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End Effector Development for Automated Sandwich Assembly

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1 Introduction

The food industry is the largest manufacturing sector in the EU, with an annual turnover of €836 billion[1]. The are 290,000 food manufacturing sites spread across the EU and these employ a total of some 3.8 million people. The European farming industry sells a large proportion of its produce to food manufacturers. This, along with the sophisticated distribution network further adds to the number of people who rely on the food industry for employment[1]. As a result of its vast size the food industry has been identified as a major growth area for the application of automation systems[2]. However, unlike the more traditional manufacturing sectors food products vary enormously, both in ingredients and more crucially between different examples of the same product.

This makes producing automated systems to handle food products extremely difficult and as a result less automation is found in the food industry than in many other sectors. The level of automation found in food factories varies enormously, ranging from completely manual operations to the use of highly advanced technology. Typically food factories in the EU use a mix of both manual operators and some automated machinery. The continued use of manual operators is due in part to the investment policy of manufacturers operating in a low margin industry and in part due to the flexibility provided by human workers. The use of manual operators is particularly high for tasks that involve the handling and manipulation of food products. Automation on the other hand is typically found where products are homogeneous i.e. final packing.

The majority of food products are non rigid meaning their characteristics change during handling, they also vary in texture, colour, shape and sizes. Humans are able adapt to this product variability with ease by using their senses, typically vision and touch, and through accumulated knowledge and experience of the behaviour of a particular product. The ingredients used in the production of triangular sandwiches are a good example of this. For example the amount a loaf of bread rises when baked is affected by weather conditions and the firmness of a tomato reduces continually after it is harvested. Due to this variability no single end-effector, or indeed end-effector technology, can handle all food substances. Typically custom designed grippers are needed for each new project.

This paper considers the end-effectors required to automate the manufacture of sandwiches. The paper begins by analysing current sandwich production processes. This is then followed by descriptions of the design and implementation of three end effectors developed for use on an automated sandwich assembly line. Finally conclusions are presented.

2 Sandwich Production

It is not possible to give an exact definition of a sandwich due to its many variations, however, this work considers the most common type of sandwich found in the UK which is formed from two slices of bread cut from a rectangular loaf. These are placed one on top of the other with a filling placed between the two slices. The rectangular sandwich is then cut diagonal to form two individual triangular sandwiches. These are then packaged in a plastic or cardboard skillet.

Until relatively recently sandwich production has been performed almost entirely manually with lines employing up to 40 people. What little automation that is used typically takes the form of slicers or depositors. The high level of labour means that there is a real incentive to look to automation. However, the only successful example of an automated sandwich line is that developed for Uniq plc by Lieder[3]. The system uses industrial robots and an indexing system to automate the entire process from buttering to packing but operates most successfully for products with paste fillings. Due to the use of robot there are significant safety issues and as such the line must be enclosed by guarding. This means it can not operate along side humans and also leads to a large machine footprint.

Through observation of sandwich lines and discussions with operators it became apparent that the most difficult sandwiches to construct were those consisting of many discrete components. For this reason the sandwich chosen for study in this work was chicken salad. This contains many individual chicken pieces and other components such as slices of tomato, cucumber and lettuce leaf making it particularly difficult to handle. An automated system capable of processing this sandwich is likely to be able to handle simpler fillings with ease.

By studying the current production line it was possible to identify a number of individual processes needed to construct the sandwich. It can be seen from Figure 1 that there are five individual operations:

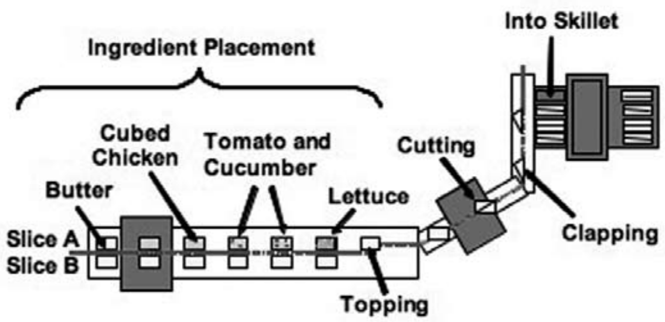


Figure 1 – Chicken salad sandwich production processes

- Ingredient Placement – Individual ingredients are placed onto a single slice of bread.
- Topping – A second slice of bread is placed on top of the first.
- Cutting – The sandwich is positioned and cut once diagonally to form two triangular sandwiches.
- Clapping – One triangular sandwich is placed on top of another prior top packing
- Packing – The two sandwiches are placed into a skillet.

From these processes it can be seen that there are a number of handling challenges, including the grasping of; individual ingredients, single slices of bread and the complete sandwich. The remainder of this paper will describe end effectors used to handle each of these processes and describe their use on a prototype production line.

3 Ingredient Placement

The placement of some ingredients can already be achieved using automation. For instance the butter and mayonnaise are automatically applied and chicken pieces are deposited from a multihead weigher. The placement of tomato and cucumber slices, however, is always performed manually due to the difficulty associated with handling the moist, semi porous and often sticky products.

To address the handling needs for tomatoes and cucumbers a number of different gripper techniques were trialled. It was found that mechanical grippers caused excessive damage to the products, particularly the tomatoes. Experiments using a standard vacuum cup were performed on a slice of cucumber. A standard vacuum cup was lowered onto a slice of cucumber as shown in Figure 2(a). When a vacuum was applied the centre of the slice was pulled into the cup as shown (b). This had two effects, firstly the deformation caused damage to the slice and secondly an air tight seal could not be maintained and the slice was dropped. To overcome this, a fine grill was fitted over the base of the vacuum cup (c). This allowed the slice to be lifted successfully, however, it did leave a pattern on the surface of the slice which would be unacceptable in a real product. This technique was also unsuited to handling tomato slices as the watery texture of the tomato meant it could still be sucked through the grill, damaging the product and degrading the grasp. For these reasons an alternative technique was required.

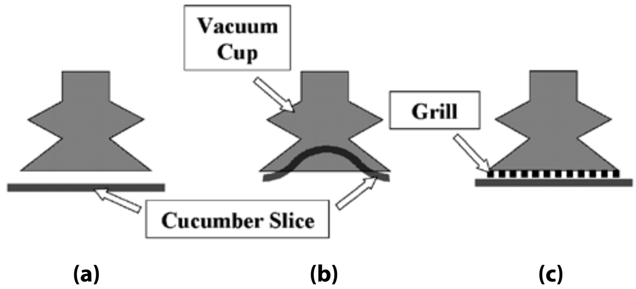
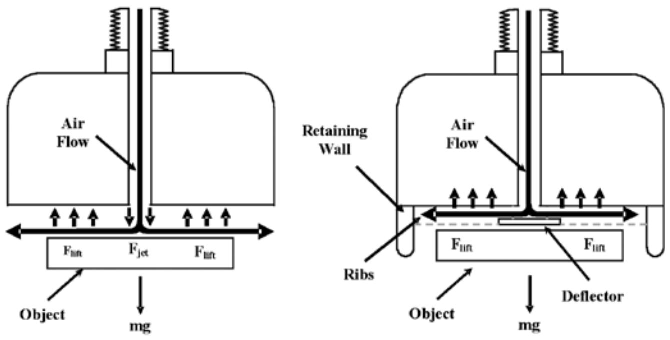


Figure 2 – Vacuum cup lifting cucumber slice.

For many years Bernoulli Effect-based grippers have successfully been used in a range of applications, although typically they have only been used to handle rigid materials. However, more recently, Erzincanli et al[4] explored the possibility of using the technique to handle non rigid materials and demonstrated the handling of slices of meats and textiles[5]. It was hypothesised that this same technique could be used to grasp slices of tomato and cucumber.

To explore this theory a prototype gripper was developed as shown schematically in Figure 3(a). The gripper consists of a flat gripping surface and a central channel through which pressurised air is supplied. Due to the driving force behind the air it travels through the channel and exits as a jet at the centre of the gripping surface. When an object is placed close to the gripping surface the air collides with the object and is deflected across its upper surface. In line with Bernoulli's principle this rapid flow of air produces a reduction in the pressure above the object and thus generates an attractive force.

This basic gripper is capable of grasping rigid objects with ease, but if the object to be handled is particularly delicate (such as tomato slices) gripping fails. The reason for this is the jet of air impacting on the object actually causes damage to the object and passes through it rather than being deflected by it. This means the rapid flow of air across the object's surface does not occur and no lift force is generated.



(a) **(b)**

Figure 3 – Operation of Bernoulli gripper.

Figure 3(b) shows how the gripper was redesigned to overcome this problem. Instead of relying on the surface of the object being grasped to deflect the air a small deflector was fitted to the surface of the gripper in the path of the air. This forced the air to travel across the gripper's surface irrespective of whether an object was placed within its reach[6]. It was found that this new design enabled delicate, non rigid and even porous objects to be grasped without becoming damaged.

In order to assess the grippers effectiveness at performing the assembly tasks a robot work cell consisting of a conveyor, an ABB Flexpicker robot and a vision system was created as shown in Figure 4. Tomato and cucumber slices entered the cell on a conveyor belt. The vision system was then used to identify the exact position of each slice and to determine if it was within the accepted size range. The position of the acceptable slices was fed to the robot controller to allow the robot to locate and pick each slice. Slices rejected by the vision system remain on the conveyor and are transported to a rejects bin.

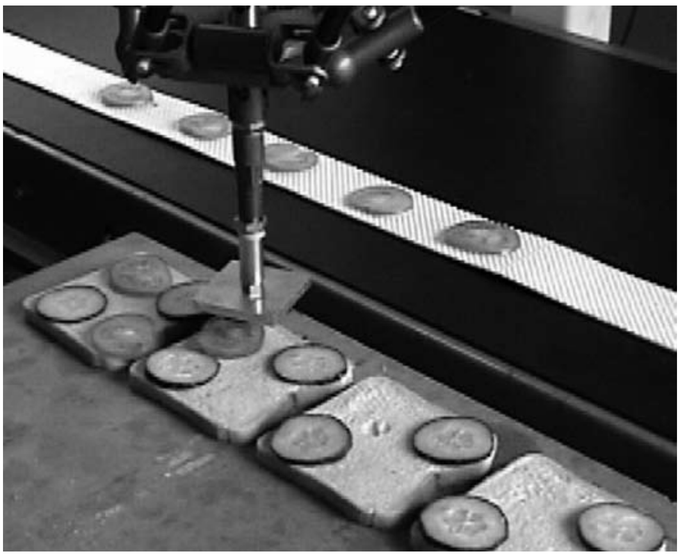


Figure 4 – Gripper mounted on robot.

Due to the cutting process the slices of tomato and cucumber have moisture on their surfaces after being cut. This needs to be removed before they can be placed in a sandwich since any moisture will produce a medium term degradation in the quality of the sandwich. Typically this is achieved by leaving the slices to stand in draining trays for a number of (>2) hours. However, it was observed that the gripper developed was able to remove the surface moisture from an object whilst handling it. This "drying" is achieved in a similar manner to an air knife where moisture is blown from an object by a high velocity jet of air[7]. Air knife technology is not uncommon in the food industry and is often found in the form of bottle driers. The high velocity air which is passed over the surface of the object being grasped causes any excess moisture to be blown from the object as it is being lifted.

The robot was programmed to perform a pick and place task and the velocities and accelerations were gradually increased to find the maximum pick rate. It was determined that a pick rate of 40 slices per minute could be achieved. This outperforms two human operators performing the same task. The slices were also dried during transit and placed with less damage than caused by a human operator.

The gripper has a number key benefits:

- The chance of damage to the product is reduced as the lifting force is spread over the entire product surface.
- Then product is lifted from above, eliminating damage caused by having to slide fingers under product.
- The whole surface is supported hence fragile parts such as tomato centres do not drop out.
- Air flow over the product removes excess moisture.
- As positive pressure is used rather than a vacuum, debris is not sucked into the air lines and there is a significantly reduced risk of baterial contaimination.

4 Topping

The process of topping the sandwich involves taking a buttered slice of bread, inverting it so that the buttered side is facing downwards and then placing it on top of the semi complete sandwich below.

A number of end effector designs were tested[8]. The most basic of these consisted of a square plate mounted on a rotary joint. The slice of bread is placed on the plate and the joint is then activated. This rotates the plate through 180° about the horizontal axis. There is no physical bond between the gripper and bread so as the gripper is inverted the bread can slid off. However, if the motion of the gripper was sufficiently rapid the force generated due to acceleration hold the bread in place allowing it to be inverted. Through testing, it was discovered that the speed at which the gripper moved was critical to the success of the topping process. The speed which was found to give the best positional accuracy was 9 rad/s. However, although the average positional error relative to the target position was approximately zero at this speed, the angular error relative to the target varied by as much as ±10˚. This would be unacceptably high for a finished sandwich and for this reason an alternative end effector design was sought.

It was felt that if the bread could be held securely during inversion it could be positioned with greater accuracy.

Experimentation showed that the method of securing the slice of bread which caused least damage was a vacuum. The end-effector developed consisted of a flat vacuum paddle with a shallow slotted channel in its surface. The channel was positioned precisely so that when a slice of bread was placed on the paddle its edges covered this channel. Despite the fact that the bread is porous, when a vacuum was applied to the gripper it held the bread slice securely. Initial tests were conducted by mounting the end effector to a robot arm. This provided a quick and low cost method of determining whether the gripper would be able to grasp the bread securely during the motions required to perform the topping task. Once it had been proven that the gripper operated as intended a prototype machine was developed as can be seen in Figure 5.

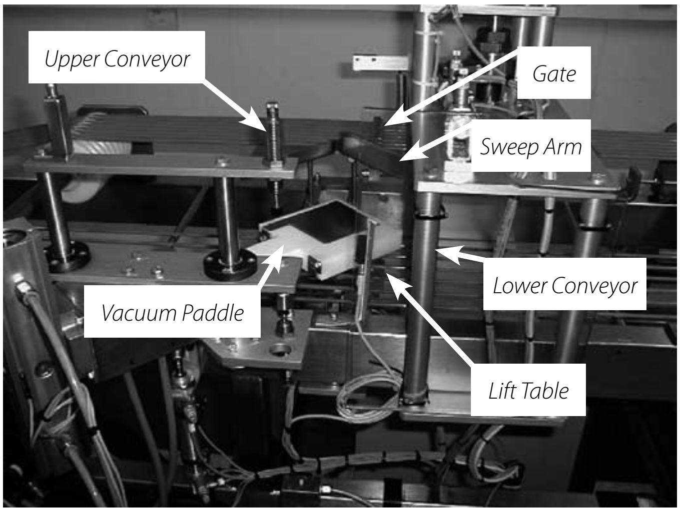


Figure 5 - Topping Workstation

The machine consists of two parallel corded conveyors. The upper conveyor is located 120mm higher than the lower one. The vacuum end effector is mounted on a two axis pneumatically powered manipulator which is able to raise and lower the paddle as well as invert it. The sandwich to be topped arrives on the lower conveyor and the paddle raises to allow it to pass below it. When the filled sandwich is directly under the paddle (detected by an infrared detector) a lift table extends between the cords and lifts the sandwich off the conveyor, thus halting its motion. The second buttered slice of bread travels along the upper conveyor and comes to rest against the gate. A photo sensor detects the presence of the slice of bread and activates the sweep arm. This causes the bread slice to slide off the upper conveyor onto the upper face of the raised paddle.

The vacuum paddle is then activated and grasps the slice of bread firmly against its upper surface. The gripper then rotates through 180˚ and lowers the now inverted top slice into place on the filled lower slice. The paddle continues to move slightly downwards which has the effect of slightly compressing the finished sandwich. The paddle then releases the bread and returns to the raised position. The lift table lowers allowing the topped sandwich to continue along the conveyor. To reduce the cycle time of the machine, the paddle was designed to have an identical vacuum gripper on both of its sides. This means that the rotary motion does not need to be reset after each topping action and therefore saves time allowing the machine to operate at far higher speeds than the 45 sandwiches per minute achieved by human operators.

5 Sandwich Clapping

After it is topped the sandwich is cut diagonally to form two triangular sandwiches. Before being inserted into a skillet the two sandwiches must be placed one on top of the other. This process is known as clapping. The most common method used by human operators to perform this task is to invert one of the triangular sandwiches and then place it on the top of the second sandwich. The operator must use their fingers to firmly clamp the sandwich to stop any filling from falling out as they manipulate it. At first glance it appears that this is not the best way of performing the task due to the high risk of filling falling out. However, it is the technique that places the least stress on the operator limbs and for this reason it is a technique used by all operators. For an automated system there is less concern about joint stresses and therefore replicating the actions of a human operator need not be seen as the driving goal.

The automated mechanism designed to perform the clapping task consist of a flat fork-like end-effector, known as a clapping hand, as seen in Figure 6(a)[8]. The gaps between each fork exactly matched the spacing of the corded conveyor on which the sandwiches are produced, allowing the gripper to be positioned below the conveyor whilst being supported from above.

The two sandwich halves approach the clapping machine on separate parallel conveyor. When the first passes above the clapping hand the hand raises and lifts it off the conveyor (b). The second sandwich continues past the clapping hand until it reaches a lift table. This rises through the cords of the conveyor lifting the sandwich clear and halting the motion. The clapping hand is then moved vertically so that its lower surface is fractionally above the height of the second triangular sandwich. The gripper then rotates 360° anti-clockwise about the vertical axis causing the sandwich on it to move through an arc (c). During this rotational motion the gripper passes below the "stripper" plate. This stripper plate is a metal barrier positioned at an appropriate height so that the hand passes under it but the sandwich being carried by the hand collides with it. When the stripper plate makes contact with the sandwich it pushes the sandwich off the hand and on to the first triangular sandwich located below (d).

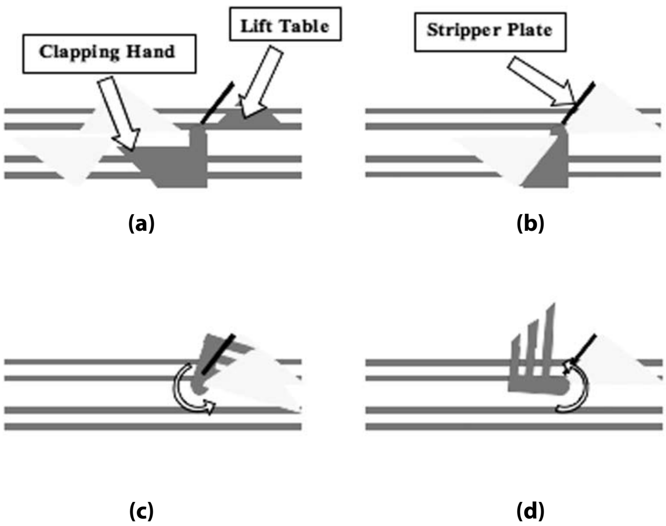


Figure 6 – Operation of clapping hand.

Experiments were conducted using different angular velocities and it was found that the accuracy of the clapping process deteriorated as its speed was increased. A minmum cycle time (for the full 360° rotation) of 1.8s (3.5rad/s) was found to give the "optimum" placement that allowed rapid placement but did not disrupt downstream packaging processes. At higher speeds the sandwiches became damaged due to the force of the impact with the stripper plate. At very high speeds the sandwich started to disintegrated during the rotational transit.

Based on these results the speed of the clapping mechanism was set to the optimum value identified. This gave a cycle time of 1.8 seconds meaning the mechanism could only produces sandwiches at a rate of 34 per minute. This was only slightly above half of the required target speed of 60 and for this reason two identical, yet independently operable, clapping mechanisms were used. This allowed one end effector to be clapping a sandwich as the other returned to its initial position. This effectively doubled the throughput of the machine meaning the prototype had a speed approaching 70 products per minute.

6 Conclusions

The objective of this research was show that the handling and assembly of food products was a process that could be addressed by robots and automation systems. In this instance the task was demonstrated through the development of end-effectors for use on an automated sandwich assembly line which is often considered to be one of the most difficult to systems to automate. The specific processes selected for automation were, ingredient placement, topping the sandwich and clapping two triangular sandwiches prior to packing. The work began by analysing how human operators perform the tasks and then designing automated solutions to perform the same tasks. It was observed that replicating the actions of the human operators with a machine did not necessarily lead to the ideal machine oriented solution.

Within the sandwich production scenario the particular area of development selected was for loose format sandwiches (chicken salad) having a series of individual products placements but no binding paste. One area within this type of production that has by tradition been particularly difficult to automate is the picking and placement of tomato and cucumber slices. To address this a new gripper was developed that operates using the Bernoulli principle. The reduction in air pressure caused by directing a high velocity air flow across the surface of an object produces a lifting force. This was found to be sufficient to lift both the tomato and cucumber slices without damaging them. The gripper is also capable of removing surface moisture from the object it is handling. This is achieved in a similar manner to an air knife where moisture is blown from the surface.

To top the sandwich two main approaches were tested. The most successful of these was a specially designed paddle which applied a vacuum generated force to the perimeter of a slice of bread placed on it. The paddle could then be inverted allowing the slice of bread to be lowered onto the remaining sandwich located below.

After completion the sandwich is cut to form two equally sized triangular sandwiches. After cutting and before packing these must be stacked one on top of the other before being inserted into a skillet. Replicating the way a human performs this task was not considered an appropriate solution. Instead a "clapping hand" was developed which lifted one of the sandwiches and rotated it about the vertical axis and then placed it on to the top of the second sandwich.

The performance of each of the processes was demonstrated through the development of a robot workcell or prototype machine.

This work has shown that robotic and automated solutions to tasks that are considered by the industry as being among the most intractable are possible with the correct development of end-effectors and design philosophies. It is believed that most areas of food automation could be addressed with a similar thorough scientific approach to the problems.

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