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Design of an Automated Cheese Cutting Machine Prototype

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Abstract

This work describes each of the parameters for the design of a prototype of an automated machine to make cuts in different types of cheese, in cubic form and slices. Each mechanical and structural component is designed, analyzed and calculated, with the implementation of a compression mechanism with power screw, simulating its operation in the SolidWorks Computer Aided Design (CAD) program, the equipment and accessories that constitute the control system for the automation of the prototype are selected, the programming of the Programmable Logical Control (PLC) in ladder language is carried out. Finally, the operation of the prototype is demonstrated through modeling and simulation with the use of the NI LabVIEW Softmotion module that allows integration with SolidWorks, making the application that involves some components of the prototype and controlling its movements from NI LabVIEW.

Keywords: CAD, Control Equipment and Devices, Design, Prototype, Simulation, Process Automation

1. Introduction

The technological advancement is not only based on giving a practical and useful use to the different mechanisms designed in antiquity, with manual movement, but also focuses on the creation of a series of mechanisms, equipment and machines with different motor sources, giving way to technological innovation in the generation of new models and the automation of processes, such as cutting, slicing and cubing cheese. [1] [2].

Aimed at the food industry, there is a series of manual and automated equipment and machines that meet a certain functionality, facilitating and improving the generation of different products that are marketed daily in cities and towns of the country, such equipment must comply with all safety and hygiene standards, ensuring the quality of the finished final product, in many cases it is recommended to use the appropriate codes and standards, complying with the parameters necessary for the design [3], and the competent regulations for equipment and utensils used in the handling of food[4].

The main function of the prototype is to perform the cutting, slicing or cubing of cheese, which has been done by hand, with manual equipment and semi-automatic or automated electrical cutters, among these we can mention the MASTERCUT - CUT150i and FILET650 - VR&A SYSTEMS; these types of machines and equipment work with standardized common slice type cuts. Sometimes it is required other types of cuts such as the shape of cubes of different sizes, becoming a problem because in most cases it is done with improvised manual equipment of artisan form or acquiring other additional automated equipment that executes this type of cut, increasing considerably the costs for the investment of a new equipment, its operation and maintenance.

The development of the project involves an Automatic control system, based on the different theories of modern control, dynamics of the automatic control system, its basic components and the parameters to be considered to avoid errors in the control of the automation of processes, represented by [5], [1], [2] and [6].

2. Materials y Methods

The appropriate mechanical elements and automated control for this prototype are defined at first, and its operation is demonstrated by Softmotion modeling and simulation of NI labVIEW and SolidWorks. For the cutting, slicing and cubing of cheese and other food products, the parameters described in table 1 are considered and for the design of the machine, those shown in table 2.

Table 1: Preliminary design parameters

ITEM	DESCRIPTION
1	Type of material used: 304 stainless steel, ANSI 201 stainless steel and anodized aluminum.
2	The equipment must be functional and safe, guaranteeing the cutting in different forms of cheese, according to customer needs.
3	Comply with minimum quality and hygiene standards for the handling of cold food products.
4	Economic and aesthetic viability.
5	Tools or cutting accessories used are knives and steel cheese lyre slicers.
6	The drive source commonly used for this equipment is electrical, pneumatic or mechanical.
7	Selection of the appropriate cutting speed of the cheese to prevent it from fading and to affect the quality of the cheese.
8	Position control of the actuators or motor source in the cheese cutting process.
9	Create a control panel with a human-machine interface for better control and visualization of the equipment status.
10	Manual and automatic operation.
11	To integrate in a main panel all the electrical and electronic elements for the control of the operation of the equipment.

Table 2. General requirements and specifications

DESCRIPTION	PARAMETERS
Product input measurements	Height: 16 x Width: 19 x Length: 30 cm
Measurements of the cut product - output	Height: 1 x Width: 1 x Length: varied cm
Production	Varied
Actuator forward speed	Experimental.
Safety, quality and hygiene	Versatile, easy to use and handle, adequate protection of moving components, suitable construction material for food handling, easy cleaning and maintenance (detachable).
Equipment design	Semi-automatic and automated handling with human-machine interface.
Ergonomics	Working table for an average operator height of 1.65 to 1.70m.
Costs	Moderated

2.1. Mechanical and Structural System Design.

Figure 1 shows the design of the prototype made in SolidWorks mechanical design software. To determine the working force or load of the power screw necessary to compress the cheese, the density of the product to be worked (Cheese) and its volume were considered. The thrust force is given by:

$$E=W*g=\rho*V*g \tag{1}$$

Where,

ρ: Product Density, V: Volume of the product and g: Gravity = 9.81 N/Kg.

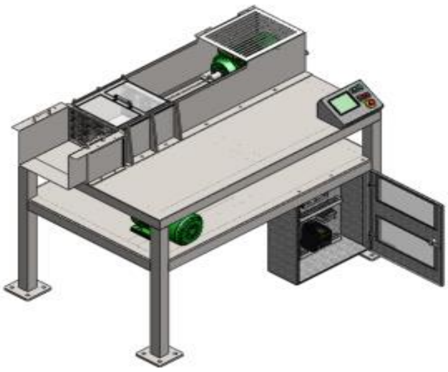


Figure 1. Automated Prototype Cheese Cutter.

- ✓ Critical working load on the power screw:

$$F = E * 3 \tag{2}$$

- ✓ Mean diameter or pitch, square thread or ACME.

$$d_m \geq \sqrt{\frac{2F}{\pi \varphi S_{d-ap}}} \tag{3}$$

Where:
F = Working load; φ = 2.5 (One-piece nut), the material of the nut will be taken from bronze and steel bolt to reduce friction; S_{d-ap} = 12 MPa (Steel bolt and bronze nut).

Figure 2 shows the mechanism designed in the CAD Solidworks system.

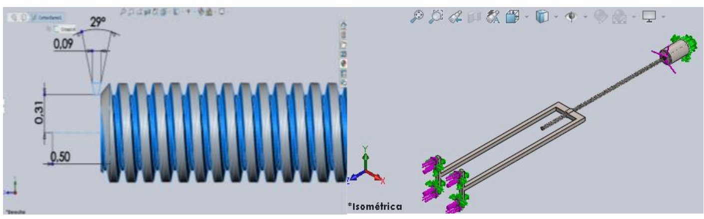


Figure 2. Prototype compression mechanism.

2.3. Design of the electrical and control system of the prototype.

Made up of the cables for the power circuit, selection of the frequency variator, PLC and its programming, for the automation of the prototype. Two three-phase electric motors are used to cut the cheese. Motor 1, IEC three-phase motor, in iron case, efficiency IE1, IP55 series 1LE0142, reference Siemens 1LE0142-0EC86-4AA4-Z D80+D81 and Motor 2 reference Siemens 1LE0142-0DC86-4AA4-Z D80+D81. For the selection of the PLC, the decision matrix-method was used; the SIMATIC S7-1200 CPU 1214C, DC/DC/RELAY programmable automaton was used. The controllability of the process was verified, defined as follows:

$$G.L = (\#VM) - (\#VC) \tag{4}$$

Where: $G.L$: Degrees of freedom, $\#VM$: Number of variables manipulated, $\#VC$: Number of variables controlled.

Table 3. Number and description of variables manipulated / controlled.

Number of variables manipulated (#VM) or input variables.	
Number	**Description**
4	End-of-stroke sensors.
3	Pushbutton; 1 start (Green), 1 stop (Red) and 1 mushroom button for emergency.
2	Pushbuttons from the HMI for automatic operating mode and fault identifier.
Number of variables controlled (#VC) or output variables.	
Number	**Description**
3	Commissioning of the inverter, ON/OFF and motor rotation inverter 1 (with frequency inverter).
2	Motor 2 starting and reversing (with SIRIUS 3RA13 reversing device).
2	Green and red LEDs

For the main panel the different control and protection devices of the automated cheese cutter prototype were located. The design was carried out in the SolidWorks CAD system, as shown in figure 3 a), b) and c).

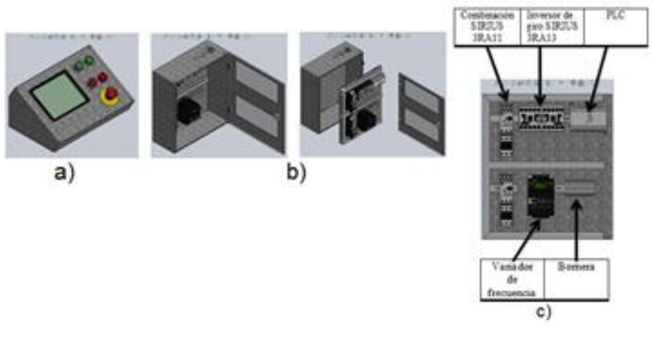


Figure 3. a) Box for HMI panel. b) Box for main panel. c) Representation of main panel devices.

3. Results

The results of the calculations for the power screw are shown in table 4 and the specifications of the power screw are shown in table 5.

Table 4. Calculation Results for Power Screw.

PARAMETERS	FORMULAS	DATA
Verification of the resistance in the body or core of the screw.		
Archimedes' Principle	$E = W * g = \rho * V * g$	$207.54\ N$
working load limit	$\mathrm{F} = E * 3$	$622.62\ N$
Mean diameter or pitch, square thread or Acme.	$d_m \geq \sqrt{\frac{2\mathrm{F}}{\pi\varphi S_{d-ap}}}$	5/16 pulg
Axial stress on the screw body due to load F.	$S_t = \sigma = -\frac{\mathrm{F}}{A_T}$	$-18.21\ MPa$
required torque of the Split ring collar	$T_c = \frac{F f_c d_c}{2}$, $d_c = 1.5\ d_m$	$0.558705\ N.m$
Torque required to raise the Acme load thread T_R	$T_R = \frac{F d_m}{2}\left[\frac{l + \pi f d_m Sec\ \propto}{\pi d_m - f l Sec\ \propto}\right] + T_c$ $with\ \alpha = 14.5º$ With friction coefficient f = 0.23 bolt material HR steel and nut in bronze.	$4.70642\ \mathrm{N.m}$
Nominal torsional shear stress τ of the screw body.	$S_{sT} = \tau = \frac{16T_R}{\pi d_r^3}$	104.50 MPa
Factor of Safety according to the theory of maximum shear force or that of octahedral shear force/von Mises.	$\frac{1}{FS^2} = \left(\frac{S_t}{S_y}\right)^2 + \left(\frac{S_{sT}}{S_{ys}}\right)^2$	4.9
Verification of the cutting resistance of the fillets.		
Maximum shear stress τ in the center of the nut root due to load F.	$S_{sba} = \tau = \frac{3\mathrm{F}}{\pi d_{ext} n_t\ p}\ \ for\ the\ nut$ $n_t = n_f = 1 \leq n_t \leq N_t = L_T / P$	7.54 MPa
Factor of Safety based on the shear stresses for the nut.	$S_{sba} \leq \frac{S_{ys}}{FS_{sba}}$	5.3
Verification of the bending resistance of the fillets.		
bending stress $\sigma_b = S_{flex}$ at the root of the thread	$For\ the\ bolt: S_{flex} = \sigma_b = \frac{6\mathrm{F}}{\pi d_r n_t P}$ $For\ the\ nut: S_{flex} = \sigma_b = \frac{6\mathrm{F}}{\pi d_{ext} n_t P}$	19.6 MPa 15.08 MPa
Factor of safety based on bending stresses	$S_{flex} \leq \frac{S_y}{FS_{flex}}$	45.7 4.6
Verification of resistance by von Mises stress concentration. σ´.		
Three-dimensional stress of von Mises	$\sigma' = \sigma_{max} = \frac{1}{\sqrt{2}}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]^{1/2}$	182.145 MPa
Factor of Safety based on the maximum stress concentration	$\sigma_{max} \leq \frac{Sy}{\mathrm{FS}_{max}}$	4.9
Efficiency of the screw with the axial collar.	$e = \frac{T_0}{T_R}$	53.2%

Table 5. Specifications of the power screw.

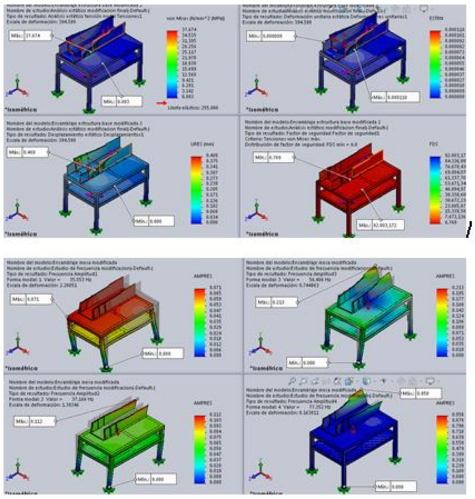
ESPECIFICACIONES	DATOS
External diameter (d)	5/16 in (0.0079502 m)
Mean diameter or pitch (dm)	0.277 in (0.0070358 m)
Minor Diameter. (dr)	0.241 in (0.0061214 m)
Bolt length (L)	39 cm (0.39 m)
nut length (*L*)	18 mm (0.018 m)
Pitch (P)	0.071 in (0.0018034 m)
Fillet height (h)	0.0355 in (0.0009017 m)
Fillet angle (α)	29º
Upper fillet width (a)	0.0355 in (0.0009017 m)
number of threads (n)	1 thread per in.
Screw feed (*l*)	0.994 in. (0.0252476 m)
Tensile stress area	0.053 in^2 ($3.419348x10^{-5}$ m^2)
Torque required to raise the Acme load thread (T_R)	4.71 N.m
Working load of the power screw (F)	622.62 N
Efficiency of screw with axial collar (%)	53.2%

The following results were obtained from the calculation for the selection of actuators (three-phase electric motor) (Table 6).

Table 6. Calculation Results for Three-Phase Electric Motor.

PARAMETERS	FORMULAS	DATA
Revolutions for alternating current motors	$n = \frac{120*f}{p}$, taking a number of poles = 6	1200 rpm
Power output at braking, mechanical or on the shaft	$Ps\ (HP) = \frac{T * N}{K}$	0.79 HP
Input power	$P\ (input) = \frac{Ps\ (HP)}{Eficiency}$	1.1 HP
maximum power at overload	$P_{max} = 1.5 * P\ (Input)$	1.7 HP
Rated current (I)	$P1 = \sqrt{3} * V * I * Cos\ φ$ $I = \frac{P1}{\sqrt{3} * V * Cos\ φ}$	3.9 Amp
Inrush current.	$I_{Inrush} = (3) * I$	11.7 Amp

Figure 4 a) and b) show the results obtained from the static analysis, frequency study and table 7, specify the list of resonant frequencies.



a).

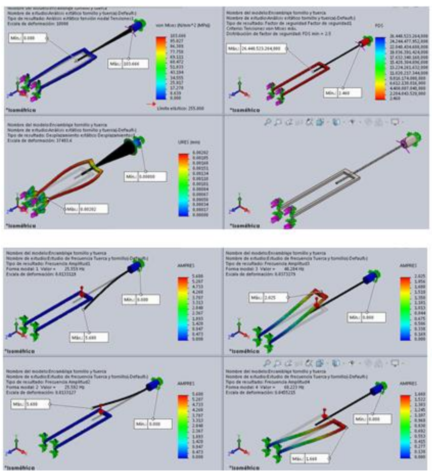
b).

Figure 4. a). Static analysis (Stresses, Displacements, Deformation and FDS) and b). Frequency study.

Table 7. Frequency study results for the base structure of the final prototype.

mode Nº	Frequency(Rad/s)	Frequency (Hz)	Period(Seg)
1	223.39	35.553	0.028127
2	233.52	37.166	0.026906
3	354.41	56.406	0.017729
4	486.02	77.352	0.012928

The results of the static and frequency analysis for the compression mechanism of the prototype are shown in Figure 5 a) and b), and the list of resonant frequencies in Table 8



a).

b).

Figure 5. Analysis for the compression mechanism. a). Static analysis (Stresses, Displacements and FDS) and b). Frequency study.

Table 8. Results of frequency studies for the compression mechanism.

mode Nº	**Frequency(Rad/s)**	**Frequency (Hz)**	**Period(Seg)**
1	160.59	25.559	0.039125
2	160.8	25.592	0.039075
3	253.11	40.284	0.024824
4	378.39	60.223	0.016605

The programming for the PLC SIMATIC S7-1200 CPU 1214C is described, by means of a truth table of 0 and 1, referring to the process and making an automation table, which is a model for the process that fulfills several stages, serving as a guide for the PLC programming, shown in table 9 and 10. In addition, the importance of the HMI visualization system, to observe in real time the operation of the process, control and simulation, linked in real time to the PLC is also considered. [9].

Table 9. Truth table for the cheese cutting process.

P1	P2	P3	PMHI	S1	S2	S3	S4	FE	K_1M1	SVF1	SVF2	L1	L2	K_2M2	$K_{2*}M2$
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0		1	1	0	1	0	0	1	1 (5s)	1	1	0	0 (5s)	0
0	0		1	0	0	1	0	0	1	1 (5s)	1	1	0	0 (5s)	0
0	0		1	0	0	0	0	0	1	0	0	1	0	1	0
0	0		1	0	0	0	1	0	1	1 (5s)	1	1	0	0 (5s)	0
0	0		1	0	0	0	0	0	1	0	0	1	0	0	1
0	0		1	0	0	1	0	0	1	1 (5s)	1	1	0	0 (5s)	0
0	0		1	0	1	0	0	0	1	1	1	1	0	0	0
0	0		1	0	0	0	0	0	1	1	1	1	0	0	0
0	0		0	1	0	0	1	0	1	0	0	1	0	0	1
0	0		0	1	0	0	0	0	1	0	0	1	0	0	1
0	0		0	1	0	1	0	0	1	0	0	1	0	0	0

Table 10. Process automation table (cubed cheese cutting).

AUTOMATION TABLE.		
INPUT	**OUTPUT**	**MARK**
1. START	All in 0	
P1 = 1, NA	K_1M1 = 1; L1=1	m0.0
P2 = 1, NC	L2 = 1; K_1M1 = 0; L1 = 0; K_2M2 = 0;	m0.1
P3 = 1, NC	system reset	m0.2
PHMI = 1	T1, SVF1 = 1	m0.3
S1 = 1		
S3 = 1	T1, K_2M2 = 0	
PHMI = 1	T1, SVF1 = 1	m0.4
S1 = 0		
S3 = 1	T1, K_2M2 = 0	
T1 (Finish)	SVF1 = 0	m0.5

Table 10. (Continued): Process automation table (cubed cheese cutting).

EVF0Hz = 1	$K_2M2 = 1$	
S4	$K_2M2 = 0$	m0.6
EVF33.27Hz = 1	T1, SVF1 = 1	
T1 (Finish)	SVF1 = 0	m0.7
EVF0Hz = 1	$K_2*M2 = 1$	
S3	$K_2M2 = 0$	m0.8
EVF33.27Hz = 1	T1, SVF1 = 1	
S2 = 1	SVF1 = 1	m0.9
S1 = 1	SVF1 = 0	m1.0
S4 = 1	$K_2*M2 = 1$	
S3 = 1	$K_2*M2 = 0$	m1.1

The control of the inverter is carried out by means of digital inputs and outputs with the PLC through a communication port via Profinet, executing command words in the programming software TIA PORTAL.

4. Conclusions

The prototype is designed to operate fully automatically, complying with the requirements of existing safety, quality and hygiene standards, is designed to be detachable and easily accessible to all parts, which need to perform preventive or corrective maintenance. The versatility of the design allows the prototype to be conditioned so that it can work manually in order to make different cuts of cheese.

With the simulation it was verified that the conditions initially taken for the prototype presented failures in its structure and instability, reason why the characteristics of the material to use, dimensions of the prototype were modified and the fixing points were improved, guaranteeing the resistance and its stability, as well as its automatic operation.

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