Robot prototyping in the design of food processing machinery

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Abstract
Purpose – Aims to show how robots can be used to prototype and prove key handling operations during the design of food processing machines. This can reduce both development time and costs.
Design/methodology/approach – A number of examples of the use of robots during the design of food processing machinery are presented in the areas of product handling, product manipulation and product packing. In each example simple grippers were mounted to robots allowing complex manipulations to be performed and rapidly tested allowing a favourite to identified.
Findings – Finds that robot prototyping and proving allows mechanisms to be assessed rapidly and at low cost and reduces the number of design modifications needed before final production.
Research limitations/implications – Provides examples of how the technique can be used in all stages of food production, particularly the grasping of products considered difficult to handle.
Practical implications – Provides a method of reducing the development cost of new food processing machinery and allow key operations to be proved without the need to construct full prototype machines.
Originality/value – Introduces the concept of using robots to prototype and prove operations found within food processing machinery. The paper is of value to both researches investigating the handling of food products and manufacturers of automation for the food industry.

Keywords Robotics, Rapid prototypes, Food industry, Automation

1. Introduction

When new industrial machinery is developed it has traditionally required extensive research and development before a final design is selected. During this time many prototypes may be developed, tested and then disregarded and this can be a long and expensive process. In an attempt to reduce costs and lead times the manufacturing industry is making increasing use of tools which aim to reduce the number of design iterations (Thompson et al., 1998). One of the most popular of these is computer simulation. However, due to difficulties in simulating the dynamics of many real world objects (Brooks, 1992) and particularly foods (Erzincanli and Sharp, 1997a) simulation is rarely able to prove the success of a real system.

An alternative approach is to use robots to test key handling and manipulation tasks found in a machine’s conceptual design. This allows complex kinematic and dynamic designs to be verified rapidly, at minimal cost and with actual food products. This allows a range of handling mechanisms to be assessed by developing robot end-effectors rather than complete machines.

This can lead to a superior final design since there is less financial drive to accept the first, but possibly not the best, successful design. Testing and proving the handling operations with a robot can increase the likelihood of the first prototype machine operating as intended.

This paper presents three examples where robotic prototyping has been used in machine design. These examples are, the automated handling of lasagne sheets, the development of a machine for producing sandwiches and a mechanism for placing lids on plastic strawberry punnets. Details of trials performed using the robots are given and it is shown how these results aided in the development of pre-production prototypes. In each of these examples simple tools or grippers are mounted to robots allowing complex manipulations to be performed.

2. Product handling

Traditionally in manufacturing, product handling is achieved using end-effectors from two general categories, clamping and attracting (Tella et al., 1982; Erzincanli and Sharp, 1997b). However, due to the nature of many food products these techniques often cannot be used (Erzincanli and Sharp, 1997b) and alternative approaches must be found.

One product, that has a reputation of being particularly difficult to handle, is fresh lasagne as it is non-rigid, fragile, wet and glutinous. Clamping type end-effectors cannot be used as they damage the surface of the pasta and so initial experiments were performed using a vacuum gripper similar
to that described by Kolluru et al. (1997). This consists of a flat plate with an array of holes across the surface allowing the lifting force to be applied across the entire surface of the gripper. This has the effect of minimising local forces and providing support to the sheet. Testing of this gripper showed that although it could successfully pick up the pasta when attempting to release it and deposit it in a tray, the moist starch residue on the surface of the pasta created an adhesion with the gripper plate which prevented reliably release. For this reason an alternative approach was sought.

The use of rollers is relatively common within the food industry, especially where the product being handled is sticky, such as dough or cherries (www.silsoetechnology.co.uk/end-effectors.html). As a roller passes over a product any bond between product and roller is broken as the roller peels away. It was hypothesised that such a technique could be adapted to handle sheets of pasta (Moreno, 2005). The conceptual design with the envisaged sequence of operations is shown in Figure 1.

The gripper is initially positioned so that the spatula arm, needed to lift the front edge of the pasta, is located close to the pasta sheet. The gripper then moves horizontally a short distance towards the pasta forcing the spatula under the leading edge of the sheet. The gripper continues moving in the horizontal direction and simultaneously rotates the roller. Providing the two motions are correctly co-ordinated the pasta should roll onto the roller in a controlled manner. To release the pasta and deposit it in a tray, it was suggested that the roller would simply be required to reverse the motions and rely on the weight of the sheet to cause it to peel free of the roller.

To determine whether the end-effector would operate as intended a simple prototype was created for testing on a CRS A460 6 axis robot (Moreno, 2005). A length of 50 mm diameter carbon fibre tube was mounted to the robot’s wrist to act as the roller. An aluminium spatula was constructed and then mounted to the roller as can be seen in Figure 2. A test program was then written which moved the robot through an appropriate horizontal path with simultaneous rotation of the wrist to allow a sheet of pasta to be lifted, Figure 2.

The robot software was written to permit testing of different translational and rotational profiles and velocities in both degrees of freedom. A number of trials were performed with the aim of proving the accurate and reliable lifting and depositing of the sheets, and subsequently optimising the final system design. The first element investigated was the angular velocity (0–2.26 rad/s) of the roller during pickup and release. In principle, successful handling was achieved at all speeds up to the robot’s maximum wrist rotational speed of 2.26 rad/s.

During system tests it was observed that there were four factors affecting the quality of the pasta pickup and release and these were (Moreno, 2005):

1. The distance the spatula was inserted beneath the pasta before rolling commenced (this has been termed the SWEEP).
2. The length of pasta sheeting left freely hanging from the roller after pickup ($L_{hang}$).
3. The size of the gap between the spatula and the roller ($d_1$).
4. The distance between the lowest point of the roller and the surface from which the pasta was picked ($d_2$).

Each of these issues was addressed experimentally by repeatedly running a pick and place routine. The success of the pickup and release motions was observed and any inaccuracy in placement was measured and recorded.

- **SWEEP effect.** It was noted that moisture and starch on the pasta sheet caused it to adhere to the spatula. This force is critical to the operation of the gripper as it secures the product when the rolling sequence begins. The magnitude of this adhesive force is proportional to the contact area between the pasta and spatula, determined by the distance SWEEP. To ascertain how this affected the performance of the gripper, tests were conducted using SWEEP values in the range 15-25 mm. It was found that larger SWEEP values aided pickup and smaller values increased the reliability of the release. The optimum compromise SWEEP was found to be 18 mm.

- **Length of unsupported sheet $L_{hang}$.** The gripper has no method to actively remove the pasta from the roller, instead it relies on the weight of the sheet to cause it to peel off when the roller is reversed. For this reason, during pickup the roller stops short of wrapping the entire length of the pasta sheet, leaving a short length hanging from the roller. When the roller is reversed the weight of this section of pasta causes it to gradually peel. The length of
the, hanging section of pasta should be minimised so as to lower the chance of the pasta tearing as it is accelerated during transit, however, if it is too short the pasta will not reliably release from the roller. Experimentation showed that the minimum length that allowed reliable release was 20 mm.

- **Effect of the spatula/roller gap.** The distance between the spatula and roller ($\delta_1$) had negligible effect on the gripper’s ability to pickup the pasta, however, if this distance were too small the pasta would remain trapped and not release fully. Similarly, if $\delta_2$ were too large then the pasta would slip off the spatula during pickup. The robot was used to perform tests using a range of values of $\delta_1$ and $\delta_2$. It was found that 4 and 3 mm, respectively, produced the most consistent results (Table I).

The result of the trails using the robot allowed a pre-production prototype to be constructed with the parameters identified using the robot. The prototype was pneumatically powered using a single rotary actuator to power the roller and two pneumatic cylinders to position the gripper relative to the pasta sheet. This prototype was able to accurately lift a sheet of pasta and placed it in a plastic ready meal tray in just 3.6 s. The machine constructed is shown in Figure 3 and is sufficiently low cost that nine identical machines could be used to produce ready meals at a rate of 60 per minute.

3. Product manipulation

Many food products require that their component parts be manipulated during production and the manufacture of sandwiches is a good example of this. Whilst the actions for sandwich making are straightforward for a human operator, automating the processes can present significant difficulties. This section describes how robot prototyping was used in the design of two of the processes used in an automated sandwich production line.

3.1 Sandwich topping

During sandwich production, fillings are placed one at a time onto a single piece of bread. The sandwich assembly is then completed by the placement of a secondary bread slice on the top of the sandwich. The latter process is known as topping. Prior to topping, the upper side of this second bread slice is coated in a layer of butter and often mayonnaise meaning it must be inverted before placement on the lower “filled” slice. A number of different end-effector designs, to perform this task, were tested using a Puma 560 robot. The first design tested can be seen in Figure 4. It consists of a flat 100 mm$^2$ plate on which the slice of bread is initially positioned, Figure 4(a). The gripper is mounted on a rotary joint, in this case the robot’s wrist, which when driven through 180° causes the gripper to invert. As there is no physical bond between the gripper and bread as the gripper inverts the bread slides off. However, if the motion of the gripper is sufficiently rapid the force generated due to acceleration holds the bread in place allowing it to be inverted as seen in Figure 4(b).

The speed at which the gripper moves is critical to the success of the inversion process as a movement that is too slow will cause incorrect positioning of the bread due to slippage. The robot provides an ideal method of assessing this need as the speed profile of the wrist can be controlled precisely. Also the high repeatability of the robot means experiments can be reproduced exactly. To measure the accuracy to which the gripper could position slices of bread a simple program (<10 lines of code) was written to invert a slice on to a printed grid. This then allowed both the angular error and the translational errors relative to an ideal, to be determined. Figure 5 show the results of tests conducted with increasing angular velocities. Test were repeated 100 times and the highest, lowest and average misalignment was recorded. It can clearly be seen that the accuracy of positioning increased with velocity, to the point where there was almost zero average angular error at a wrist rotational velocity of 9 rad/s. It was found that as the speed was increased still further the accuracy began to again decrease. The optimum speed was found to be in the region of 9 rad/s. However, although the average positional error at 9 rad/s was approximately zero the range of angles measure varied in the range $\pm$ 10° which was unacceptably high. The reason for this appears to be that as the bread is not secured to the end-effector it is able to move relative to it and therefore introduce misalignments. For this reason an alternative end-effector design was sought that would grasp the bread during inversion.

The next end-effector design tested used a vacuum gripper to grasp the bread. The gripper consisted of a 130 $\times$ 125 mm polyacetal “paddle” as can be seen in Figure 6. A narrow channel is cut in the face of the paddle to form a rectangle slightly smaller than that of the bread slice. When a small vacuum is applied to the gripper, the air pressure in the channel reduces, and in contact with a bread slice the pressure differential across the two sides of the bread creates a grasping force. This was found to be effective in spite of the “porous” nature of bread. To invert the bread a slice must first be placed on the surface of the gripper with the coated side facing up. The gripper then rotates 180° about its central axis and then lowers the slice onto the sandwich base below. To test the performance

![Figure 3 Pre-production prototype during trials](image)
of the gripper it was again mounted to the Puma robot and a series of tests conducted as seen in Figure 6(a).

As the bread is held, the air flow causes moisture to be removed, and this can be quantified by measuring its mass before and after handling. The longer the bread is held the drier it becomes and ultimately this makes it unfit for sale. It is therefore critical that the length of time for which the bread is held be kept as short as possible. Experiments were again performed using the robot to invert the gripper and place the bread slice with increasingly higher velocities. It was found that the gripper was able to hold the slice securely during all velocity profiles and that the amount of moisture loss was insignificant for grasps of less than approximately 1 s.

Owing to the success of these trials this end-effector design was chosen for inclusion on the final pre-production prototype, Figure 6(b). The use of the robot enabled the initial end-effector to be designed, tested, redesigned and ultimately dismissed within days and at minimal expense. Had the pre-production prototype been built without this design step, the cost, both financial and in terms of time, would have been significantly higher as a substantial proportion of the machine would need redesigning.

3.2 Sandwich clapping
After the sandwich has been assembled it is sliced diagonally to form two triangles which must then be stacked one on top of the other (a process known as clapping) before being packed into a plastic skillet. The process of inverting the filled and topped sandwich is simple for human workers with
dexterous fingers but to achieve a similar inversion using machine end-effectors is a daunting task.

The first end-effector design tested is shown in Figure 7. The sandwich is placed on a corded conveyor, which allows access to its underside between the cords. A small clapping arm then reaches between the cords and lifts the leading edge of one half of the sandwich from the conveyor. The arm then follows a predetermined path that causes the first triangular sandwich to invert and come to rest on the top of the second as can be seen in Figure 7.

To test this theory a simple aluminium rod was mounted to the wrist of the Puma robot, which allowed it to reach between the conveyor cords and make contact with the sandwich. Paths were then programmed to perform the clapping action. It was found that although the upper sandwich located on the top of the lower one, it is orientation differed from that of the lower sandwich. Experimental results showed that this variation was in the range 37 to 36° which was unacceptable and for this reason the method was abandoned.

Based on the difficulty of achieving a clapping action consisting of moving the sandwich from the horizontal to the vertical and then back to the horizontal a new technique was proposed requiring only a horizontal rotation. This is not typically attempted by humans as it places undue strain on the wrists and forearms.

As a result of these experiments a second clapping method consisting of a flat fork-like end-effector was developed. The gaps between each fork exactly matched the spacing of the corded conveyor allowing the gripper to be positioned below the conveyor whilst being supported from above as seen in Figure 8. When a sandwich arrives on the conveyor the end-effector raises and lifts it off. The end-effector is 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. During the rotational cycle the gripper passes below the clapping guide. This vertical guide makes contact with the sandwich triangle and pushes it off the end-effector and on to the sandwich below. The triangles of the sandwich are now one on top of the other completing the clapping process.

Experiments were conducted using the Puma robot to control the motion of the end-effector, with different paths and speeds being tested. It was found that the accuracy of the clapping process deteriorated as its speed was increased as shown in Table II. A maximum cycle time (for the full 360° rotation) of 1.8 s (3.5 rad/s) was found to give the “optimum” placement that did not disrupt downstream packaging processes (misalignments of less than 10° are passively corrected as the sandwich is placed into the skillet). At higher speeds the impact between the sandwich and the guide caused a bouncing that moved the sandwich or dislodged the filling. At very high speeds greater than 8 rad/s the sandwich started to disintegrated even before contact with the guide.

Based on these results a pre production prototype was produced which used a stepper motor to rotate the clapping mechanism with its speed being set to the optimum value identified using the robot. This cycle time of 1.8 s meant the mechanism could only produce sandwiches at a rate of 34 per minute, which is significantly short of typical targets of 60. 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.

### Table II Clapping process tested a various cycle times

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<thead>
<tr>
<th>Cycle time (s)</th>
<th>Angular misalignment (degrees)</th>
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<td>Best case</td>
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4. **Product packaging**

The final stage of any food production process is packaging the goods for dispatch to customers/retailers. Often it is here
that a robot is most likely to be found as the products are usually very regularly shaped and located outside of high care environments meaning current technology can be used. Installation of a robot is not always the best solution and it is more common to install purpose built machinery, however, the use of robotic proving and prototyping is as applicable here as in the two previous examples.

The soft fruit industry is an example of a food sector that can benefit from automated packaging. In recent years there has been a move to standardise the design of punnets in which much fruit is packaged and this broadens the market for potential machine builders. Whilst systems are available for the automatic application of punnet lids these are considered not suitably reliable and too slow by many in the industry. For this reason, a study was conducted to investigate alternative approaches to this problem.

Analysis of the actions of human operators placing lids on punnets revealed that the most common approach was to lower the lid at an angle of a few degrees from above the punnet. Clips on each corner of the lower edge of the lid then easily mate with the rim of the punnet before the opposite edge is forced downwards securing the two remaining clips. Subconsciously the operators are monitoring the forces between punnet and lid and continually adjusting their actions to achieve the correct positioning. This ability is not typically available to the robot, which in most instances simply follows a routine and if there is any error in the position of the lid, placement may fail.

Tests were performed using a CRS robot to compare a number of different approaches to placement of the lids. A gripper was developed which grasped the punnet lid using two small vacuum cups, this ensured that the lid could not rotate on the gripper. The robot was then programmed to replicate the actions of the human operator. It was found that although the robot positioned the lid correctly it was unable to consistently latch all four clips. The reason for this was that when the lid was resting on the rim of the punnet the vertical force applied by the robot would on occasion deform the lid rather than mate each of the clips. A redesign of the gripper added a flat plate (135 × 175 mm), the same size as the lid, which made contact with its entire surface spreading the forces, Figure 9.

This increases the reliability of the lid application significantly. This method of applying the lid required adjustment of both the vertical height and the pitch of the lid during placement. While this is simple to achieve using a robot, a mechanism to achieve the same motions is likely to be complex and therefore costly. For this reason, experiments were performed to determine if the lid could be applied using purely a vertical motion.

Owing to the increased force that would need to be applied to the punnet (to latch all four clips simultaneously) a structure was developed to support the punnet around its rim as can be seen in Figure 9(a). This meant that when a vertical force was applied to the punnet, the structure, rather than the sides of the punnet, which could buckle, absorbed the pressure. This technique proved highly reliable and caused no damage to either the punnet or lid. However, the need to support the punnet would reduce the speed of any machine developed as there would be a delay whilst the support was positioned and then retracted and so trials were conducted to determine if there really was a need for the support structure. The same procedure was repeated with the only difference being the absence of the punnet support, Figure 9(b). It was found that the lid could still be placed reliably and critically no damage was evident to the sides of the punnet. Repeated use of the same punnet did eventually cause minor damage after ≈ 30 uses but as in reality each punnet would only be used once this was not considered a problem.

The accuracy with which the lids were positioned was critical to successful operation of the machine, incorrect positioning of the lid would prevent the clips mating and prevent proper closure. To determine the tolerances within which the lid must be placed to ensure successful operation a range of robot paths were tested during the lidding process. This enabled both translational and rotational misalignments between punnet and lid to be tested as each path had a successively larger misalignment. Each path was tested 50 times with the number of failed closures being recorded. A single failure within the 50 tests was considered unacceptable and allowed the maximum allowable misalignments to be identified as can be seen in Table III.

**Figure 9** Punnet lid placement with (a) and without (b) rim support
The tolerances identified during the robot trials were then used to develop a simple machine which forced the lids onto the punnets from above. Ensuring that the machine met these specifications meant that when it was constructed it operated as intended removing the need for potential system redesign.

### 5. Conclusions

This paper has shown how robots can be used during the design of food processing machinery. Many of the individual processes required can be prototyped using a robot arm and a customised end-effector. Tests can then be conducted to assess the suitability and reliability of the proposed solution. Three examples have been presented that have used this approach.

In the first example an end-effector for the automated handling of lasagne sheets was described. Tests conducted using the robot allowed the optimum value for each of the four parameters identified as being critical to the success of the gripper (SWEEP, \( L_{\text{hang}} \), \( d_1 \) and \( d_2 \)) to be identified. Furthermore, the range and speed of motions required to lift the lasagne were identified and this lead to the production of an automated machine, considerably simpler than the robot, consisting of two linear and one rotary pneumatic actuators.

The second example presented concerned the development of a system for the automated construction of sandwiches. Two processes were considered, topping and clapping. In both cases simulation using a robot showed that the reliability of the initial solutions would not be suitably high and both were redesigned. It was determined that during the topping process the slice of bread being handled should be securely held to ensure accurate positioning and a vacuum gripper was developed. Further tests using the robot were conducted to determine the maximum operational velocity of the final clapping mechanism. The results of these tests were then used to construct a piece of dedicated automation to perform both tasks.

The final example presented looked at the placement of a lid onto a plastic soft fruit punnet. An end-effector was developed to grasp the lid and this was then mounted to a robot. The robot was then programmed to place the lid on the punnet with a range of both translational and rotational misalignments. By repeating the program many times it was possible to identify the tolerance with which the lid should be placed to ensure successful closure. A dedicated machine was then developed to these tolerances to perform the lidding task.

In each of the examples presented the use of robots allowed mechanisms to be tested without the time and expense of building full prototype systems. Tolerances and critical design parameters were identified which meant that when full prototypes were constructed it could be guaranteed with a high level of confidence that they would operate reliably and as intended. This then reduced the number of design modifications needed before final production.

### References


### Further reading


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