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ON THE DEVELOPMENT OF A COMPLIANT GRASPING MECHANISM FOR ON-LINE HANDLING OF LIVE OBJECTS, PART I: ANALYTICAL MODEL

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ABSTRACT

This paper presents the design, modeling and analysis of a novel compliant mechanism for automating the process of transferring live objects from a moving conveyor to a moving processing line. Unlike industrial man-made objects, natural objects are typically characterized by varying sizes and shapes in batch processing and their natural reflexes (or voluntarily motion) contribute to the overall dynamics. The dynamic model of the manipulating system consists of two parts; namely, the forces acting on the object and the natural reflexes of the live object to the manipulation. In Part I, an analytical model is presented to predict the forces/moments acting on the live objects. Part II describes the design and development of an experimental setup and the experimental investigation of live broilers' natural reflexes to mechanical singulation, and evaluates the ability of the compliant grasping mechanism for handling live broilers.

1. INTRODUCTION

Many processing industries of natural products require transferring of live objects from conveyors to moving processing lines. The repetitive task of transferring live objects from a conveyor to a moving processing line is often laborious, unpleasant and hazardous and thus an ideal candidate for automation. The challenge here is to develop design criteria for machines to enable live natural objects to be handled without causing damage or stress and yet be able to meet the production throughput requirement at reasonable cost.

In the poultry industry, the task requires individuals to grasp a live bird by one or both legs and insert both legs into a shackle on a moving conveyor line. Conveyors typically run at speeds of 180 shackles per minute and require about 8 people to fill the lines with birds. The birds are usually moved to a dark room to quiet them down to facilitate grasping and hanging them. The dark room, in combination with high-speed conveyors, dust, feathers, pecking and scratching from the birds provides for a hazardous working environment and has the potential for a variety of injuries. There is the potential for workers to suffer injuries if they get their hands or fingers caught in the moving shackle line. There is also the possibility for a variety of respiratory and visual ailments resulting from the high level of dust and feathers that come off the birds. The birds tend to flail about when they are caught which sometimes results in cuts and scratches which can easily become infected in that environment. The unpleasantness of this task sometimes results in high turnover rates at some plants, which requires constant retraining of new employees. In addition, it is also extremely difficult to attract new workers to the job. This makes the live-bird transfer task an ideal candidate for automation.

Although the demand to automate hanging of live birds at the processing plant has been high, a recent survey has indicated that little or no practical solutions are yet available to adequately address the problems of automating the hanging of live birds. Most studies conducted to date that are relevant to live hang problem have been done on an empirical basis and results assessed subjectively. Extensive reviews of prior work in related areas can be found in a number of references (Kettlewell *et al.* 1985; Scott, 1993; Thornton, 1994).

The contributions of Part I of this paper are briefly summarized as follows: (1) The design concept of a compliant grasping mechanism has been developed for singulating and manipulating live objects. The mechanism provides a means to temporarily constrain the live objects to permit on-line handling while they are moving in the processing line. The flexibility provides an effective means to accommodate a limited range of varying sizes and shapes and to adapt the natural reflexes of the object. (2) A detailed model of a flexible finger has been developed analytically. The model serves as an engineering basis for design, modeling and control of the compliant mechanism. It also provides a basis for predicting the forces and analyzing the system dynamics of the compliant mechanism. (3) We apply the concept of compliant grasping to live broiler handling using the concept of counter-rotating fingers. (Broilers or meat chickens are reared in large groups of up to 30,000 broilers in environmentally controlled houses. They are typically transported from the growing farm to the poultry processing plant at 5-8 weeks of age, when they weigh about 1.25 – 3kg. Food is usually withheld for 8-12 hours, water 1 hour before catching to reduce risk of carcass contamination at the processing plant.) Unlike the poultry harvester (Briggs *et. al*, 1994) where the rotating bristles are designed to drive the broilers into a cage at the farm, the broilers must be orientated to allow grasping of legs for transferring them live onto moving shackles at the poultry processing plant.

The remainder of this paper is organized as follows: Section 2 presents the design concept of a compliant grasping mechanism for automated transfer of broilers. Sections 3 and 4 provide a detailed model to describe a flexible finger on a rotating frame and its application to singulation of live broilers respectively. The conclusions are given in Section 5.

2. DESIGN CONCEPT OF A ROTATING COMPLIANT GRASPING MECHANISM

Figure 1 shows a conceptual layout of an automated system for transferring live broilers from a moving conveyor to shackles in a processing line.

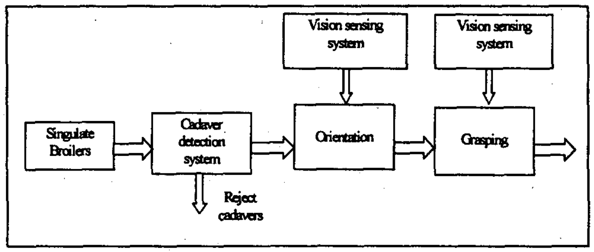


Figure 1 Conceptual Automated Transfer System

A typical cycle of the system begins with the incoming broilers unloaded from cages onto a moving conveyor. The conveyor transfers the broilers through a singulating system so that the broilers leave the singulating system in a single file. Next, the singulated feed is led through a cadaver detection system, which detects and removes cadavers from the feed. Then, the singulated broilers are directed to an automated transfer system, which inserts both legs of the broiler into an awaiting shackle for subsequent transferring to a processing line.

Of particular interest in this transfer problem is the design, modeling and control of a compliant grasping mechanism with flexible fingers for singulating, manipulating, and grasping of live broilers. The grasping mechanism consists of three main components as shown in Figure 2; namely, a drive system, a pair of rollers, and flexible fingers. The rollers, which are hollow cylinders, hold the fingers in place and transfer torque from the drive motor(s) to the fingers. Each of the rollers carries n columns of evenly spaced rubber fingers. The rollers driven by servomotors rotate at the same speed but in opposite direction. The rollers are spaced such that only one object can pass through at a time, yet the fingers are compliant to accommodate a range of sizes and shapes.

Figures 3(a)-(c) show some other potentially useful applications of such a compliant grasping mechanism:
1. singulating (Figure 3a) objects into single file,
2. rejecting cadavers (Figure 3b) from the feed,
3. sorting the singulated objects by orientation, and re-orienting the singulated objects (Figure 3c) so that all the broilers face the same direction.

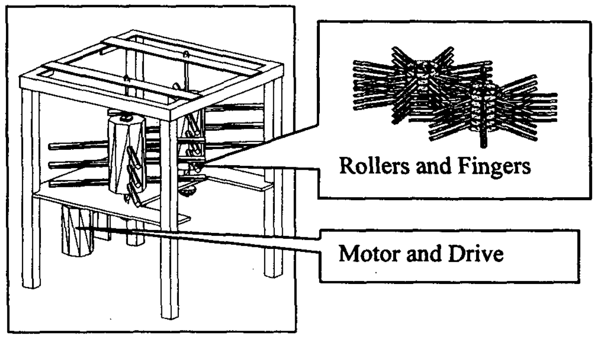
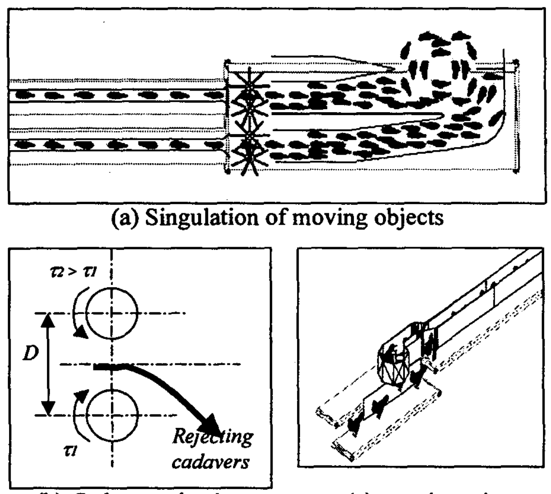


Figure 2 CAD models of the grasping mechanism



(a) Singulation of moving objects

(b) Cadaver rejection (c) re-orientation

Figure 3 Example applications

In operation, the entry conveyor feeds the object to the rollers, which grasps the object by the fingers and presents it for subsequent handling on the exit conveyor. The pose of the object on the exit conveyor depends on the finger configuration of the grasping mechanism, which is designed to meet the requirements of subsequent processes. The design parameters include (1) the number of fingers and their spacing, (2) the properties of the fingers, (3) the spacing between the rollers, (4) the orientation of the rotating axes, and (5) the height, inclination and the relative distance of the conveyors with respect to the grasping mechanism. The operating parameters are the torque and speed of the rollers, and the feed rates of the entry and exit conveyors.

3. MODEL OF COMPLAINT GRASPING MECHANISM

When the finger is in contact with an object, the reaction force causes the finger to deflect. It is of interest to determine the deflection of the finger due to the contact force exerted at an angle α with respect to the x-axis for a given object's position and orientation. In this section, the kinematics of the fingers on a rotating coordinate frame is described and a model to relate the contact force on the finger to the deflected shape is outlined. which serve as a basis for force analysis and design of a compliant grasping mechanism.

3.1 Equation of a Flexible Finger

The deflection of the rubber finger at the contact point with the object can be modeled as a bent elastic rod as shown in Figure 4. The basic equations for the deflection of a flexible finger can be modeled using the elastic bar theory described by Frisch-Fay (1962):

$$x = \frac{1}{k}\left[2p\sin\alpha(\cos\varsigma - \cos\xi) - h(\psi_o)\cos\alpha\right] \qquad (1a)$$

$$y = \frac{1}{k}\left[2p\cos\alpha(\cos\varsigma - \cos\xi) + h(\psi_o)\sin\alpha\right] \qquad (1b)$$

where $$k = \sqrt{\frac{f}{EI}}; \qquad (2)$$

E is the Young's modulus; I is the moment of inertia of the finger respectively;

$$h(\psi) = \left[F(p,\xi) - F(p,\zeta) - 2E(p,\xi) + 2E(p,\zeta)\right] \qquad (3)$$

$$\varsigma = \sin^{-1}\left[\frac{\sin(\alpha/2)}{p}\right]; \qquad (4a)$$

$$\xi = \sin^{-1}\left[\frac{\sin[(\psi+\alpha)/2]}{p}\right]; \qquad (4b)$$

$$p = \sin[(\psi_o + \alpha)/2] \qquad (5)$$

and where $F(p,\varsigma)$ and $E(p,\varsigma)$ are Legendre's standard form of the first and second kinds:

$$F(p,\zeta) = \int_0^{\zeta} \frac{d\zeta}{\sqrt{1-p^2\sin^2\zeta}} \qquad (6a)$$

$$E(p,\zeta) = \int_0^{\zeta} \sqrt{1-p^2\sin^2\zeta}\, d\zeta . \qquad (6b)$$

Equations (1a) and (1b) describe the shape of the finger with ψ as a parametric variable for a specified force f as shown in Figure 4. The point of contact (x_f, y_f) can be computed by noting that $\psi = \psi_o$ and thus $\xi = \pi/2$. The modulus p, which governs the deflected shape of the finger, is related to the property of the finger by

$$kL = \left[F(p, \pi/2) - F(p,\zeta)\right] \qquad (7)$$

where L is the arc length along the finger between the fixed end and the point at which the force is exerted. If L is a constant, Equation (5) yields the value of ψ_o.

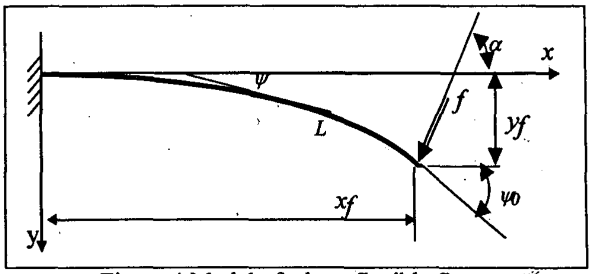


Figure 4 Model of a bent flexible finger

3.2 Kinematics of the rotating finger

Figure 5 shows the coordinate systems for describing the kinematics, where XYZ is the fixed (reference) coordinate frame attached at the center of a rotating cylinder, with its Z-axis along its rotating axis. In Figure 5, the coordinate frame x_C-y_C is the body coordinate frame of the object. The fingers are attached at the circumference of the rotating cylinder, where x_f-y_f is a moving coordinate frame attached at the base of the finger. When the object is in contact of the finger, the contact point (x_i, y_i) on the finger can be described with respect to the fixed reference frame by Equation (8):

$$\begin{bmatrix} X_i \\ Y_i \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}\begin{bmatrix} x_f \\ y_f \end{bmatrix} + \begin{bmatrix} X_r \\ Y_r \end{bmatrix} \qquad (8)$$

where $\phi(t) = 2\pi - \omega t$ and ω is the angular speed of the roller;

$$(X_r, Y_r) = (r\cos\phi,\ r\sin\phi); \qquad (9)$$

and r is the radius of the rotating cylinder. Similarly, the same contact point on the object can be described with respect to the reference frame by Equation (10):

$$\begin{bmatrix} X_i \\ Y_i \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} x_c \\ y_c \end{bmatrix} + \begin{bmatrix} X_o \\ Y_o \end{bmatrix} \qquad (10)$$

where θ is the orientation of the $x_C y_C$ coordinate frame; and (X_O, Y_O) is the center of the ellipse with respect to the body reference frame.

The contact point (X_i, Y_i) between the finger and the object must satisfy the equations that characterize the finger and the object, which can be described with respect to the reference frame using Equations (8) and (10) respectively. In addition, the finger and the object share the same tangent line at the contact point.

For a specified object geometry, the equation of the tangent line at the contact point (X_i, Y_i) on the object can be written as

$$Y = \sigma X + \beta, \tag{11a}$$

where σ and β are the slope and the intercept of the tangent line with respect to the reference frame respectively. Similarly, the tangent line at the contact point on the finger on the finger has the following form:

$$y_f = (\tan\psi_o)x_f + c. \tag{11b}$$

From Equation (8), we have

$$\begin{bmatrix} x_f \\ y_f \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} + \begin{bmatrix} X - X_r \\ Y - Y_r \end{bmatrix}.$$

Thus, $$\tan\psi_o = \frac{\sigma\cos\phi - \sin\phi}{\cos\phi + \sigma\sin\phi}. \tag{12}$$

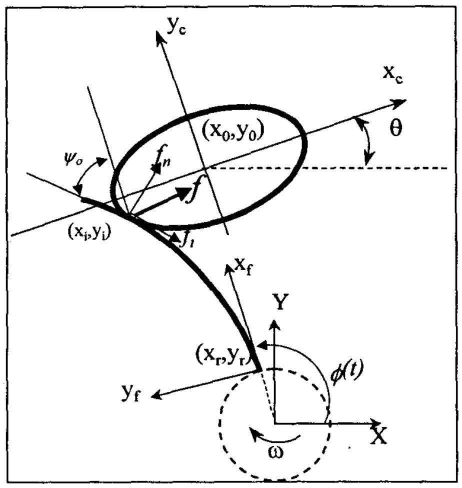


Figure 5 Kinematic model of the finger/ellipse interaction

3.3 Contact force/moment on the object

When the roller rotates, the finger exerts a force equal to

$$\vec{f} = \frac{-\tau}{\sqrt{X_i^2 + Y_i^2}}(\vec{i}\sin\phi_i - \vec{j}\cos\phi_i) \tag{13a}$$

on the object at the contact point (X_i, Y_i), where the angle

$$\phi_i = \tan^{-1}\left(Y_i / X_i\right); \tag{13b}$$

τ is the applied torque about the shaft; $\vec{i}$ and $\vec{j}$ are the unit vectors in X and Y directions respectively. In Equation (13), the torque is considered positive in the counter-clockwise (ccw) direction. The reaction on the finger is acting at an angle α equal to $\pi/2 - (\phi_i - \phi)$.

The normal and tangential components of the contact force, perpendicular to and along the direction of the tangent line at the contact point, are respectively given by

$$f_n = |\vec{f}|\cos(\phi_i - \tan^{-1}\sigma) \tag{14a}$$

$$f_t = |\vec{f}|\sin(\phi_i - \tan^{-1}\sigma) \tag{14b}$$

For a positive grasp, $\mu f_n > f_t$ in order to prevent the finger from slipping past the object, where μ is the static coefficient of friction between the object and the finger.

The contact force tends to cause the object to rotate about its center due to the moment

$$\vec{M} = \vec{d} \times \vec{f} \tag{15}$$

where the displacement $\vec{d}$ from the object center to the point of the contact force can be determined by noting that the force is acting along the direction perpendicular to the straight line from the rotational axis of the roller to the contact point. Thus, we have

$$\vec{d} = \left|\frac{\tan(\phi_i - \pi/2)(Y_i - Y_o) + (X_i - X_o)}{\sqrt{1 + \tan^2(\phi_i - \pi/2)}}\right|(\vec{i}\cos\phi_i + \vec{j}\sin\phi_i) \tag{16}$$

4. APPLICATION TO SINGULATION OF BROILERS

Figure 6 shows a computer-controlled singulator, which use the flexible grasping mechanism to separate the broilers into a single file for subsequent handling processes.

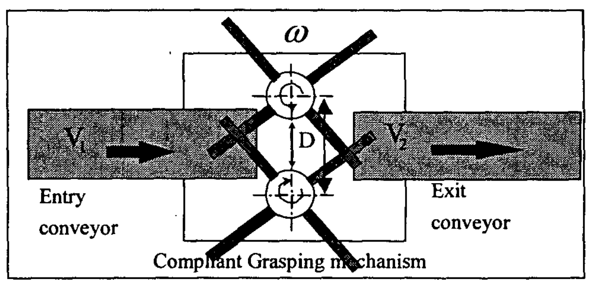


Figure 6 Schematic of the compliant grasping system

The system consists of an entry conveyor, a compliant grasping mechanism, and an exit conveyor. The compliant grasping mechanism is essentially a pair of counter-rotating rollers with flexible fingers. In Figure 6, the second roller is located at the coordinates (X=0, Y=D) with respect to the first roller, which rotates in the clockwise direction. Both the rollers rotate with the same speed ω but in opposite directions.

In the following discussions we model the forces/moments acting on the broiler by a single finger on a rotating coordinate frame. It is expected that the model can be extended to a combination of rollers with multiple fingers. Since the relative locations of the rollers are known, the net force acting on the object along each axis can be determined from the vector sum of the individual forces with respect to a common reference coordinate frame.

4.1 Geometrical Model of a Broiler

In order to analyze the motion of the broiler independent of its natural response, the broiler is modeled as a rigid ellipsoid:

$$\frac{x^2}{\eta^2}+\frac{y^2}{\lambda^2}+\frac{z^2}{\gamma^2}=1 \tag{17}$$

where η, λ, and γ are constants characterizing the broiler's dimension. In Figure 5, the ellipse is a cross-section of the ellipsoid (broiler) by a plane at $z_c = z_i$ and $|z_i| < \gamma$ given by

$$x_c^2+\rho^2 y_c^2 = a^2 \tag{18}$$

where $x_c y_c$ is the ellipse body coordinate frame; $\rho^2 = \frac{a^2}{b^2}$; $a^2 = \eta^2[1-\frac{z_i^2}{\gamma^2}]$; and $b^2 = \lambda^2[1-\frac{z_i^2}{\gamma^2}]$.

Using the coordinate transformation, the equation of the ellipse with respect to the reference frame is given by

$$\begin{bmatrix}(X-X_0)\cos\theta + \\ (Y-Y_0)\sin\theta\end{bmatrix}^2 + \rho^2\begin{bmatrix}-(X-X_0)\sin\theta + \\ (Y-Y_0)\cos\theta\end{bmatrix}^2 = a^2$$

or

$$A_1(X-X_0)^2+A_2(X-X_0)(Y-Y_0)+A_3(Y-Y_0)^2=a^2 \tag{19}$$

where $A_1 = \cos^2\theta+\rho^2\sin^2\theta$;

$A_2 = (1-\rho^2)\sin 2\theta$;

and $A_3 = \sin^2\theta+\rho^2\cos^2\theta$.

4.2 Determination of Initial contact point

For a given object location and orientation (X_O, Y_O, θ), the initial contact point can be determined by noting that the finger is initially straight before coming into contact with the ellipse. Thus, the initial contact point can be obtained by finding the intercept of Equation (11) with $\beta = 0$ and Equation (19) or

$$X^2-2a_1X+a_0=0 \tag{20}$$

where

$$a_1=\frac{X_oA_1+\frac{1}{2}(Y_o+\sigma X_o)A_2+\sigma Y_oA_3}{A_1+\sigma A_2+\sigma^2A_3} \tag{20a}$$

$$a_0=\frac{X_o^2A_1+X_oY_oA_2+Y_o^2A_3-a^2}{A_1+\sigma A_2+\sigma^2A_3} \tag{20b}$$

The general solution to Equation (20) is $X_{io}=a_1\pm\sqrt{a_1^2-a_o}$. We are interested in the specific solution where the straight line describing the finger is tangent to the ellipse at one point. This solution corresponds to

$$a_1^2=a_o$$

which can be shown to be

$$\sigma^2+\left(\frac{d_oA_2-2d_1d_2}{d_oA_3-d_2^2}\right)\sigma+\left(\frac{d_oA_1-d_1^2}{d_oA_3-d_2^2}\right)=0 \tag{21}$$

where $d_0=X_o^2A_1+X_oY_oA_2+Y_o^2A_3-a^2$

$d_1=X_oA_1+\frac{1}{2}Y_oA_2$

and $d_2=\frac{1}{2}A_2X_o+A_3Y_o$.

The choice of the solution depends on the direction of the angular rotation with respect to the object. For the kinematics shown in Figure 5, both the slope and the coordinate X_{IO} have a negative value. Once the initial slope is found, the coordinates are given by $X_{IO}=a_1$, and $Y_{io}=\sigma X_{io}$. The forces and its components as well as the moment acting on the object can then be computed from Equations (13)-(16).

4.3 Determination of subsequent contact points

Once the finger deflects under the contact force, it is no longer straight but both the object and the finger share the contact point and have a common tangent line. To solve for the contact point and forces, we express the ellipse with respect to the finger frame. By substituting (X_i, Y_i) from Equation (8) into Equation (19), the resulting equation of ellipse with respect to the finger frame becomes

$$b_1x_f^2+b_2y_f^2+b_3x_fy_f+b_4x_f+b_5y_f+b_6=0 \tag{22}$$

where $b_1=A_1C_\phi^2+A_3S_\phi^2+0.5A_2S_{2\phi}$,

$b_2=A_1S_\phi^2+A_3C_\phi^2-0.5A_2S_{2\phi}$,

$b_3=-A_1S_{2\phi}+A_3S_{2\phi}+A_2C_{2\phi}$,

$b_4=2A_1(X_r-X_o)C_\phi+2A_3(Y_r-Y_o)S_\phi+A_s(Y_rC_\phi+X_rS_\phi)$

$b_5=-2A_1(X_r-X_o)S_\phi+2A_3(Y_r-Y_o)C_\phi+A_2(Y_rS_\phi+X_rC_\phi)$

$b_6=A_1(X_r-X_o)^2+A_3(Y_r-Y_o)^2+A_2(X_r-X_o)(Y_r-Y_o)-a^2$

where $S_\phi=\sin\phi$ and $C_\phi=\cos\phi$.

The finger shape under deflection (x, y) are given by Equations (1a) and (1b) in terms of the slope ψ_0 and the reaction force f which causes the finger to deflect. Theoretically, the contact point and force can be solved from a set of seven equations. These equations include the four finger Equations (1a), (1b), (4a), and (5) where $\psi = \psi_o$ and $\xi = \pi/2$ describe the finger deflection at the contact; the equation describing the direction of the reaction force or Equation (13b); and the other two equations related to the ellipse. They are the ellipse Equation (22), and the equation relating the slope of the elliptic and the finger at the contact point. The corresponding 7 unknowns are x_i, y_i, k, ψ_O, α, p and ς.

To reduce the problem to a more tractable form, the finger shape could be approximated by a hyperbolic function as follows:

$$y_f = ax_f^2 \tag{23}$$

Since both Equations (22) and (23) must have a common slope at $x_f = x_i$, we have

$$2ax_f = -\frac{2b_1x_f + b_3y_f + b_4}{2b_2y_f + b_3x_f + b_5} \tag{24}$$

In other words, $x_f = x_i$, $y_f = y_i$ and a can be solved from simultaneous Equations (22), (23) and (24). Note that the substitution of y_f from Equation (23) into Equation (22) and (24) lead to a 4th order equation of x_f and a quadratic equation of a respectively. The solution of x_f can be obtained by first solving for a in terms of x_f from the quadratic equation and then the 4th order equation for x_f. Alternatively, the problem may be more conveniently computed numerically from the 4th order equation for x_f by stepping a, and examine the form of the solutions, which is known as follows: All the solutions will be imaginary if the finger does not intercept the ellipse. On the other hand, if $x_f > 0$ and the finger intercepts the ellipse, two of the solutions will be real and distinct. Thus, we note that for a given a, the specific solutions corresponding to touching the ellipse are characterized by two real repetitive roots and a pair of complex conjugates.

With the computed contact point, the arc length L can be determined from Equation (25):

$$L = \int_0^{x_i} \sqrt{1 + (2ax)^2}\,dx \tag{25}$$

and k and f can be computed from Equations (7) and (2) respectively. The component forces can then be resolved from Equations (14a) and (14b), which provide a means to examine the condition for positive grasp: If $\mu f_n \geq f_t$, positive grasp would occur. Otherwise, the finger would slip past the broiler, and the new contact point must be calculated.

5. CONCLUSIONS

The design concept of an automated system for transferring randomly oriented live broilers from a conveyor to a moving shackle line has been presented. Specifically, the paper has focused on the development of an analytical model of a compliant grasping mechanism with flexible fingers for separating and orienting live broilers for subsequent transferring process. It is expected that the model, which is essential for design, analysis, and control of the dynamic grasping process provides a good understanding of the force interaction between the flexible fingers and the object. The model consists of two main components:

1. The kinematics of a flexible finger on a rotating frame and its interaction with a moving object has been derived.
2. The methods of solving for the contact point and thus the forces/moments acting on the object have been outlined and discussed. An approximated finger shape provides a means to estimate the components of the contact forces and a way to analyze the finger's action on the object.

Both the mechanical forces and the broiler's natural reflexes contribute to the overall dynamics as the broiler passes through the singulator. The analytical model described in Part I provides a better understanding of the mechanical system on the object independent of the object's natural reaction. In part II, we experimentally determine the parameters necessary for the simulation of finger forces. In addition, the design and development of a prototype to facilitate the study of the broiler's natural reflexes to mechanical singulation as well as the results of the experimental investigation with live broilers will be described.

ACKNOWLEDGEMENT

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