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Fuzzy Logic Control Application: Design of a Fuzzy Logic Decorticator Controller of Morama Bean (Tylosema Esculentum L.)

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Abstract*— As the demand for leguminous fruit crops increased, mechanical tools were developed to improve the decorticating process. These tools include manually operated jaw-levers and decorticating power machines. However, decortication of the morama fruit (bean) is still a manual process. The most important benefit a customer derives from a decorticating machine is the effort saved in handling and decorticating the fruit. The force required depends upon the characteristics of a particular morama fruit; on the husk thickness, the space between the seed and the husk and the dryness of the fruit (length of the seasoning period). Yet with current decorticating machines the user is compelled to apply the same force to all morama beans since the element of control is restricted; machines are not as automated as they could be. This paper presents the idea of controlling the decorticating force using fuzzy logic control. It describes the procedure that can be used to determine the force required to decorticate different morama beans. The process is based entirely on the principle of taking non-precise inputs from sensors, subjecting them to fuzzy arithmetic and obtaining a crisp value of the decorticating force. It is quite clear from the results obtained that this method can be used to further automate decorticating machines.

Index Terms—**Decorticating, Fuzzy Controller, Morama.**

I. INTRODUCTION

Decorticating machines are used to crack the husk of many crops including peanuts, walnuts, almonds, peas and beans. Legume crops provide proteins, vitamins, cholesterol-free oils and fatty acids and are considered a nutritious, healthy food source. However, the utilization and commercial production of some legumes has been limited due to their hard husk. This is true of the morama *bean (Tylosema Esculentum)* which is endemic to Botswana and arid parts of neighboring countries (South Africa, Namibia and Zambia). Many of the native people of Botswana are ignorant about this species which is not yet a cultivated crop while those who do harvest it in the wild encounter difficulties in decorticating the fruit, due to its extremely hard husk. The National Food Technology Research Centre (NFTRC) has organized conferences in Kanye, Botswana in an endeavor to inform people of the potential importance of this potential crop [1].

Different types of morama bean require varying levels of force to crack open the husk. The force required is a dependent variable, being influenced by the following main factors; thickness of the husk, seasoning period (how long it has been dry) and the proximity between the outside of the seed and the inside of the husk, referred to as the clearance gap. Decorticating a morama bean by hand is an extremely difficult task, it commonly involves cracking the nut with a stone. The use of decorticating machines is growing but those that are commonly used in Botswana are operated manually using mechanical levers to open and close the machine jaws without any form of incorporated control attribute. As a result, the seed is often damaged which exposes it to microbial contamination and loss of quality. A decorticating machine with a controller which would apply the correct amount of force according to seed properties would mitigate against damage to the seed.

This paper proposes an automated fuzzy-controlled decorticator machine. The control aspect in this paper is based on a fuzzy controller algorithm which has been designed based on the properties of the morama bean. As in any fuzzy control design, the fuzzy logic controller (FLC) takes at least two input variables from sensor readings and the controller returns the desired single or multiple outputs as per design specifications. The properties selected were used to form linguistic input parameters for the fuzzy controller. These parameters are non-precise inputs obtained by sensors which are subjected to fuzzy logic computation and analysis, which then yield as output a crisp value of the force required to crack the husk. This methodology can be used to automate the decorticating machine.

Sensors are essential in detecting the internal and external parameters of the morama bean which then enable the controller to determine the control law realized when the machine exerts force on the husk, making a machine 'decision' [2], [3]. The lack of a clear relationship between input and output presents a design constraint which is addressed in this paper using fuzzy logic control which will allow the controller to provide the correct amount of force required to decorticate a particular morama bean.

To simplify the design process the input variables, which allow the FLC to determine the correct control law for the machine, have been reduced to two. The variables selected are;

1. Degree of thickness of the husk; the thicker the husk the harder it is to crack.
2. Clearance gap between the inner surface of the husk and the outer skin of the seed (the testa); the smaller the clearance, the harder the bean is to crack.

Fig. 1 shows a streamlined approach to the problem. The

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controller has two input variables and one output; force required. The two input variables are detected by sensors and are then subjected to the fuzzy controller's arithmetic and criterion. The functionality of the sensors is not under investigation since for the purposes of this paper the values of the input variables are assumed to be known.

Sometimes the clearance gap is very small or even non-existent and in these cases the seed is usually damaged when employing manually operated machines. The larger the clearance, the lower the force that has to be exerted since the clearance allows for some compression of the husk. Intuitively, a thin husk and adequate clearance would imply minimal force required. This is rarely the case, however, as the morama bean incorporates an extremely thick and hard husk with minimal or no clearance between it and the seed. If reliable designated sensors can provide such information for fuzzy processing the desired output (force required) can be determined and the process automated; every time the decorticator is loaded these input variables would be detected and processed.

II. FUZZY LOGIC CONTROL

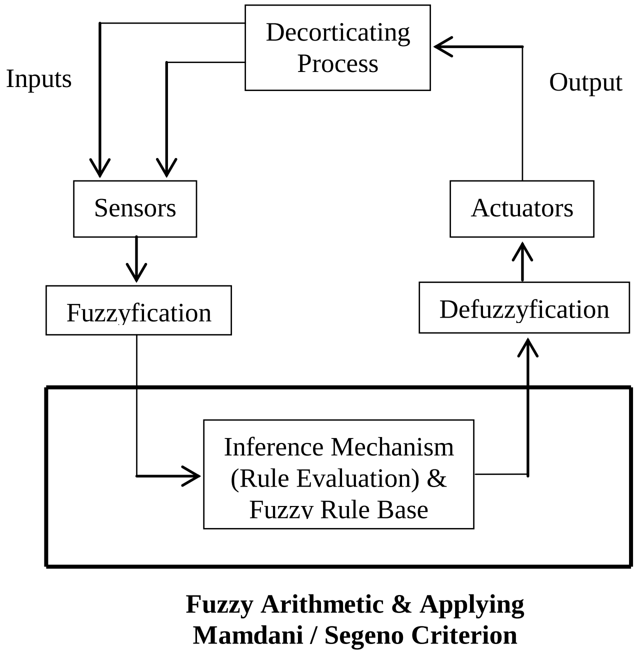

Fig. 1: Decorticator Fuzzy Logic Controller (D-FLC) [[2]-[5]

Fuzzy logic control in its broadest sense is a form of control algorithm that mimics human thinking. It is possible to develop a controller that is almost as effective as the human brain using fuzzy logic control [2]-[5]. The fuzzy logic controller illustrated in Fig. 1, shows the FLC architecture for a decorticating machine.

Although various input and output (I/O) relationships may be used, Fig 1 illustrates a range-to-point I/O relationship. This is a commonly applied relation for most fuzzy controllers where there are several input values and only one output value. This output relation can be expressed as a function of the input values, as shown in Equation (1), [3].

$$Y = f(X_1, X_2) \tag{1}$$

Where Y is the system controller output (dependent variable, here force), f is a function of X_1 *and* X_2 which are independent input variables. This function relation maps the input domain into the output domain of the controller based on the arithmetic computation of the associated membership functions (MFs).

The fuzzy controller output value in Fig. 1, is a derivation of the fuzzyfied input values subjected to fuzzy arithmetic and criterion (Mamdani inference rule base). The fuzzy arithmetic and criterion have associated membership functions which are responsible for computational procedure. For instance, during fuzzyfication of the input values from sensors, inputs are converted into different membership groups depending on the nature of the input, thus the output is dependent on the input membership group value [3], [5].

Fig. 1, is analogous to human thinking in the sense that our daily routines are engulfed by fuzzy thoughts, judgments and other related assimilations without much consideration of the control algorithm employed. For instance one might give *"very good"* or *"good"* as a response to a questionnaire survey. Generally these answers do not give much information to the surveyor since they are just simple linguistic variables without any degree of measurement. How much is *"very good"* and *"good"?* Although this is lack of quantification is normal for human beings it is not appropriate for a machine, which has to be precise and accurate. To implement a fully functional fuzzy logic technique for the problem in this paper, the following primary components are defined [6].

A. Fuzzyfication

This is the first step of any fuzzy logic controller, where all associated input variables are converted to fuzzy shapes and then values. This progression is of utmost importance and to accomplish it, designated sensors need to be installed exclusively for the purpose of providing desired measurements for the process. The fuzzyfication process is a meticulously executed process involving sorting input variables into assimilated MFs. The MF shapes vary depending on the preference of the designer; they can be semi-circular/gaussian, triangular, etc. Here, a triangular shape has been used. Each MF has a strength value associated with it, crucial for fuzzy computation [7]. MFs are superimposed one over another forming a complete diagram of the inputs and their strengths.

B. The Rule Base or Inference Engine

The fuzzy rule base is composed of linguistic variables; IF-THEN statements which are built on the reasoning, intuitiveness and experience of the designer and which should be easy to understand [8]. The statements are stored in a set of rules. The linguistic statements are conditional statements which aggregate to yield a sound solution to a problem. These condition statements incorporate a certain degree of precision

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(strength) ranging from zero (0) to one (1), so that any rule fired can attain any number between 0 and 1 whilst the universe of discourse presents the amount of control output at the quantization level. Anything outside the range is deemed inadmissible. The range $0 \le x \le 1$ (where x represents the strength of the fuzzy rule) presents the aspect of MFs with universe of discourse within the fuzzy rule base (the inference engine).

The fuzzy rules have their own associated MFs while the aspect of degree of precision (strength) is dependent on the input, which helps sort each rule according to their strength on the MF graph. As already noted, MFs can have different shapes but at the designer's discretion the number of MFs can be increased or decreased, which alters the universe of discourse, without changing the membership range [8], [9]. The MFs are crucial in fuzzy control as the fuzzy output is derived from the associated MFs and the rules stored in the database [10].

The rules used in this paper were derived from common sense, experience and simulation conducted in a controlled environment using Matlab software. The set of rules fired to derive the output are shown in Section 3 of this paper.

C. Defuzzyfication

Defuzzyfication is a procedure used to generate a measurable result in fuzzy logic, given all membership degrees (i.e. the strengths of the rules) and corresponding fuzzy sets. The result brings about the control action or decision. In defuzzyfication a fuzzy set is either minimized or maximized according to the membership degrees. This is accomplished by using logic operators; commonly-used fuzzy logic operators are 'OR' and 'AND' which correspond to Union and Intersection respectively. In fuzzy logic control, Union is interpreted as the minimum and Intersection as the maximum value of the respective rule fired. How these operations are executed is shown in Section 3.1.

Different methods can be employed when defuzzyfying a fuzzy consequent. These methods are the weighted average, mean of maximum, smallest of maximum or centroid of area (also known as center of gravity, COG) [6], [8]. The latter approach has been used in this paper; here rules have to be joined and added together to give the outcome of the combination. In this paper triangular MFs are joined together with the logic operator AND. As explained above all the rule consequents are minimized which means the lowest value of the rule takes precedence. From that minimal point a straight line is drawn, cutting through the triangle; the top part is discarded and the remaining part forms a trapezoid. Remaining shapes are superimposed one upon another forming a complete single shape, from which the center of gravity can be determined according to the rule strengths and universe of discourse. At this point, a vertical line would slice the aggregate fuzzy set into two equal areas [11]-[13]. The overall center of gravity i.e. the consequent denotes the control action of the system. The center of gravity can be determined in two ways; either the continuous or the discrete universe of discourse [14]-[16]. The latter is used here.

Discrete Universe of Discourse; this process produces a discrete (crisp) value; the desired output or machine decision, here the required force. It is expressed as follows [9], [16], [17];

$$Y_{COG} = \frac{\sum_{j=1}^{n} y_j \times \mu_c(y_j)}{\sum_{j=1}^{n} \mu_c(y_j)} \qquad (2)$$

where n is the number of quantization levels of the output, y_j is the amount of control output at the quantization level j, and $\mu_j(y_j)$ represents its membership value in the output fuzzy set c.

III. FUZZY RULES TABLE AND RULES FIRED

A summary of the fuzzy rules used in this paper are shown in Table I, which can be used to generate linguistic rules for the controller, structured as IF-THEN statements. The statements are actually constructed in the form 'IF A and B THEN C', where A, B and C are propositions (statements involving defined terms) containing linguistic variables [7], [8], [11], [14], [18], [19]. Note that A and B are antecedent and C a consequent of the rule. The *and* means an intersection of the rules therefore using fuzzy equivalence and would minimize the rule result.

A total of twenty-five rules can be generated from Table I which in turn provide the optimal outcome at each juncture [20]. For example, two rules that can be fired are; IF Husk Thickness is NH and Clearance Gap is NH Then Force is NH; and IF Husk Thickness is PH and Clearance Gap is PH Then Force is PH. Rule intersection thus provides the desired outcome; the force required to crack the husk, as the consequent of the rule.

Thus the outcomes from firing a set of rules results in coherent reasoning, allowing subjective decision-making.

Table I: Input / Output (I / O) Rule Relationship

		Husk Thickness				
	I / O	**NH**	**NL**	**Z**	**PL**	**PH**
	NH	NH	NH	NH	NL	Z
	NL	NH	NH	NL	Z	PL
Gap	**Z**	NH	NL	**Z**	**PL**	PH
	PL	NL	Z	**PL**	**PH**	PH
	PH	Z	PL	PH	PH	PH

NH – Negative-High, NL – Negative-Low, Z – Zero, PH – Positive-High, PL – Positive-Low [20]

Consider a scenario where four rules are fired to give a response by the system. The different levels of inputs are defined by specifying the membership functions for the fuzzy sets illustrated in Fig. 2. For simplicity and assimilation equal spread of the membership functions is assumed. No scales are given in Fig. 2 but values can be estimated.

The four fuzzy rules used in deriving Fig. 2 are as follows;

- → IF Husk Thickness is Z and Clearance Gap is Z Then Force is ZERO.
- → IF Husk Thickness is Z and Clearance Gap is PL Then Force is PL.
- → IF Husk Thickness is PL and Clearance Gap is Z Then Force is PL.

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→ IF Husk Thickness is PL and Clearance Gap is PL Then Force is PH.

These rules have specific values (strengths) associated with them and indicate how each rule will influence the response of the system. Referring to (a) in Fig. 2, the strength of each input is measured to be 0.75 for Z and 0.35 for PL. In (b) the rule strengths are 0.45 for Z and 0.65 for PL. Referring again to (a) and considering rule 1, the actual value belongs to the fuzzy set zero with a degree value of 0.75 (thickness) and 0.45 (clearance). The operator is and, therefore the minimum criterion is used for all the fuzzy sets [20].

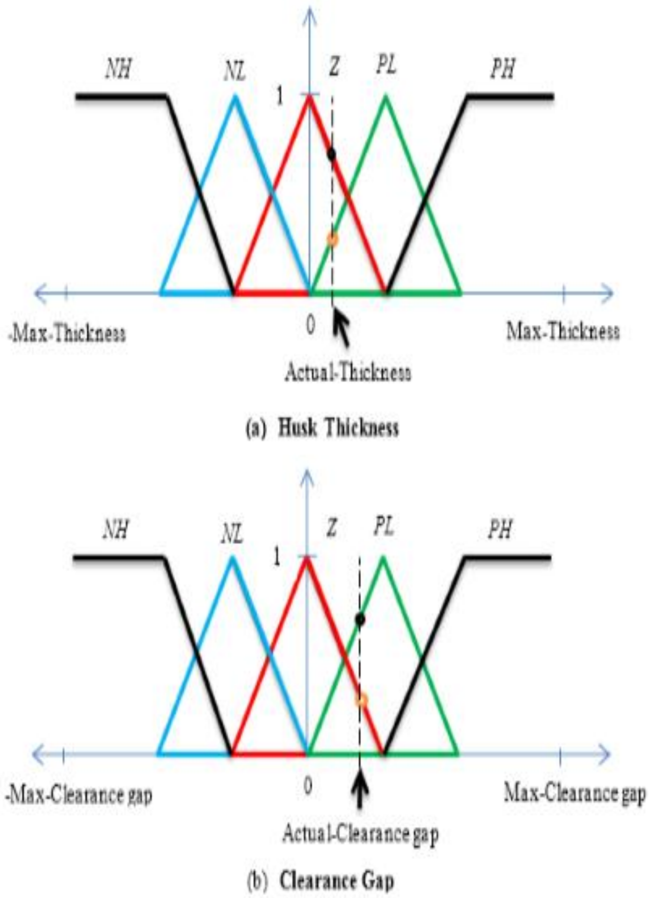

Fig. 2. Input membership functions

A. *Intersection of Rules using Minimization*

The outcome of applying minimum criteria to Rule 1 is illustrated in Fig. 3. The resulting forces for minimizing the remaining rules are shown in Fig. 4.

The strengths of each rule fired are as shown below:

$$Rule\,1 \rightarrow \mu_{Thickness \cap Clearance} = \min(\mu_{Thickness}, \mu_{Clearance}) = \min(0.75, 0.45) = 0.$$

$$Rule\,2 \rightarrow \mu_{Thickness \cap Clearance} = \min(\mu_{Thickness}, \mu_{Clearance}) = \min(0.75, 0.65) = 0.$$

$$Rule\,3 \rightarrow \mu_{Thickness \cap Clearance} = \min(\mu_{Thickness}, \mu_{Clearance}) = \min(0.35, 0.45) = 0.$$

$$Rule\,4 \rightarrow \mu_{Thickness \cap Clearance} = \min(\mu_{Thickness}, \mu_{Clearance}) = \min(0.35, 0.65) = 0.$$

The minimized diagrams overlap and reduce to the dotted shape shown in Fig. 5.

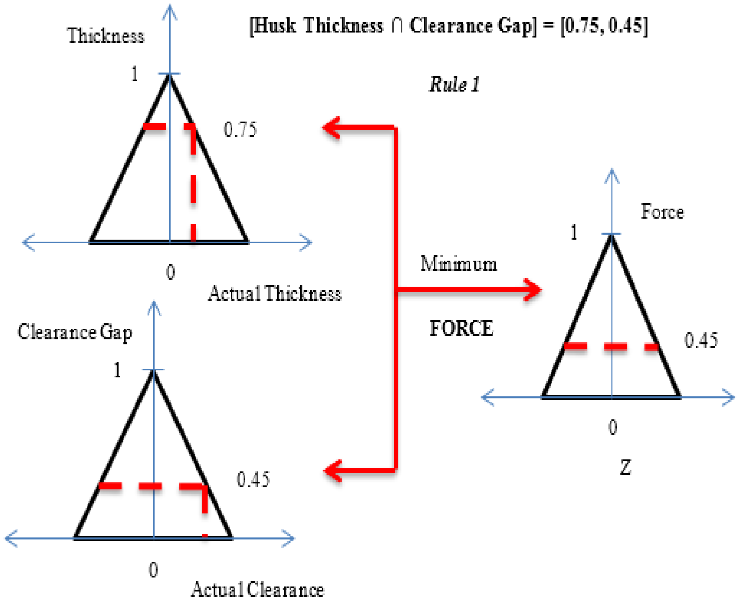

Fig. 3. Resulting force from minimizing criteria with rule 1

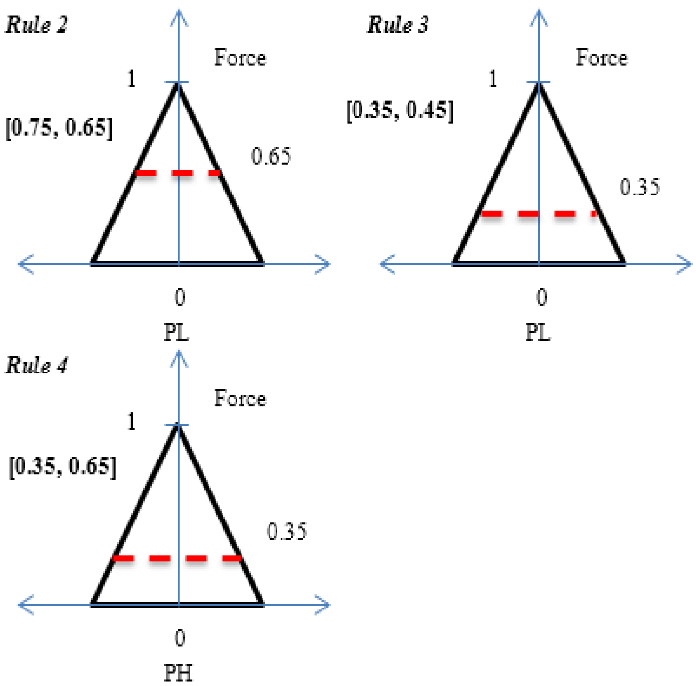

Fig. 4. Forces resulting from rule minimization

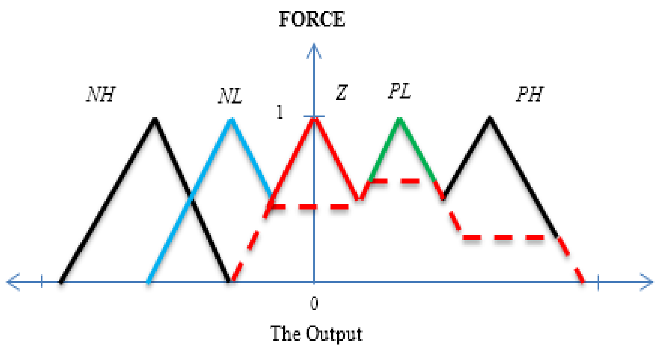

Fig. 5. The fuzzy set of the output force

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Centroid Method: The area under the dotted line signifies the overall force output of the fuzzy rules of the controller. At this stage this output remains the fuzzy set of the force yet to be defuzzified to obtain a crisp value of the force required. Using the COG method the dispersed weights are accumulated/aggregated to yield a composite force as shown in Fig. 6.

The value represented by a fuzzy set or collection of membership degrees now needs to be defuzzified to a crisp value; a genuine consequent for any fuzzy controller is a numerical value as an output. The crisp value becomes the non-fuzzy control action taken by the machine which results in it imposing sufficient force on the husk to cause it to crack.

Values for y_j and μ_c can be read from Fig. 6 and substituted in Equation (2) as follows:

$$Y_{COG} = \frac{-0.05(0.45)+0.25(0.65)+0.65(0.35)(2)}{0.45+0.65+0.35(2)} = \frac{0.595}{1.8}$$

$$= 0.33 \, units\ of \ \ force$$

The same crisp value is obtained directly using the fuzzy toolbox in Basic Matlab software which saves time as well as precluding errors in calculation [11], [13]

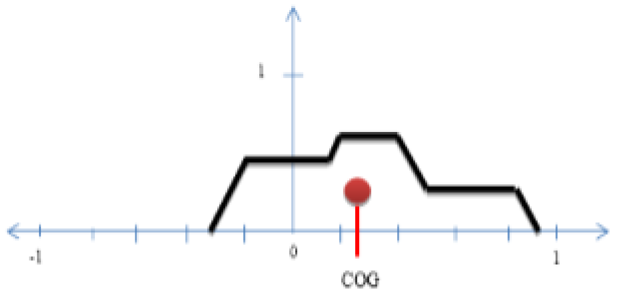

Fig. 6. Final output - Crisp Value of Force

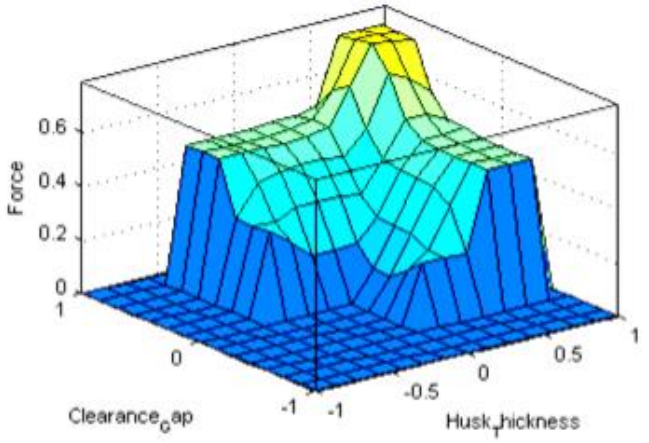

Fig. 7. 3-D Graphical Surface View of the Input-Output Relation

IV. RESULTS AND DISCUSSION

Designated sensors concurrently detect input quantities which are fuzzyfied as described in *section A*. The fuzzyfication process maps each input quantity to the associated membership functions. Using these MFs along with their IF-THEN rule strengths and fuzzy set operations, a fuzzy output is determined using cognition of fuzzy rules and a fuzzy inference engine. The fuzzy output is converted to a non-fuzzy output (crisp value) through the defuzzyfication criteria as described and illustrated above. The non-fuzzy output in this paper is the decorticating force.

A three-dimensional graphical surface [21]-[23] of the fuzzy rules given in Section 3 is shown in Fig. 7. This input-output surface relation is illustrates a continuous spread of force dependent on the input quantities being detected. The graph shows how the decorticator machine will respond when subjected to different input quantities. For instance, if the husk thickness and clearance gap are both zero (0), Fig. 7 shows that the modeled output force is also equivalent to 0. At values close to one (1) for husk thickness and clearance gap, the force required is maximum. This is a plausible, particularly suitable and highly convincing outcome for a decorticating machine with controller.

V. CONCLUSION

Through the use of fuzzy logic the force required was determined for each input quantity detected and a crisp value obtained. The human designer's interpretation of the problem has aided in the determination of the overall output force required to be imposed on each individual morama bean and enabled the decision making of the decorticator. The designer's intuition and knowledge has been transferred to the decorticator machine control mechanism which allows automation of the decorticator machine. The results obtained indicate that the approach developed in the paper is plausible and this opens the way for design of sensors and other control aspects to be researched. These control aspects include the loading time and alignment of the morama bean at loading as well as separation of the husk from the seed. Furthermore, the approach used could be applied to other commodities.

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