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ON THE DEVELOPMENT OF A COMPLIANT GRASPING MECHANISM FOR ON-LINE HANDLING OF LIVE OBJECTS, PART II: DESIGN AND EXPERIMENTAL INVESTIGATION

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ABSTRACT

This paper addresses the problem of automating the process of transferring live broilers (meat chickens) from a conveyor to a moving shackle line. Since both the mechanical forces and the broiler's natural reflexes contribute to the overall dynamics as the broiler passes through the singulator, an experimental prototype singulator has been developed to facilitate the study of broiler's natural reflexes to mechanical singulation. In Part I, an analytical model is presented to predict the forces/moments acting on the broilers. In Part II, we focus on establishing the criteria for designing an automated system for singulating and orienting the broilers for subsequent transferring to a moving shackle line. We experimentally investigate the use of the compliant grasping mechanism for live broiler singulation with a spectrum of broilers at the Gold Kist research farm, UGA research farm, and a poultry-processing plant in Georgia. It is expected that the results will provide significant insights into the design and control of future mechanical singulators.

1. INTRODUCTION

Over the past two decades, a number of ideas were proposed to catch broilers in large quantities by means of a machine at the farm and hanging live broilers on shackles on processing plant kill lines. The ideas range from shackling the broilers at the farm to the use of broilers' natural reflexes and gas stunning to ease manual hanging. Extensive reviews of prior work in related areas can be found in a number of references (Kettlewell *et al.* 1985; Scott, 1993; Thornton, 1994). Perhaps, the most relevant outcome of the poultry harvester development efforts is the development of the contra-rotating bristles for singulating, which allows live broilers to be counted electronically (Briggs *et. al*, 1994). However, unlike the poultry harvester 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 their legs for transferring them live onto moving shackles at the poultry processing plant. Recently, a method to automate hanging of live broilers, similar to that commonly used in the cattle and pork industries where the animals are herded into lanes, was suggested in (Sluis 1996). The method requires a cycle time of 28 seconds for grasping a broiler, which is clearly too slow for the typical shackle line speed of 180 broilers per minute. No studies have been conducted on carcass injuries on the method of mechanically guiding the broilers into a locking mechanism.

Figure 1 shows an alternative conceptual design for an automated system for transferring live broilers onto shackles in the processing line. The automated live-broiler transferring system consists of the following subsystems: a distribution system, a singulator, a leg-presentation and shackling system, and a moving shackle line. A typical cycle of the system will begin with the incoming broilers unloaded from cages onto moving conveyors. This is accomplished by the distribution system, which consists of a large conical drum filled with rubber bristles. As the drum is rotated, tangential motion disperses the broilers over the peripheral of the rotating drum while the centripetal and gravitational forces cause the broilers to move away from the drum and drop onto one of the moving lanes. The feed is singulated and led through a cadaver detection system where dead birds are removed. The singulated broilers are led to a leg-presentation and shackling system, which grasps the broiler by its body and allow the awaiting shackle to locate both legs of the broiler.

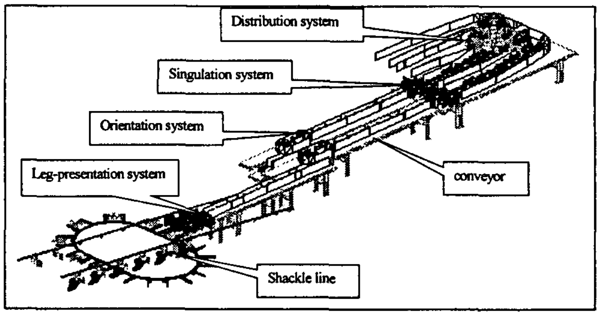

Figure 1 System Overview

Of particular interest is the design and development of a compliant grasping mechanism, which provides a means to temporarily constrain the broiler to permit on-line handling of the broilers. In this paper, we perform a design analysis on a flexible finger and experimentally investigate with live broiler the grasping concept with flexible fingers. Although inexpensive rubber fingers are available commercially for applications in poultry industries for feather plucking, little is known of the mechanical properties of the finger. Often, those who work with these fingers simply learn by experience which type of finger to use for a particular application. Thus, we develop a

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method to determine the mechanical properties of the finger, which is essential for analyzing the contact forces on the object. It is expected that the results will provide significant insights to the design and control of future mechanical singulators.

The remainder of this paper is organized as follows: Section 2 is the design analysis of the flexible finger. Section 3 describes the experimental setup to study broiler's natural reflexes to mechanical singulation. Section 4 discusses the experimental setup and results of the broilers' natural reflexes to mechanical singulation. Finally, the conclusions are given in Section 5.

2. DESIGN OF THE FLEXIBLE FINGER

Figure 2 shows a CAD model of the compliant grasping mechanism. It consists of a pair of counter-rotating rollers, each of the rollers carries *n* columns of evenly spaced rubber fingers and is driven by a servomotor. As the rollers rotate, the fingers grasp one of the broilers from the conveyor and present it on the exit conveyor for subsequent processing. For singulating the broilers, it is desired that the broilers leave the system in a single file and that the distance between the broilers can be monitored.

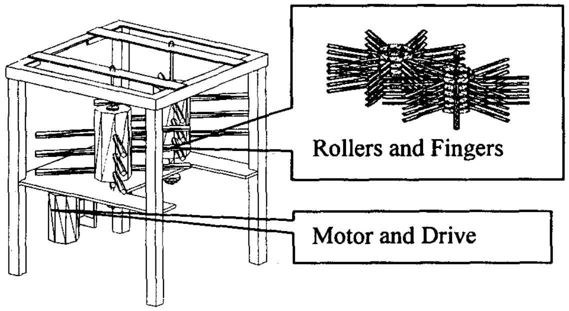


Figure 2 CAD model of the singulating system

2.1 Selection of Fingers

As discussed in (Lee, 1999), the frictional force between the finger and the broiler must be sufficiently large in order to have a secure grasp to allow the tangential component of the contact force to transfer the broiler without slipping. The flexible finger should have high coefficient of friction.

Relatively inexpensive flexible rubber fingers characterized by their high coefficient of friction are available commercially for applications in poultry industries for feather picking. Primary differences in the properties are in the exact composition of the rubber used, and this information is usually proprietary. The fingers are made in a variety of shapes and sizes, ranging from about 0.0762 m to 0.2794 m in length. Typically the length and stiffness of the fingers are inversely related. In order for the fingers to have the reach of the entire distance between the rollers (in the range of 0.1524 to 0.254m), 10-inch long fingers (manufactured by the Waukesha Rubber Company) as shown in Figure 3 were chosen in this application.

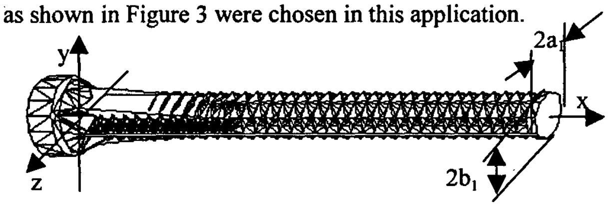


Figure 3 CAD model of the flexible finger

The finger has a non-uniform cross-section along the length of the finger. The finger has two sections with very different geometrical properties. The base of the finger has a circular cross-section about 31.75mm in diameter, which allows easy insertion into a circular hole on the roller and is thicker than the rest of the finger. Over the first 114.3mm the shape tapers down to a flattened oval shaped cross-section which is about 24mm along its major axis and 12.7mm along the minor axis and there are a number of ribs evenly space along the length of the finger. The elliptical shape provides rigidity in the z-direction and flexibility in the x-y plane. The last 139.7mm of the finger is characterized by the elliptical cross-section with a number of ribs along the length of the finger. Other finger properties are summarized in Table 1.

Table 1: Finger properties

Parameters	Values
Mass	0.079 kg
Density	1023.4213 kg/m^3
a_l	12 mm
b_l	8.45 mm
$I_y = 0.25\pi\, ab^3$	5.70812e-9 m^4
$I_z = 0.25\pi\, a^3 b$	1.16492e-8 m^4

Based on the web page reference from Cornell University, the Young's Modulus for rubber ranges from 0.01GPa to 0.1GPa. The corresponding EI_y ranges from 0.05708 to 0.57081Nm^2 and EI_z ranges from 0.1165 to 1.1649Nm^2.

2.2 Experimental determination of finger parameters

The force analysis of the compliant finger on the broiler requires the properties of the finger. Information regarding the specific rubber's composition and properties are generally not available. We develop the method to determine the product of the Young modulus and the moment of inertia *EI* for a flexible finger experimentally. From the theory of elastic bar given by Frisch-Fay (1962), we express *EI* in the form of Equation (1):

$$EI = \left[\frac{C(\psi_o)}{h(\psi_o)}\right]^2 \qquad (1)$$

where $$C(\psi_o) = y_f\sqrt{f} \qquad (2)$$

$$h(\psi_o)=\left[F(p,\frac{\pi}{2})-F(p,\zeta)-2E(p,\frac{\pi}{2})+2E(p,\zeta)\right] \quad (3)$$

$$\varsigma=\sin^{-1}\left[\frac{1}{p\sqrt{2}}\right] \quad (4)$$

$$p^2=(1+\sin\psi_o)/2 \quad (5)$$

Figure 4 shows an experimental setup for determining the *EI_z of* the finger. The finger was loaded with a known weight at a specified location along the finger. In Figure 4, the variables (x_f, y_f and ψ_o) are measured for a known force f applied perpendicular to the x-axis at a known location on the finger.

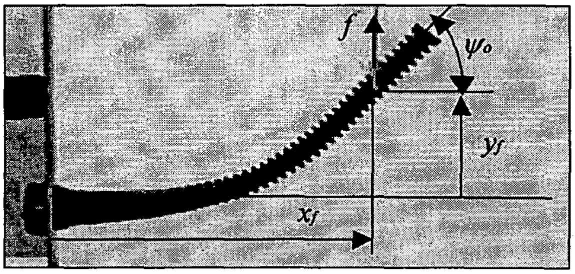


Figure 4 Experimental determination of finger's properties

Since the manufacturer of these fingers would not provide us with information regarding the rubber's composition and properties, EI_z was estimated as a product. Figure 5 shows a typical family of data obtained experimentally, where the deflection y_f is plotted as a function of $f^{-1/2}$ for different locations of the force on the finger. The location ranges from 0.1524-0.2032 meters from the base of the finger and for each location, the loads were varied from 0.4448 - 1.7793N. From the experimental data in Figure 5, the two functions $C(\psi_o)$, and $h(\psi_o)$, are plotted in Figure 6 using Equations (2) and (3) respectively.

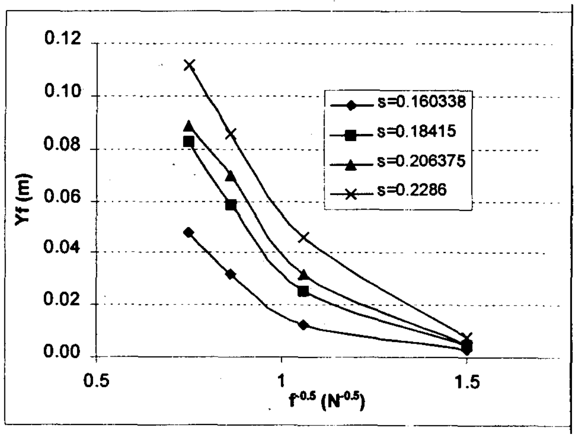


Figure 5 Experimental force-displacement data

The relationship between $C^2(\psi_o)$, and $h^2(\psi_o)$ is shown in Figure 7 and can be linearly approximated as

$$C^2(\psi_o)=0.1644\,h^2(\psi_o)+0.0011 \quad (6)$$

Note that the slope of the plot is essentially the EI_z of the rubber finger and thus, the experimentally determined EI_z is equal to 0.1644 Nm^2.

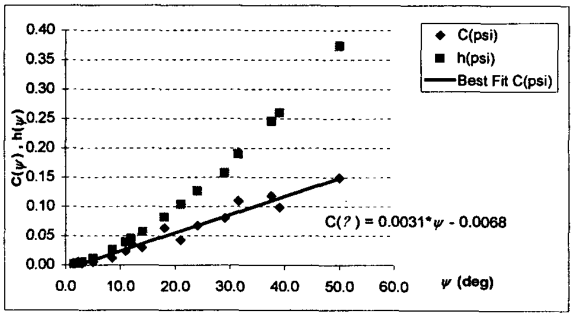


Figure 6 Plots of functions $C(\psi_o)$ and $h(\psi_o)$

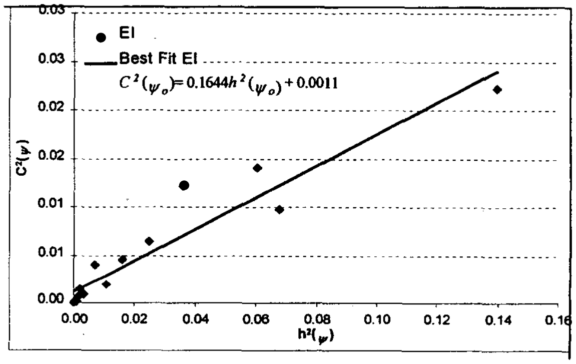


Figure 7 Relationship between $C^2(\psi_o)$ and $h^2(\psi_o)$

2.3 Design Analysis of the contact forces and moments

We model the broiler as an ellipsoid and the fingers are treated as flexible bars as discussed in (Lee, 1999). For a given broiler's position and orientation, it is of interest to determine the normal and tangential components of the contact forces and the moment acting on the broiler. For clarity, we present the simulation results based on a single rotating finger on a two-dimensional ellipse that characterizes the cross-section of the broiler as shown in Figure 8. The values of the parameters used in the simulation are given in Table 2, where the coefficient of friction between the finger and the bird was experimentally. It is expected that the simulation will provide us with a better understanding of how the fingers would affect the motion of the broiler independent of its natural response.

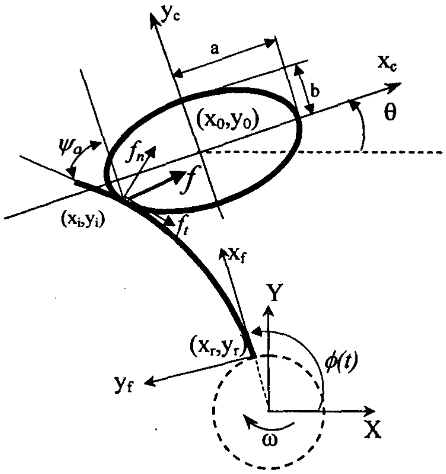


Figure 8 Model of the finger/ellipse interaction

Table 2: Simulation parameters and values

Simulation Parameters	Values
Half width along major axis	$a = 0.075$ m
Half width along minor axes	$b = 0.05$ m
Location of the ellipse,	$X_o = 0$, Y_o=0.15m, $\theta = 0°$
Angular position of finger	ωt=250° to 290°
Radius of the roller	$r = 0.075$m
Coefficient of friction	0.4104

To reduce the problem to a more tractable form, we use a hyperbolic function to approximate the shape of the finger and estimate the contact point as discussed in (Lee, 1999). With the estimated contact point, the contact force can then be calculated. Figure 9 compares the finger shape approximated by the hyperbolic function and the analytical solution given by Frisch-Fay (1962) for $\phi=90°$ ($\omega t=270°$) using the estimated force.

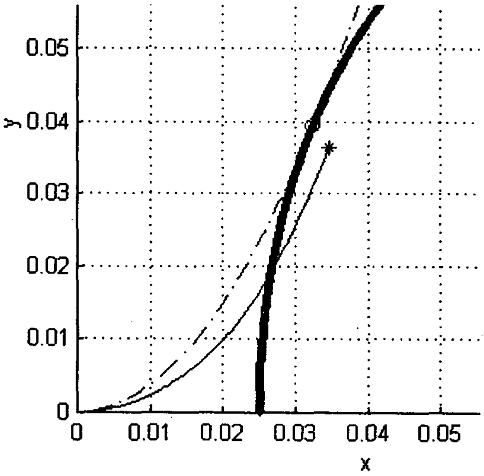


Figure 9 Finger shape comparison

Figure 10 shows the finger shape and the contact point with respect to the finger coordinate frame as the finger rotates from ωt=250° to 290°. The estimated errors of the contact point are summarized in Table 3. Once the contact point on the finger is known, the normal and tangential components of the contact force as well of the moment acting on the bird can be computed. Table 4 summarizes the moment and contact forces as the finger rotates from ωt=250° to 290°.

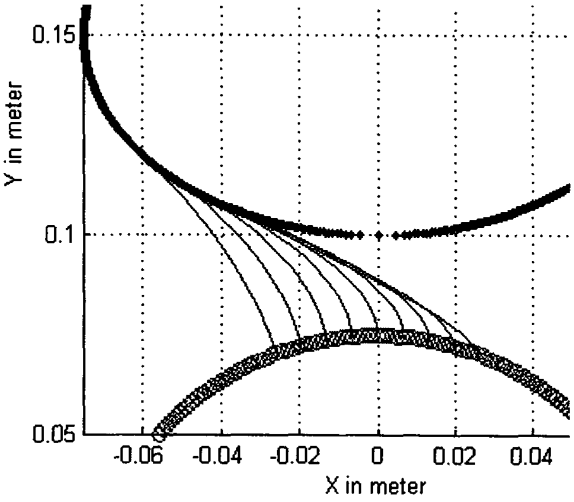


Figure 10 Finger shape as a function of ωt

Table 3: Estimated error of contact point

ωt (degrees)	Δx (m)	Δy (m)	$\sqrt{(\Delta x)^2+(\Delta y)^2}$ (m)
250	0.001	-0.004	0.004
255	0.002	-0.004	0.004
260	0.001	-0.002	0.002
265	0.000	0.000	0.000
270	-0.002	0.003	0.004
275	-0.006	0.006	0.008
280	-0.011	0.009	0.014
285	-0.017	0.013	0.021
290	-0.025	0.016	0.029

Table 4 Contact forces on moment

ωt (degrees)	moment	$\lvert \mu f_n \rvert$ (N)	$\lvert f_t \rvert$ (N)
250	6.1	17.3	16.4
255	10.9	30.4	45.0
260	15.6	41.8	82.0
265	19.2	48.4	114.8
270	20.4	49.1	130.3
275	19.5	45.2	125.6
280	17.2	39.4	107.8
285	14.6	33.5	86.2
290	12.3	28.3	66.5

3. PROTOTYPE EXPERIMENTAL SETUP

As the overall dynamic is a combination of the motion caused by the mechanical input and the broiler voluntary motion in response to the mechanical action, we developed an experimental setup shown in Figure 11 to facilitate the studies of live broilers' natural reactions to mechanical handling processes. The broilers' natural reflexes as they pass through the experimental setup are recorded using video camera recorders for analysis. It is expected that the experimental studies will provide us a means to examine the ability of a singulator for separating multiple broilers into single file; to determine the nominal operating parameters; to study the sensitivity of the design parameters. The design considerations of the experimental investigation are as follows:

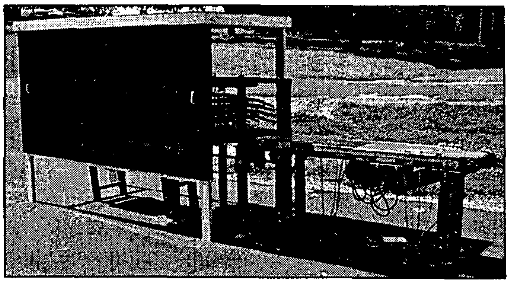
1. In order to characterize the broilers' natural reflexes, we compare two specific design configurations. A significant difference between the two designs is the broilers' ability to orient themselves within the singulator. The first design configuration has been designed to have adequate space to allow the broiler to orient itself voluntarily while the second aims at fully constraining the broiler during the singulating process. The two design configurations and their parameters are compared in Table 5.
2. To provide a spectrum of broiler configurations, the system has been experimentally tested with live broilers at the Gold Kist Research Farm and with broilers from two poultry-processing plants in Georgia. The primary differences in the test between the two facilities are as follows:
    - The broilers at the Gold Kist Research Farm are about 5-6 weeks old and weigh between 1.36-1.6kg or 3.0-3.6lbs. The broilers at the poultry processing plant are 7 weeks old and weigh between 2.7 and 3.2kg or 6-7 lbs.
    - The broilers from the processing plants are typically more stressed due to fasting, catching, transporting, and waiting at arrival in cages.

Table 5 Comparison of design parameters

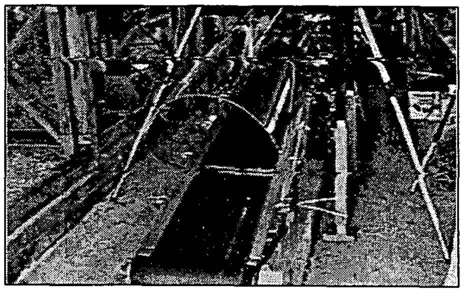
Parameters	**DESIGN 1**	**DESIGN 2**
Singulator Rotational Speed (rpm)	*150*	*100*
Columns of fingers evenly spaced	*4*	*8*
Spacing between rows of fingers	*0.1m (4 in.)*	*0.05m (2in.)*
Number of fingers per columns	*3*	*4*
Number of fingers (total)	*20*	*72*
$V_1 = 0.12$ m/s, $h = 0.0875$m, conveyor width = 0.3m.		

4. RESULTS AND DISCUSSIONS

In general, most of the naïve broilers enter the singulator backward to avoid the agitating effect of the fingers if they are given time to react. Controlling the conveyor speed provides a means to regulate the reaction time.



(a) Overall view of the experimental basic setup



(b) Loading conveyor

(c) The singulating manipulator

Figure 11 Experimental Prototype

Design Configuration 1

The observations of the broiler going through the first design configuration are summarized as follows. When the naïve broilers are given adequate space between fingers, they voluntarily re-orient themselves. Thus, both the rotating fingers and the broiler itself contribute to the resultant motion. The corresponding settling distance and time are given in Table 6. When the broiler entered the singulator in the forward direction, it flapped its wings in an attempt to fly through the singulator. As a result, it moved with a much larger momentum than other entering poses. However, when the broiler crossed the singulator backward, its motion was more predictable and typically settled in a shorter distance and time than the forward entering pose. In some occasions, the broiler entered the singulator sideway and resisted the fingers' motion. However, the broiler generally re-orients itself and allows the system to push it through.

Table 6 Effect of entry poses

Entering pose	Settling distance	Settling time
Forward	0.4-0.5m (16-20inches)	1 second
Backward	0.2-0.25m (10-12 inches)	0.67 second
Side	0.2-0.25m (10-12 inches)	1.5 seconds

Design Configuration 2

The second design configuration is capable of supporting the broiler between the fingers as shown in Figure 12. The results suggest that by appropriately configuring the fingers, the contra-revolving fingers can be developed as an effective grasping mechanism as well as a singulator. Figure 13 shows a typical plan view video sequence as two of six broilers (labeled 1 and 2) go through the singulator and are separated into single file. View #1 shows the broilers are close together as they enter the singulator. The image taken 4/30 of a second later show that broiler #1 is in the center of the singulator and broiler 2 is still at the entrance. The instant after 6/30 of a second have passed, as broiler #1 is being pushed through and broiler #2 is still held back at the entrance. Finally, after 8/30 of a second, broiler #1 is exiting the singulator and broiler #2 is entering the singulator. These series of images illustrate the effectiveness of the singulator design configuration 2 in separating the broilers into single file, which agree with our results simulated analytically.

For the design configuration 2 tested, the broiler typically settles in the order of 0.5 second and at the distance about 0.25m-0.3m (10inches - 12 inches) from the center of the singulator.

5. CONCLUSIONS

The paper presented the design and development of a singulating manipulator for separating and orienting live broiler for subsequent transferring process. A static force model and its role in predicting the dynamics of the singulator have been developed. Since both the mechanical forces and the broiler's natural reflexes contribute to the overall dynamics as the broiler passes through the singulator, an experimental prototype has been developed to facilitate the study of broiler's natural reflexes to mechanical singulation. The system has been experimentally tested with live broilers at the Gold Kist research farm and at a poultry-processing plant in Georgia. The results of the tests have been discussed.

ACKNOWLEDGEMENT

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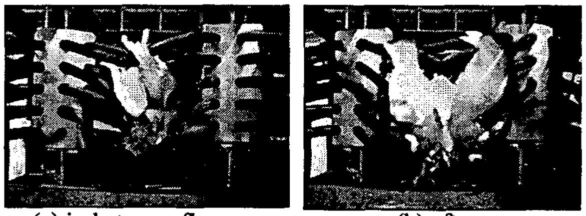
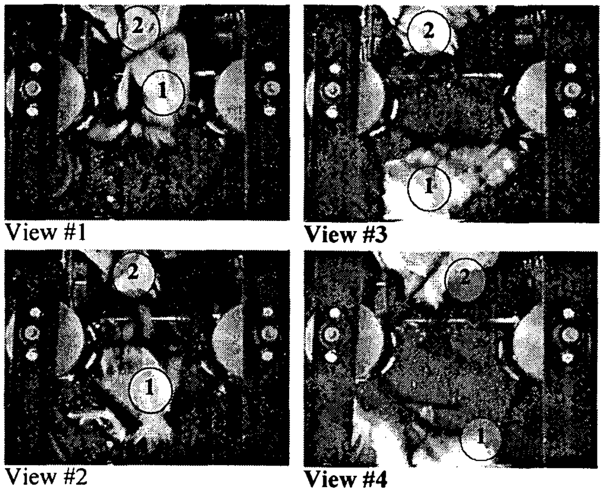


(a) in-between fingers (b) after

Figures 12 Design Configuration 2



View #1 View #3

View #2 View #4

Figure 13 Motion sequence showing singulating action

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