impact with the surface of the gripped object to deflect the air but rather a deflector is included as part of the gripper, Figure 3(b). In this case air travels down the central channel and is forced by the deflector to flow laterally across the face of the gripper. The result of this is when the gripper approaches an object the lateral flow passes over the surface and generates an attractive force as previously but without the central repulsive jet. As the object is pulled towards the gripper its central section comes into contact with the deflector and no lift is generated at this point. However, the remainder of the object is supported on a cushion of air as previously.

As there is minimal contact between the gripped object and the gripper there is very little friction to hold it in place and it is possible for the object to slide across the face of the gripper. This presents two problems, firstly if the object moves too far from the centre of the gripper it will be dropped and secondly if the position of the object changes accurate placement is not possible. To overcome this problem the face of the gripper was fitted with a restraining wall as seen in Figure 3. This wall lies along the perimeter of the gripper’s face, if a supported object moves it makes contact with the restraining wall which stops any further movement. To ensure that there is no obstruction to the flow of air across the face of the gripper, a regular series of gaps are located in the restraining wall to allow the air to escape.

Non rigid products are able to flex whilst being held and this means that unlike a rigid object it is possible for a portion of the object to make contact with the face of the gripper and this results in no lifting force being generated on this part of the object. This does not prevent the gripper from holding the object as the rest of its surface can still be supported by the Bernoulli effect. However, this can cause problems if the object is tacky or damp as this can cause it to stick to the surface of the gripper making it difficult to release. To overcome this the face of the gripper is fitted with a number of ribs arranged in a spoke like manner, Figure 4. These spokes protrude 1.5mm from the surface of the gripper and break up the smooth surface. When an object is held by the gripper it rests on the ribs thus preventing it from making direct contact with the gripper face. The contact area is therefore minimised and the adhesive effect reduced. As the ribs are arranged like spokes they do not significantly affect the flow of air across the surface as can be seen in Figure 4. The air flows from the central orifice between each pair of ribs and then exits the gripper through the gap in the restraining wall.

4.2 Force calculation

The theoretical force that the gripper can produce is given by the following equation.

$$F = \Delta P \cdot A_{obj} \qquad (2)$$

where ΔP is the pressure differential between the upper and lower surfaces of the object being held and A_{obj} is the surface area of the object being lifted. As the object is in contact with the ribs and the deflector there is no lifting force applied at these points, therefore the area on which the lifting force operates is given by equation (3).

$$A_{obj} = pr_{obj}{}^{2} - pr_{def}{}^{2} - n \cdot t_k (r_{obj} - r_{def}) \qquad (3)$$

where r_{obj} is the radius of the object being held, r_{def} is the diameter of the deflector, n is the number of spokes and t_k is the width of each spoke.

Bernoulli’s equation states that given the following assumptions

i) fluid is incompressible

ii) fluid is nonviscous.

iii) fluid flow is laminar.

the differential pressure generated by differing air velocities above and below an object can be calculated as follows:

$$\Delta P = \frac{1}{2} r (V_2{}^{2} - V_1{}^{2}) \qquad (4)$$

where V_2 is the velocity of the air below the object and V_1 is the air velocity above it. For the case of the gripper we assume the air below the object is stationary. Whilst this is not strictly true, especially in the case where the gripper is mounted to a robot, it is likely to be minimal in comparison to the flow in the gripper. The difference in pressure is therefore calculated using (5).

$$\Delta P = \frac{-r \cdot V^2}{2} \qquad (5)$$

It is not possible to use this equation directly because it requires the velocity of the air across the surface of the gripper to be constant. As the air travels away from the centre of the gripper its path becomes wider, as can be seen in Figure 4, and its velocity therefore reduces. However, it is possible to calculate the air velocity at any point on the surface of the gripper using the following equation.

$$V = \frac{Q}{A} \qquad (6)$$

Where Q is the volumetric air flow rate through the gripper and A is the cross-sectional area of the air channel created between the gripper face, the upper surface of the object being held and the ribs. This can be calculated for any point located a distance r from the centre of the gripper as follows:

$$A_r = (2pr - nt_k)h \qquad (7)$$

where h is the height of the ribs. This can then be used to calculate the velocity of air at any given radius.

$$V_r = \frac{Q}{(2pr - 8t_k)h} \qquad (8)$$

Figure 5 shows the calculated air velocity profile across the surface of a gripper with a 10mm diameter deflector and ribs of height 1.8mm when holding a 42mm diameter disk and with a volumetric flow rate of 54l/min.

Equation (5) can be used to calculate the pressure differential on the object being handled, however, this equation again requires a constant air velocity. It is therefore necessary to calculate an average air velocity across the face of the gripper and use this to calculate the pressure. This is achieved by calculating the area under the velocity graph and dividing this by the radius over which the air passes as follows.

$$V_{av} = \frac{\int_{r_{def}}^{r_{obj}} V}{r_{obj} - r_{def}} = \frac{Q}{h(r_{obj} - r_{def})}\left[\frac{1}{2p}\ln(2pr - 8t_k)\right]_{r_{def}}^{r_{obj}}$$

$$V_{av} = \frac{Q}{2p\,(r_{obj} - r_{def})h}\left[\ln(2pr_{obj} - 8t_k) - \ln(2pr_{def} - 8t_k)\right] \qquad (9)$$

substituting (9) into (5) gives

$$\Delta P = \frac{-r}{2}\left(\frac{Q}{2p\,(r_{obj} - r_{def})h}\left[\ln(2pr_{obj} - 8t_k) - \ln(2pr_{def} - 8t_k)\right]\right)^2 \qquad (10)$$

The force generated can then be calculated by substituting (10) and (3) into (2).

5 LIFTING FORCE

To analyse the performance of the gripper a prototype was constructed, Figure 6 and a number of experiments were performed.

Firstly to determine what effect the deflector has on the force generated by the gripper, a comparative test was conducted using a gripper both with and without a deflector. Figure 7 shows the experimental rig used. It consists of a plate mounted on a load cell that is located a predetermined distance (d) below the face of the gripper. As air is applied to the gripper a force is generated on the grasping plate which is measured by the load cell. The diameter of the grasping plate is 42mm and the distance between the gripper and the grasping plate was 2.0mm.

Figure 8 shows the force generated at four arbitrarily selected flow rates for a gripper with no deflector and grippers with 6mm and 10mm diameter deflectors. It can be seen that the introduction of the deflector reduces the force generated. This result may seem unexpected as the deflector removes the force F_{jet} and so the overall grasping force would be expected to rise. However in both cases the deflector has a larger diameter than that of the central channel meaning that some of the lifting force is also lost.

The size of the loss seems large considering the overall area of the deflector in comparison with the area of the object being grasped. However, from equation (1) it can be seen that the pressure differential generated is at its largest towards the centre of the gripper and therefore the effect of the deflector on F_{lift} is significant. It can be seen from Figure 8 that if the diameter of the deflector is reduced the lifting force of the gripper increases.

To verify the model presented in the previous section, experiments were performed to determine the force that the gripper could produce at any given air flow rate. The gripper was clamped above a flat surface so that the face of the gripper was aligned in the same plane as the surface as shown in Figure 9. The supply of air was controlled using a regulator and the volumetric air flow was recorded using a flow sensor. The flow of air to the gripper was initially set to its maximum, a 42mm wooden disc weighing 5.4g was then placed against the gripper face where it was held securely. The flow of air was gradually reduced to a point where the weight of the disk could no longer be supported. This flow was then recorded. A second identical disk was bonded to the first resulting in an object with the same upper surface area but twice the weight. The experiment was repeated and the minimum flow needed to support the disks was recorded. More disks were added allowing a force/flow profile to be produced, Figure 10.

Two grippers were tested, one with a 10mm diameter deflector and the other with a 6mm diameter deflector. The other properties of the gripper were identical and were as follows:

$t_k = 1.5\text{mm}$

$h = 1.8\text{mm}$

It can be seen from Figure 10 that the force generated by the gripper appears to have an approximately linear relationship with the air flow. Also when a smaller deflector is used the force generated at any given airflow is approximately 80% higher than that obtained with a larger deflector.

The theoretical force calculated using equation (10) is included in Figure 10 for comparison. It can be seen that the measured and modelled forces initially match well but as the air flow rate increases so the accuracy of the model deteriorates. This is due to the assumptions made in order to generate the model. The model assumes that the air flow is laminar, whilst this may be the case for low flow rates it is not likely to be the case as the air flow increases.

6 DRYING EFFECT

The primary requirement of this new design of gripper for handling sliced products was the need to lift the products without causing damage particularly to the central very delicate sections of tomatoes. The secondary need was a requirement to remove the surface moisture resulting from slicing thereby permitting on-line slicing and placement. This “drying” is achieved in the same manner as an air knife where moisture is “stripped” from the surface by a high velocity flow of air [7]. Essentially this means the moisture is atomised by the air and blown off the surface. Air knife technology has seen use in the food industry but this has typically been limited to drying bottles or packets before packing.

When the Bernoulli gripper is used to picked up an object, by its very nature, there is a rapid flow of air across the upper surface of the object. As a results any moisture on the surface of the gripper is removed.

In order to determine how effectively the gripper could dry products a comparison was made with the traditional drying technique. Conventionally, in the sandwich manufacturing industry, tomato slices are typically left to drain for two hours before being placed in sandwiches. Firstly the effectiveness of this technique needed to be determined. This was achieved by cutting a number of fresh slices of tomato and recording the weight of each. The slices were then placed on a rack, in two layers, and placed in a refrigerated environment (to simulate factory conditions) for 2 hours. After disposing of the liquid that had accumulated in a collecting tray below the rack, the slices were weighed and the average loss of mass calculated. The experiment was repeated several times and the average loss of mass in two hours was found to be 1.3%. In a manufacturing situation it can be assumed that the loss of mass would be less than this experimental figure as the slices would be more densely packed in the draining trays and this would reduce the draining effect.

To determine the drying effect of the gripper, individual slices of freshly cut tomato were placed on a set of accurate scales and the weight recorded. The gripper was then used to lift the slice off the scales, hold it for a predetermined time and then place it back on the scales for re-measurement. This ensured that any moisture dripping from the bottom of the slice (i.e. not removed by the gripper) remained on the scales and did not affect the results. By comparing the weight of the slice before and after handling it was possible to determine the percentage of the tomatoes mass lost due to Bernoulli gripper drying. The test was repeated a number of times to produce an average value and tests were conducted for a range of handling times. The results are shown in Table 1. It can be seen that handling a slice of tomato for 2 seconds with the gripper results in a drying effect that is at least equal to allowing the slices to dry for 2 hours using the traditional method.

7 AUTOMATED SANDWICH ASSEMBLY

To test the effectiveness of the gripper to perform assembly tasks the robot work cell shown in Figure 11 was created. The cell consists of two conveyors, an ABB Flexpicker robot and a vision system (to identify the sliced products).

A slicing machine places individual slices of tomato and cucumber onto the first conveyor. These pass below the vision system which determines the position of each slice and checks that they are within the tolerance of acceptable sizes. This tolerance is defined by the manufacturer for their product. Reject slices are ignored by the robot and proceed to the rejects bin. Pieces of bread are input to the cell on a secondary conveyor. The robot then picks slices one at a time and places them on the bread as shown in Figure 12.

These experiments showed that the robot was capable of placing over 40 slices per minute which outperforms two human operators. The slices were also dried during transit and placed with less damage than that caused by the human operator.

8 BENEFITS

The gripper has a number of benefits over traditional handling devices. These are:

- The grasping force is spread over the entire surface of the product thus reducing likelihood of damage.
- The gripper lifts products using the top surface rather than having to slide beneath it as a human's finger might. This results in less damage to the object.
- As the whole surface is supported fragile parts such as tomato centres do not drop out or remain stuck to the gripper surface.
- When higher air flow rates are used surface moisture is removed.
- The gripper operates using positive pressure rather than vacuum and this eliminates the chance of debris being sucked into and blocking air lines.

9 CONCLUSIONS

This paper has described the design and testing of a gripper for use in the handling of delicate sliced fruit and vegetable products. By way of an example the gripper has been used for the handling of tomato and cucumber slices during sandwich production.

The gripper operates using the Bernoulli principle. This involves directing air across the surface of the object to generate lift. A deflector on the face of the gripper ensures that the jet of air at the centre of the gripper does not damage the object being handled allowing delicate objects to be grasped. The introduction of this deflector reduces the force that the gripper can produce and it has been shown that higher forces can be generated when smaller deflectors are used.

Further, the gripper face has a number of ribs which minimise the contact between object and gripper allowing "sticky" or moist foods to be handled without adhering to the gripper.

The gripper is also capable of removing surface moisture from the objects it is handling. This is achieved in a similar manner to an air knife where moisture is blown from the surface. This feature is of particular benefit to the sandwich assembly industry where tomato slices are left to drain for two hours before use. The gripper described in this work is capable of achieving similar levels of drainage in less than 2 seconds.

The gripper has been used in conjunction with an ABB Flexpicker robot and a vision system. This enabled slices of both tomato and cucumber to be automatically placed on pieces of bread. The vision system also provided a degree of quality control.

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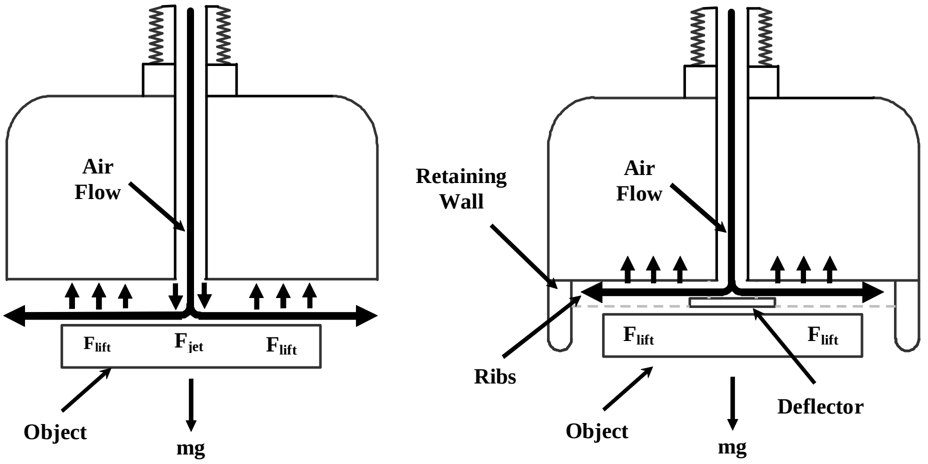
Figure 1 – Tomato and cucumber sliced into trays.

Figure 2 – Manual tomato placement.



(a) (b)

Figure 3 – Gripper operation.

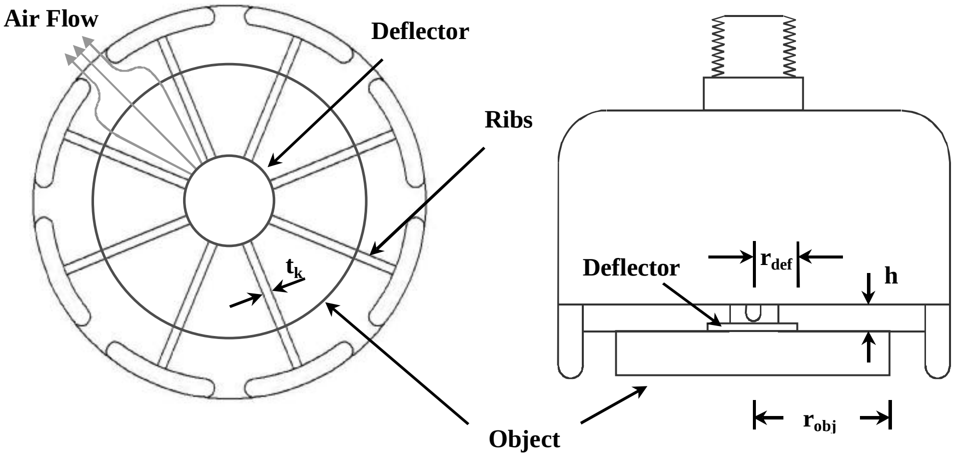


Figure 4 – Gripper design.

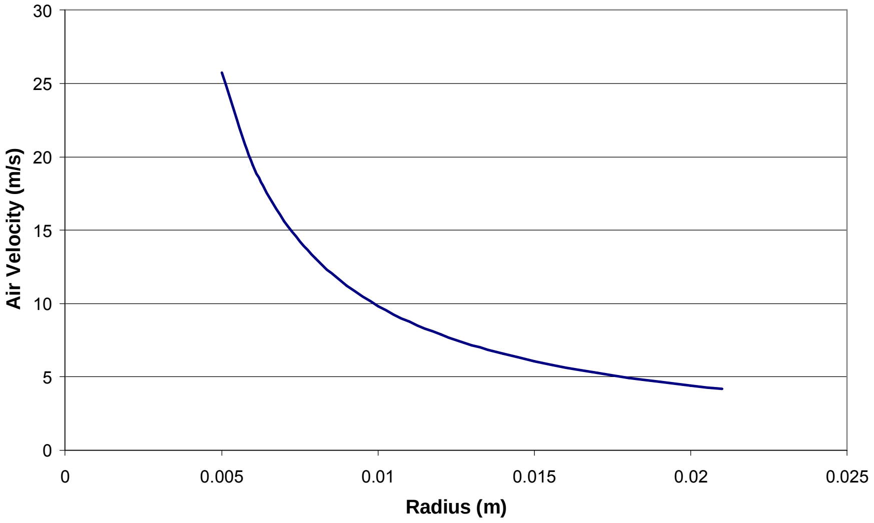


Figure 5 – Air velocity across face of gripper.

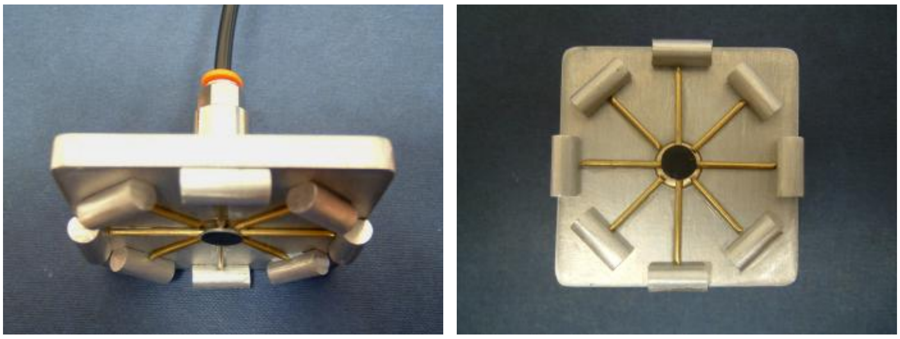


Figure 6 – Prototype gripper.

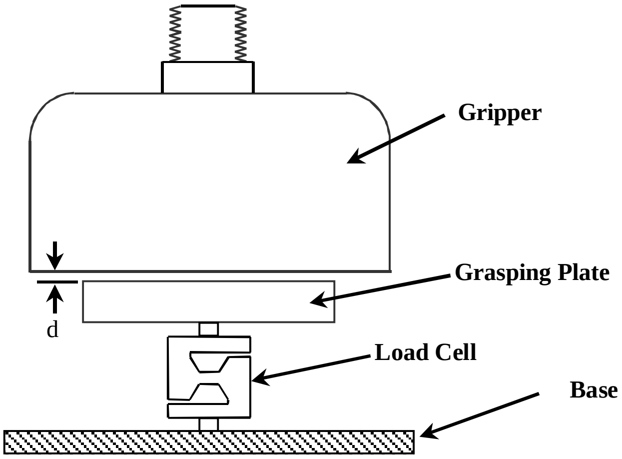


Figure 7 – Deflector test rig.

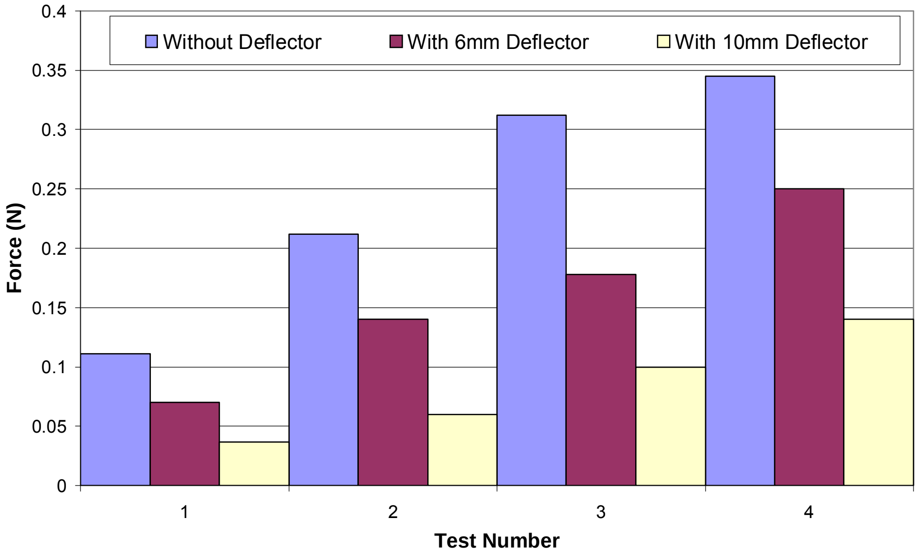


Figure 8 – Gripper with and without deflector.

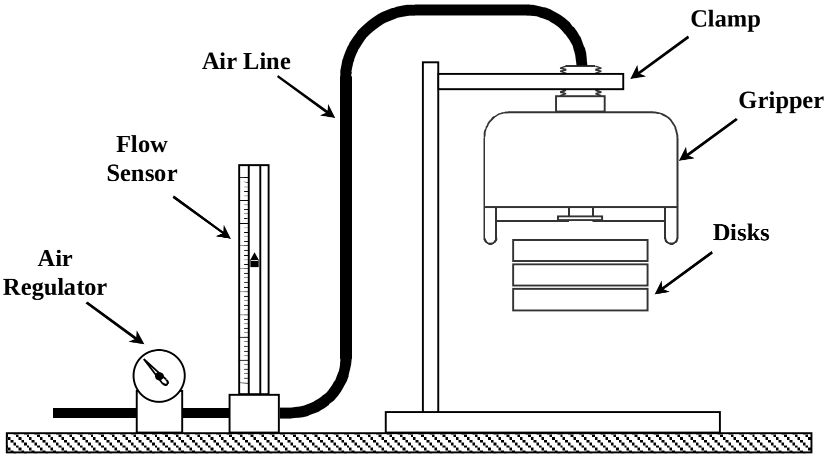


Figure 9 – force test rig.

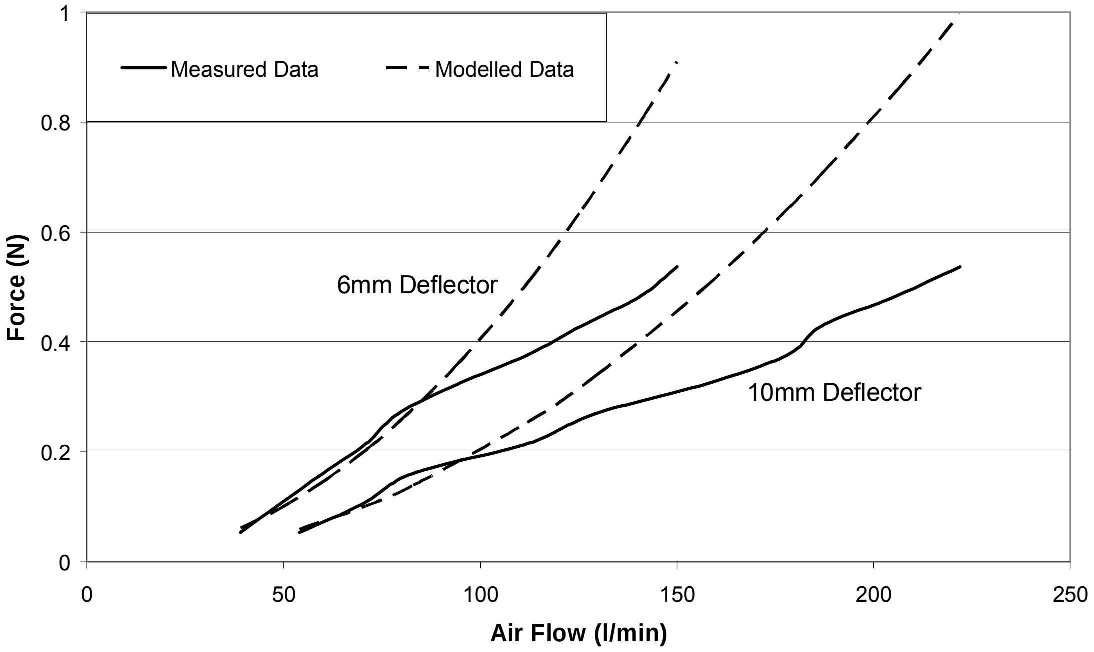


Figure 10 – Gripper force/flow profile.

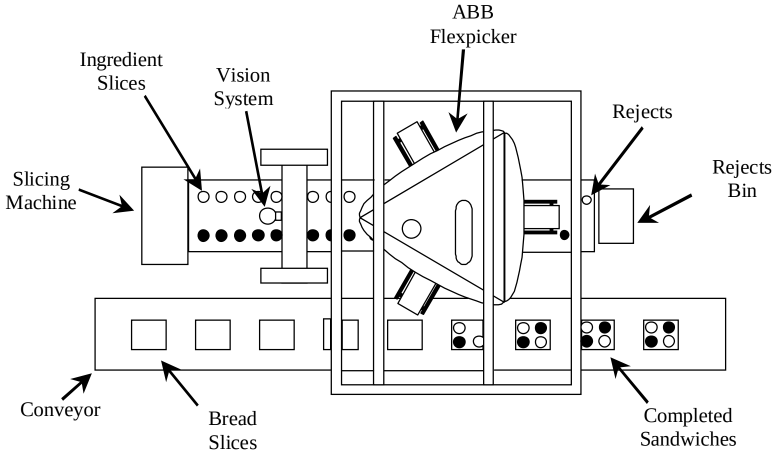


Figure 11 – Robot work cell layout.

Figure 12 – Gripper mounted on robot.

Handling Time (s)	% Loss of Mass
1	0.98
2	1.31
5	2.50

Table 1 – Percentage loss of mass with handling time.