Proceedings of the 2nd World Congress on Mechanical, Chemical, and Material Engineering (MCM'16)
Budapest, Hungary – August 22 – 23, 2016
Paper No. ICMIE 121
DOI: 10.11159/icmie16.121

Robotic Tray-Handling in Medical Chewing Gum Production

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Abstract **-** This work presents a robotic solution to the automation of medical chewing gum production. The automation requirements are defined based on the discussions with the industrial customer, and then the concept design of a robotic system is conducted. In this paper, a robotic gripper has been developed to handle the trays in medical chewing gum production, and has been integrated to a safe and lightweight Universal Robot manipulator. The experimental testing has been performed using a UR5 robot arm to simulate the tray-handling in the process of medical chewing gum production: picking up, rotating, and placing down. The testing results are analyzed and demonstrate that the developed robotic solution and gripper meet the required tray-handling performance. The solution is accepted by the industrial partner for production testing.

Keywords**:** Gripper Design, Robotic Handling, Grasping, Dynamics

1. Introduction

Robots have been widely employed to provide solutions to the automation in industrial manufacturing and production (electronic, automobile, medicine, food, etc.), medical surgery, biological manipulation, health and housing care, laboratory research, undersea exploration, aerospace operation, nuclear waste disposal, military action etc. The demand for industrial robots is increasing due to the accelerating trend towards automation all over the world. According to the report from IFR (international federation of robotics), industrial robot sales have increased by 9% on average per year since 2002 [1].

The medical chewing gum producer (Fertin Pharma) in Denmark has been motivated to develop robotic solutions to automating existing manual production processes. One of the existing manual production processes is transporting chewing gum products using trays. Besides the high laboring cost, the manual tray-transporting process leads to the situation where it is challenging to follow the strict regulation of FDA and GMP and to meet the high throughput requirements. The final goal for the production is to achieve unmanned production factory environment.

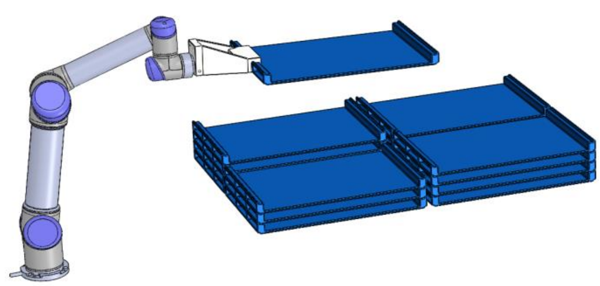

Fig. 1. Robotic tray-handling for chewing gum transportation.

It is critical to design an appropriate gripper (end-effector) for robotic operations as the robots don’t work without grippers. Significant efforts have been devoted to the development of robotic grippers for macro and micro manipulations in industrial manufacturing or production and medical/healthcare applications [2-10]. However it is difficult, if not possible, to find commercialized universal grippers that are capable of grasping and handing different objects as human hands do. Therefore, a variety of industrial grippers need to be developed to meet the different industrial manipulations. One of the important tasks for this project is to develop a robotic gripper and integrate the gripper into a robotic system for tray-handling. The challenges include the complex features of the tray side, strict FDA and GMP regulations, high speed (short cycle time).

In this work, a robotic solution is proposed to automate the chewing gum transporting process that currently is conducted manually in Fertin Pharma. A robot gripper is designed and manufactured. The developed gripper is integrated into a safe and light weight UR5 robot. The experimental testing of tray handling has been conducted to demonstrate that the robotic solution being developed in this work is ready for the onsite production testing. The project is completed by the students who were attaching the course Robotics offered by Department of Engineering and Aarhus School of Engineering at Aarhus University with collaboration and supports from the production industry engineers.

2. Concept Design of a Robot System

2.1. Tray-Handling Tasks and Requirements

Based on the analysis of the medical gum production processes, one laborious process that needs to be automated using a robot manipulator is handling the tray loaded with nicotine gum coming from an oven and being glazed. As shown in Figure 1, the tray-handling involves the manipulations: 1) picking up a tray from a tray-stack which has multiple tray-layers (up to 45). Each tray-layer consists of 4 trays that stay close each other. Each tray is loaded with chewing gums sitting on one sheet; 2) lifting up the tray, and dumping the chewing gum with the sheet together into a conveyor; 3) placing and palletizing the empty tray at another location, and forming a tray-stack with tray-layers, each of which has four trays to stay close each other; 4) repeating the above steps until the production is done. The tray-handling requires: no contamination (strictly follow FDA standard)-no vacuum, and no damage to product, trays etc.; no vision system because of environment limitations; materials for gripper following the FDA regulations; limited velocity and acceleration of handing motion to prevent the gum sheets slipping from the trays; no contact or touching to chewing gums and the sheets; less than 0.8 micro meter for the roughness of contact area; grippers featured with being waterproof, no leakage, and easy to clean; less than 80 dB noise level (measure one meter away); 10 second for handling cycle time. The weight of the tray with gum products plus a sheet is around 3.8 kilograms. To automate the process, a robot manipulator should be selected and a robot gripper should be designed and fabricated to handle the trays.

2.2. Robot Manipulator Selection

To achieve the defined manipulation and requirements, a Universal robot UR5 is finally selected to conduct the tray-handling task. The major reason is that the universal robots are lightweight and safe. As a result there is no need to build safety cell which needs time-consuming cleaning routines. The other reasons include that Universal robots are easy to set up, operate, maintain etc. The UR5 robot is a six Degree-of-Freedom (DOF) robot manipulator, and its major specifications include 850mm reach, 5 kilogram payload capability, 0.1mm repeatability etc.

2.3. Gripper Design and Manufacturing

The challenges of designing a gripper to handle the trays include: 1) the trays might not be aligned well on the tray-stack. The maximum misalignment can be up to 50mm; 2) the edge of the tray is featured with complex geometry, and limited area for grasping; 3) trays stay very close to each other (each layer has four trays) on the pallet. To overcome these challenges, the gripper jaws should be designed to adapt the complex geometry of the tray edge, gripper mechanism and actuator should apply appropriate contact force to guarantee that the tray is clamped tightly, and the gripper and trays are not to be damaged. The gripper should be small-size and low-cost as well. The sensors should also be selected and integrated to the gripper to prevent the mishandling due to the large misalignment of tray-stacking.

1) Gripper Design and Evaluation: Based on the tray-handling requirements, three concepts of grippers are proposed for the final consideration of gripping, as shown in Figure 2. Concept A is to achieve a one-piece-structure of gripper for the simplicity and low-cost. No actuation is needed for gripping. The gripping is conducted by taking advantage of the gravity of the gripped tray plus loaded chewing gum. The gravity makes the tray and gripper produce contact force at the two contact points to provide lifting and holding forces for gripping the tray. The disadvantage is that the tilting angle of the tray is limited because the griping and lifting forces become zero when the tilting angel is 90º. Concept B is to achieve the high gripping stability and reliability. One linear actuation is added to generate lifting and holding forces for tray-handling. Compared with Concept A, Concept B has cleaning issues but the cleaning issues can be solved by adding a piece of rubber or plastic membrane to cover the actuation piston. Concept C is to design a two-moving-piece-structure for clamping the tray along both horizontal and vertical directions. This concept design provides the flexibility of gripping as the two jaws have controllable relative motion along both horizontal and vertical directions. Compared with Concepts A and B, Concept C design has complex structure that will lead to cleaning issues.

To choose the final concept design for the tray gripping, a weighted-comprehensive evaluation strategy is made based on four major performance indices corresponding to the four design criteria. The score allocated to each index Si is set with the minimal score: one and the highest score: five. The weighting coefficient Wi for each index is set from one to zero based on the priority and importance to the tray-handling task. The total score of a concept is calculated as $S = W_i \cdot S_i$. The concept with the highest score is chosen as the final gripper design.

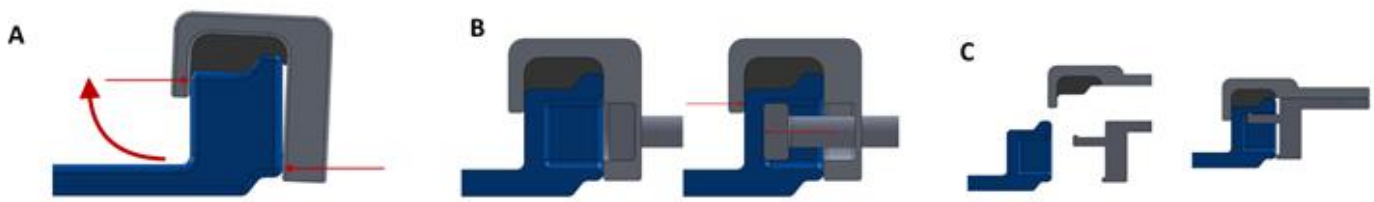

Fig. 2: Three concepts of grippers for lifting and holding a tray: a) Gravity-based actuation one-piece-structure gripper, b) Linear actuation gripper with stable lifting and holding forces, c) Two-moving-clamping-structure gripper.

Table 1: Evaluation of the design concepts.

Index Weight	Gripping 1	Hygiene 1	Speed 0.7	Reliability 1	Total score -
Concept 1	1	5	4	5	13.8
Concept 2	4	3	5	4	14.5
Concept 3	5	2	2	2	10.4

The four major performance indices are chosen based on the detailed analysis of the tray-handling and chewing gum production requirements. With the consideration of the priority and importance of fast gripping, easy to clean, and steady gripping etc., the four performance indices: gripping, hygiene, speed, and reliability are employed to decide the final concept design. The four indices and the scoring are defined in this work as: 1) Griping is defined as the tool's capability of holding and lifting trays in a steady and locking way during production. The concept design that has a higher risk of slipping or moving between a gasped tray and the gripper will be scored with a lower point. The weighting coefficient of gripping is set to be one because the gripping capability and stability is essential for the tray-handling; 2) Hygiene is defined as the easiness of cleaning. Based on the regulation of pharmaceutical industrial production, proper hygiene has to be obeyed to design a gripper. Furthermore it is mandatory that that the tool does not contaminate the product with, e.g. oil, shaving etc. The hygiene is of highest importance to the tray-handling in chewing gum production, and therefore the score of the hygiene index is weighted on a scale of one; 3) Speed is defined as how fast the gripper grasp the tray for lift and rotation. The cycle time is required to be reduced as much as possible to increase productivity. Low cycle time requires firm gripping and fast sequences of handling the tray. Additionally the moving speed of the mechanical parts in the gripper is also considered in weighting the score. The weighing factor of the speed index is included and set to be 0.7 because the high-speed of gripping is important, but not as essential as the griping capability, and the hygiene factor based on the discussion with the engineers of the company; 4) Reliability is defined based on the possibility against the failure during the long term operation with consider manufacturability, assembly, fatigue etc. The tray-handling is a repetitive process of a large production line, and hence the reliability is critically important, and should be included by weighting on a scale of one.

Based on the definition of indices and scoring strategies, the total scores of each concept design are calculated and summarized in Table1. The table shows that each concept has its own strengths and weaknesses. Concept C scores maximum in terms of gripping, but it is not as good as Concepts A and B in terms of hygiene, speed, and reliability. Concept A has the best performances in terms of hygiene, speed, and reliability. However it has the fatal weakness in gripping due to the lack of stable and controllable grip forces, especially during the rotation of a tray. Concept B has the highest overall score and performs best in terms of the four major evaluation indices. Concept B is simple enough to keep clean and strong enough to handle the tray in a fast and steady manner. Furthermore the design based on Concept B has fewer mechanical parts leading to that the reliability of Concept B is high. Finally Concept B is used to design and fabricate the gripper for tray-handling.

2) Force analysis: The force analysis of the gripper is conducted: (1) for calculating the gripping force (actuation, friction, and contact) to lift and hold the tray during the production; (2) for verifying that the maximum contact force will not damage the gripper or the tray.

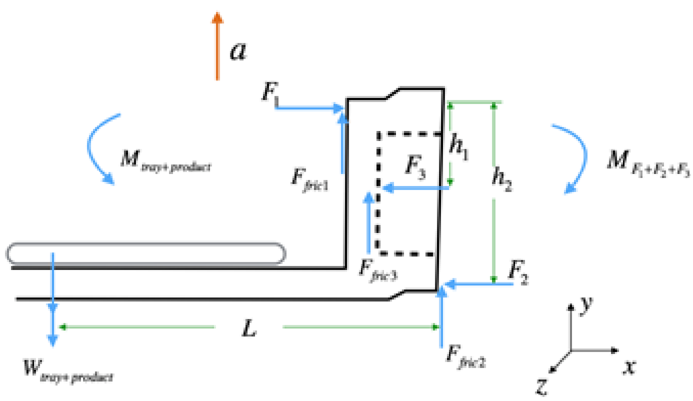

Fig. 3: Force analysis of the tray orientated at horizontal direction.

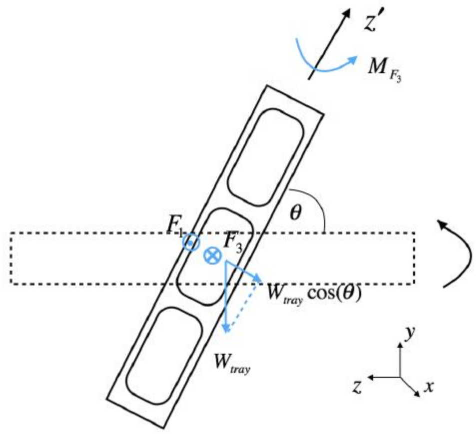

Fig. 4: Force analysis of the tray tilting around x-axis at θ angle (viewed from A direction in Fig. 3)

The schematic diagrams of the tray force analysis are given in Figs. 3 and 4. To estimate the actuation force F_3, two following critical scenarios are considered to estimate the actuation force F_3 . Minimum F_3 estimate: the important step for the proposed tray-handling is to tilt the tray to a certain angle θ so that the chewing gum product is dumped into the conveyor. The critical scenario can be illustrated by the following force balancing equations when that there is no acceleration for the tray and no actuation,

$$\left(W_{tray} + W_{product}\right)L \cdot \cos(\theta) = F_2 \cdot h_2 \quad (1)$$

$$W_{tray} = (F_1 + F_2) \cdot \mu \quad (2)$$

$$F_1 = F_2 \quad (3)$$

where W_{tray} and $W_{product}$ are the weight of the tray and the product, L the distance from the center of the tray to its edge, h_2 the distance between from the rotation point to F_2, and μ the friction coefficient. Equations (1)-(3) clearly shows that the tilting makes the contact forces (F_1 and F_2) between the tray and gripper decrease with the increase of the tilting angle θ , and the friction forces between the tray and gripper decrease to be not large enough to hold the tray. To achieve the required tilting angle, the actuation force F_3 is needed to generate the contract forces and friction forces.

Minimum F_3 estimate: the actuation force F_3 can not be too large as it could lead to the flipping of the tray around z′ direction. The critical scenario can be shown by the following balancing equations when that there is no acceleration for the tray,

$$W_{tray} \cdot L\ \cos(\theta) = F_3 \cdot h_1 = M_{F_3} \quad (4)$$

Equations (4) demonstrates that a very large actuation force F_3 leads to $W_{F_3} \geq W_{tray} \cdot L\ \cos(\theta)$, and hence the tray flips around the axis z′.

To summarize, the actuation force F_3 should be: (1) large enough so that the tray can be tilted a required large angle to dump the products onto the conveyor but keep hold the tray tightly (enough large friction forces between the tray and the gripper); (2) less than the actuation force calculated from Equation (4) so that the tray does not flip around z'. In addition, it is desirable to achieve the well-distributed stress for the tray. Therefore, the actuation force F_3 is estimated and chosen to be 260N.

A dynamic analysis is then conducted to define the maximum force acting on the tray during operation with the consideration of the acceleration a_y of the tray as below:

$$(g + a_y)(m_{tray} + m_{product}) = (F_1 + F_2 + F_3)\mu \tag{5}$$

$$(g + a_y)(m_{tray} + m_{product})L = F_2 \cdot h_2 + F_3 \cdot h_1 \tag{6}$$

$$a = \Omega \times (\Omega \times R) + \dot{\Omega} \times R \tag{7}$$

Where a is the acceleration vector of the tray $(a_x, a_y, a_z, \emptyset_x, \emptyset_y, \emptyset_z)^T$, Ω is joint angular velocity vector of the robot , R is the link length vector of the robot arm. The maximum linear acceleration of the tray is estimated to 5.891 m/s^2 based on the specification and kinematics of the UR5 robot. The contact forces F_1 and F_2 are estimated to 580 N and 320 N, respectively.

The contact force F_1 acts at the surface with the area $645.5 mm^2$. The generated maximum surface stress is estimated to be 0.90MPa that is less than the tensile strength 40MPa of the tray material (polystyrene) and the gripper material (ABS). The friction coefficient μ is estimated based on the dynamics, and it should be larger than 0.05. The friction coefficient between ABS and polystyrene is approximately 0.1-0.3, and make the friction force large enough to lift and tilt the tray without the failure with the consideration the maximum acceleration. The maximum tilting angle is estimated to be 53° (it is large enough to dump the chewing gum) without the risk of flipping the tray.

3) Actuation and sensing: Based on the selected concept design of the gripper, a linear actuation should be provided to generate enough large clamping force so that the gripper can stably and tightly grasp trays during the production. Major factors that are taken into account for selecting the actuation method include: low cost; ease and simplicity of being manufactured, assembled, cleaned, and controlled; small size so that the lowest tray stacked on the pallet can be picked up and the payload to the robot manipulator can be reduced as much as possible. The pneumatic cylinder is finally decided to employ for the gripper. Norgren RM-28025-M-25 is selected based on the required opening range of the gripper.

To implement the automation of tray-handling during the production, position or displacement sensors need to be integrated into the system: to locate the trays whose position and orientation vary, especially the top ones of the stacks as they might have the largest position and orientation deviation. The laser or ultrasonic sensors are decided as the two suitable solutions with the consideration of the production environment (dust interference, lighting condition etc.) and simplicity. The robotic gripper solution with ultrasonic sensors is under onsite production testing.

4) Fabrication and mounting: The prototype of the gripper is fabricated using 3D printing so that the one-piece-structure gripper can be made simple and easy for cleaning and control, as shown in Fig.5. The gripping surface of the gripper has to match the geometry of the tray edge which has a complex surface profile. 3D printing is chosen to fabricate the gripper as 3D printing allows a high complexity of geometry for the gripper design, and it has advantages, such as fast production, high accuracy, a low cost at production of small batches etc.

The optimization of the geometry is conducted to achieve the tradeoff between the strength and weight. The experimental testing is conducted and shows that the actuation force of 260N generated by the pneumatic cylinder actuator is sufficient to hold the tray with a payload of 1.6 kg. The material used is natural (uncoloured) ABS, which is a hard plastic with a good strength and stiffness. Natural ABS is compatible to FDA regulation. One of the disadvantages of 3D printing is the resulted rough surface due to the layers of plastic. However, surface roughness can be improved using available techniques such as sanding, bead blasting, and vapour smoothing. All these technologies are applicable to ABS.

The surface area of the piston head should be as large as possible to increase contact with the tray and avoid damaging it. Since the piston head needs to fit in the recess of the tray, the size of it is limited to fit the dimensions of the recess 105 mm x 17 mm. To gain large tolerances, the dimensions of the piston head is chosen to be 88 mm x 16 mm (a surface area 1324 mm^2).

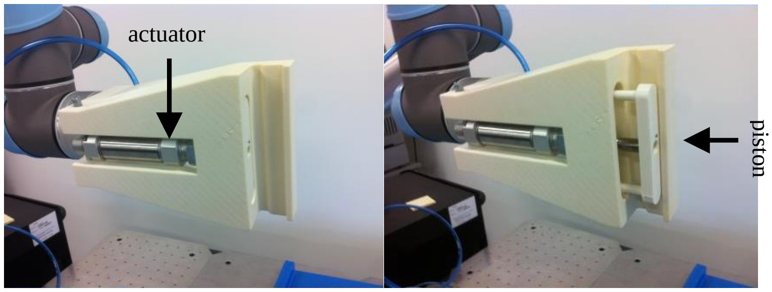

Fig. 5: The photos of the 3D-printed gripper mounted on a UR5 robot (release and grasp).

3. System Setup and Experimental Testing

To validate the developed gripper and robotic solution to the automation of tray-handling, an experimental setup is established using a Universal Robot experimental system. As shown in Fig. 6, the experimental system setup consists of a UR5 robotic manipulator and its controller with pneumatic regulation system for the linear actuator (a pneumatic cylinder Norgren RM-28025-M-25), the developed gripper mounted to the wrist of the UR5, and a tray used for the chewing gum production provided by Fertin Pharma. Three experiments were conducted to test the performance of the gripper, to simulate the work tasks in the chewing gum production, and to investigate how the gripper performs in each step of the production cycle. The maximum angular velocity of the UR5 robot is 183.33^o/s, and the maximum angular acceleration is 250^o/s^2. Experimental velocities and accelerations are set in terms of the percentage of the maximum values in the control panel of the teaching pendant.

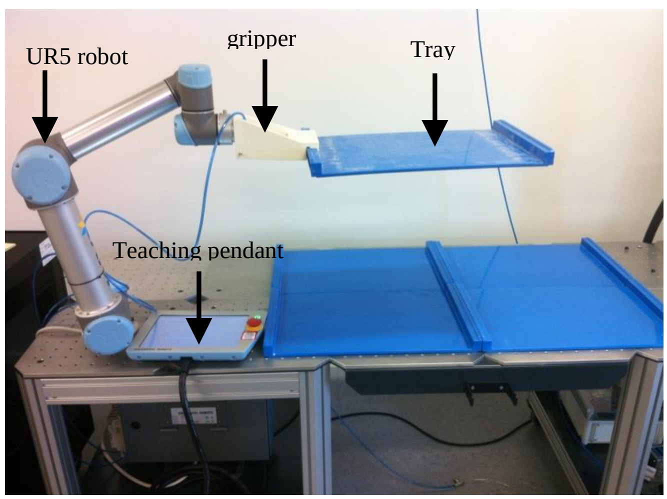

Fig. 6: Experimental setup consisting of a robotic manipulator, a controller, the prototype of the gripper, and a tray.

3.1. Experiment I: Lifting and carrying capability

The first experiment was conducted to test the gripper's capability of lifting the tray from the rest position and carrying a payload. The testing was performed as shown in Fig. 7. The manipulator first approached the tray that situated on the steel table, and then grasped it at one side and lifted it up. At Position C, payload (weight) was incrementally added to the tray to test the strength of the gripper. With the consideration of the maximum load capability of the UR5 manipulator of 5 Kg, the payload 1.6 Kg was added to the tray (weight of the tray 3.4 kg). No more than 1.4 kg of chewing gum is placed on the tray during operation, and a payload of 1.6 kg is sufficient to test the gripping and holding capability of developed the gripper. When the loading on the gripper is increased, the weight was placed at as far as possible to the gripper thus resulting in a larger momentum. The time from Position A to Position C is measured and recorded together with the success or failure of the grasping. The experiment was repeated five times with increased speed. The velocity and acceleration do not exceed 33% since the experiment was preliminary to test the overall performance. The grasping time and success or failure results of the experiments are listed in Table II. All of five tests succeeded with the shortest time of 3.32s at 33% velocity which demonstrates that the gripper is capable of grasping and lifting the tray at required velocity to meet the production requirements.

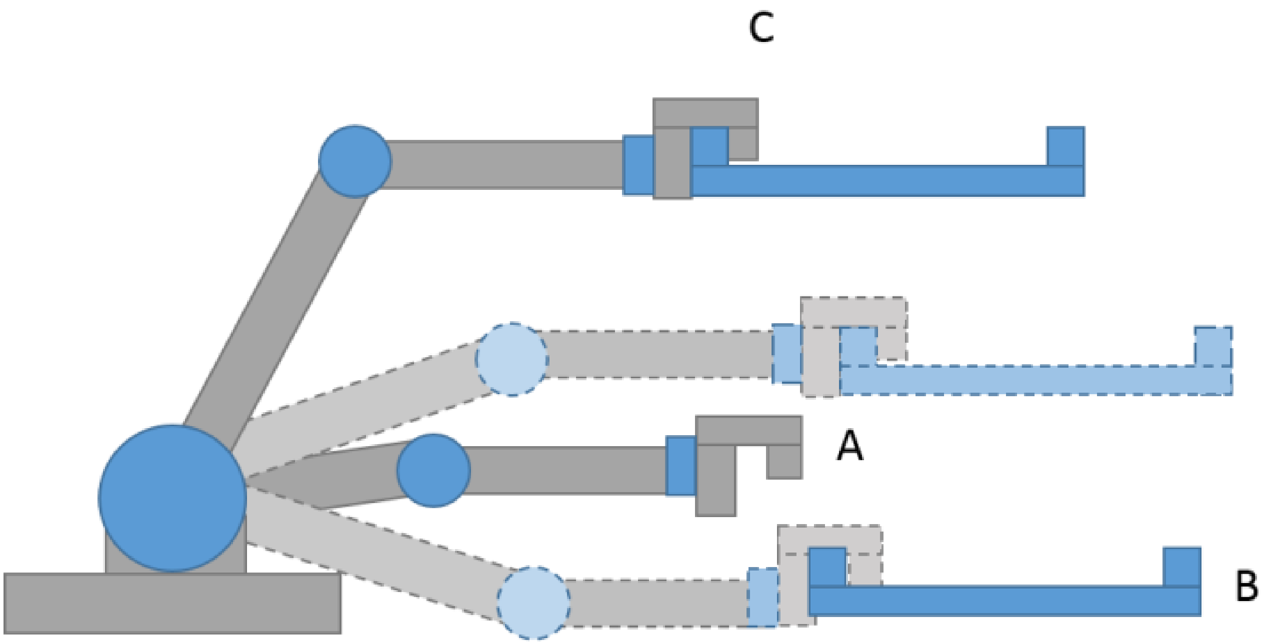

Fig. 7: Steps in experiment I: a) The gripper approaches the tray, b) The gripper grasps the tray and lifting is initiated and c) the tray is successfully lifted.

Table 2: Results of Experiment I: velocity.

Velocity (%)	Acceleration (%)	Time (second)	Successful grasp
7	7	16.75	✓
13	13	8.85	✓
20	20	5.85	✓
26	26	4.5	✓
33	33	3.32	✓

Table 3: Results Experiment: payload.

Payload, g	Successful
0	✓
320	✓
640	✓
960	✓
1280	✓
1600	✓

The testing results of the second part of Experiment I are shown in Table 3 where the payload of the tray was increased incrementally with 320g. The results illustrates that the gripper is capable of carrying a payload of 1.6 kg.

3.2. Experiment II: Movement of the gripper

The second experiment was conducted to validate the fast motion of the gripper as a rapid execution of the work task is desired. The experimental strategy is shown in Figure 8 where the tray is manipulated for a half of circle and tilted to 60º to simulate production requirements. The steps in experiment II are: the tray was lifted by the manipulator in a horizontal position; The manipulator rotated 90º, the tray was tilted 60º, and then the tray was returned to horizontal orientation; The tray reached the end position after rotating another 90º. The experiment was repeated five times by incrementally increasing the velocity of the manipulator but making the velocity and acceleration not exceed 33% of the maximum. The time for running and successfulness were recorded for each step. Successfulness is defined as if the gripper is capable of holding the tray steadily throughout the movement.

The results of experiment II are listed in Table IV. All five experiments succeeded and demonstrated the gripper was capable of grasping the tray at all time during the movement. The cycle time of handling the tray was achieved to be 5.09 second when the testing was run at the velocity of 33% of the manipulator's maximum speed.

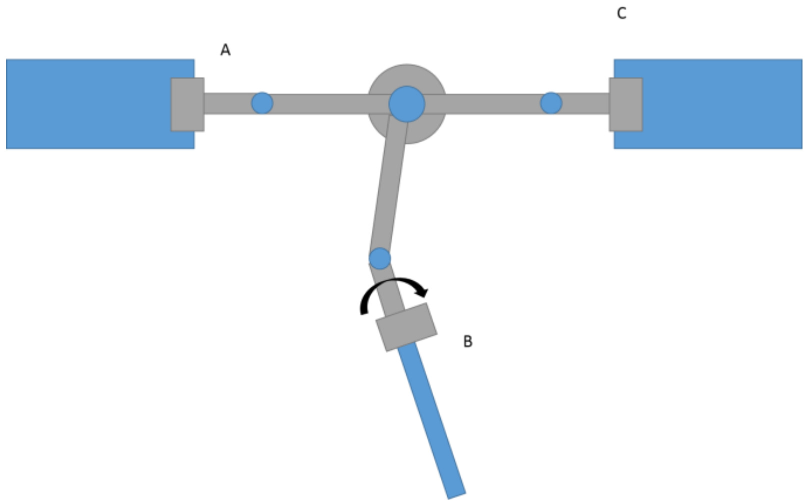

Fig. 8: The Schematic diagram of Experiment II (Top view of the manipulator).

Table 4: Results from movement experiment.

Velocity (%)	Acceleration (%)	Time (second)	Successful grasp
7	7	26.46	✓
13	13	12.62	✓
20	20	8.79	✓
26	26	6.03	✓
33	33	5.09	✓

Table 5: Results of Experiment III.

Velocity (%)	Acceleration (%)	Time (second)	Successful grasp
40	40	9.28	✓
48	48	8.63	✓
60	60	7.65	✓
70	70	7.14	✓
100	100	5.81	✓

3.3. Experiment III: overall performance

Experiment III was conducted to investigate the overall performance of the gripper during a full task cycle and validate a rapid execution (less than 10s) of it. The testing combined the tasks in Experiment I and Experiment II. The manipulator first approached the tray, and grasped and lifted the tray. The manipulator then rotated the tray for a half of circle and tilted the tray at 60°. Finally, the manipulator placed the tray down and released it. The experiment was repeated five times with increasing velocity. However, this experiment differs from Experiments I and II by increasing the velocity either until the maximum capacity of the manipulator or until the gripper was not capable of grasping the tray.

The results of Experiment III are listed in Table V. The velocity reached up to the maximum velocity of the UR5, and the gripper never failed in griping for five tests. With maximum running velocity, the cycle time of the task was 5.81 s which proves that the end-effector is capable of implementing the operations at required cycle time and payload. However, the testing results may change a little bit in the onsite production since the company uses a UR10 that has the maximum velocity 120 °/s compared to the maximum velocity 183.33°/s of the UR5. Based on the kinematic analysis and the difference in velocity, it is estimated that the cycle time 8.85s can be achieved using UR10 robots.

4. Discussion and Conclusion

This paper reports a robotic application in chewing gum industries. A robotic solution has been proposed to automating tray-handling, a laborious process in medical chewing gum production. A gripper has been designed and fabricated. The gripper was integrated into the selected UR5 robot manipulator. The tray-handling testing was conducted using a UR5 robot system equipped with the developed gripper. Testing results demonstrate that the developed robotic tray-handling solution can meet the production requirements. The concept design has been accepted by the industrial partner, and the onsite production testing is ongoing.

Acknowledgements

The authors wish to thank all the other students attending the course Robotics at Aarhus University in fall 2014 and the engineers of Fertin Pharma for their discussions and inputs.

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