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MECHANICAL STRAWBERRY HARVESTING

by

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ABSTRACT

Total strawberry production in both Canada and the United States has been steadily declining for the past decade. This trend can, to a large extent, be attributed to the increasing cost and difficulty of getting this crop manually harvested. This research, therefore, is directed toward development of a mechanical harvesting system for strawberries.

During initial development of any new concept, a system analysis should be undertaken to ensure that excessively complicated problems will not arise unexpectedly and to ensure that redundant research is not undertaken. Such an analysis indicated that the development of a once-over harvesting system is more feasible than the development of a selective harvesting system. The analysis also indicated that system development will require input from engineers, fruit growers, fruit processors and horticulturalists. An attempt is made to allocate appropriate areas of investigation and research to each of these groups. Group interactions are also investigated.

To successfully develop the proposed system, one essential step is development of a mechanical picking machine. A design, based on the physical and mechanical properties of the strawberry fruit and plant, was used to build a picking machine model. This model was field tested and evaluated. Limited field tests indicated that some field preparation for mechanical harvesting is essential and that a vacuum fruit pick up device should be considered to assist machine feeding. Tests indicated, however, that the proposed concept can be used to remove berries from the plant with very little fruit damage.

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TERMINOLOGY

Bioyield Point: The first point on the force-deformation curve at which there occurs no increase in force with increased fruit deformation. For visco-elastic materials, the corresponding force (the bioyield force) will increase with increased deformation rate.

Bruising: Damage to plant tissue by external forces causing change in texture and/or eventual chemical alteration of color, flavor and texture (9)[1]. In this study, bruising was assumed to occur when the bioyield stress was exceeded.

Fruit Retention Force: The tensile force required to detach a strawberry from its plant. In this study, detachment occurred at either the fruit-petiole interface or at a secondary stem location.

Growth Regulator: An organic compound which, when introduced into a plant in a relatively small quantity, induces effects in the growth pattern of the fruit (9).

Initial Tangent Modulus: The slope, at the origin, of the force-deformation curve for strawberries under compressive loading.

Linear Limit: The force at which the force-deformation curve for a compressed berry deviates from linearity.

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1 Numbers in parentheses refer to references listed in the literature cited.

Normal Population: A population whose frequency function is

$$f(Y) = [\frac{1}{\sqrt{2\pi}\ \sigma}]\ e^{-\frac{1}{2\sigma^2}(\gamma-\mu)^2}$$

where:

γ = any random variable

σ = population standard deviation

μ = population mean

All biological populations which were investigated in this study were assumed to be normally distributed. Furthermore, the sample mean and deviation were assumed to equal the mean and deviation for the population.

Runners: Vine-like structures, grown by strawberry plants, which subsequently root and form new plants.

Solid-bed Plantings: Cultures where plants are not confined to rows but are permitted to cover the entire field area.

Terminal Velocity: The velocity at which the drag forces on a particle equal its gravitational force.

Upright Varieties: Strawberry varieties that produce fruit which mature above the ground surface.

NOMENCLATURE

A_b — a constant, used in the Hertz contact stress problem, dependent upon the elastic and deformation properties of strawberries and picking belts.

A_p — a constant, used in the Hertz contact stress problem. dependent upon the elastic and deformation properties of strawberries and steel.

BYF — bioyield force of whole strawberry fruit under uniaxial compression at a loading rate of .5 cm/min.

d — sphere diameter used in the Hertz equation.

d_p — particle diameter.

D_b — base diameter of strawberry fruit.

D_c — calculated fruit diameter.

D_f — spacing between adjacent picking fingers.

D_m — sample mean of berry base diameters.

E_b — Young's modulus for picking belts.

E_p — Young's modulus for steel.

E_s — Young's modulus for strawberries.

$f_1, f_2, \ldots f_n$ — functional relationships.

f_d — drag coefficient.

f_L — factor dependent upon picking finger length and nozzle shape.

F_d — difference between the tensile strength of the main stem and the FRF (fruit retention force).

F_h — compressive force between a spherical body and a flat plate.

F_{max}	the estimated maximum compressive force that picking belts can exert on berries without causing bruising.
F_r	compressive force exerted on berries by the picking belt during the fruit removal operation.
FRF	force required to remove berries from the plant (fruit retention force).
g	gravitational constant.
G	terrain suitability for shoe floatation.
ℓ	stem length (this is also the maximum height that a berry can be lifted without removing it from the plant.
ℓ_m	sample mean of stem lengths.
L	picking finger length.
μ_b	Poisson's ratio for picking belts.
μ_p	Poisson's ratio for steel.
μ_s	Poisson's ratio for strawberries.
M	strawberry volume.
P_c	fruit conveying efficiency.
P_f	fruit feeding efficiency.
P_r	fruit removal efficiency.
P_a	air density.
P_p	particle density.
R	berry bruising resistance to impact force.
S_b	estimated fruit bruising stress.
S_n	nozzle shape factor.
S_s	shoe shape factor.
S.D.	sample standard deviation.

S_{max}	maximum contact stress as estimated by the Hertz equation.
θ	the angle between the upper belt surface and the soil surface (also called the tool inclination).
T	type of picking belt.
V_1	velocity of the upper belt surface with respect to the picking machine.
V_2	ground speed of the picking machine.
V_3	velocity of the upper belt surface with respect to ground $(\vec{V}_3 = \vec{V}_1 + \vec{V}_2)$
V_b	blower face velocity.
V_c	estimated fruit conveying velocity at maximum tool inclination.
V_f	terminal or floating velocity for a spherical particle.
V_t	terminal velocity for strawberries.

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INTRODUCTION

1.1 The Purpose of this Research

In spite of the introduction of high yield, disease resistant strawberry varieties and the widespread use of cost saving chemicals, strawberry production in both Canada and the United States has been steadily declining for the past decade. This trend can be attributed to the increasing difficulty of recruiting pickers to manually harvest the strawberry crop. People are becoming increasingly reluctant to accept the wage rates which growers are presently offering to harvest their crop. Growers, on the other hand, find it economically impossible to offer more attractive rates. If commercial strawberry production is not to become obsolete within the next several decades, a system for mechanically harvesting this crop must be developed.

1.2 The Scope of this Research

All harvesting systems, whether manual or mechanical are of two types. Fruit can be selectively harvested as the crop matures or the entire crop can be harvested at an optimum harvesting time (once-over system). Once-over harvesters are simpler to construct and easier to design than selective harvesters. Most existing mechanical harvesters for all types of crops are the once-over type. Preliminary investigation shows that, for strawberries, the once-over concept is more suitable than the selective harvesting concept. Many problems associated with selective harvesting do not have practical solutions at present. Practical and economically sound solutions to problems associated with once-over harvesting are easier to find.

This thesis, therefore, outlines the phases for development of a once-over harvesting system for strawberries.

1.3 Survey of Previous Work

Due to the increasing cost and decreasing availability of appropriate labor, much research has recently been directed towards the mechanization of fruit and vegetable crops. Labor difficulties have prompted several researchers to search for means of mechanically harvesting strawberries.

Buchele and Denisen (2) were among the first to attempt to develop a mechanical strawberry harvesting system. As well as suggesting several cultural modifications, they suggested that the "stone fork" principle could be used to mechanically harvest strawberries. Only moderate success is indicated by their reported results; however, suggested cultural modifications such as the use of certain types of mulches, removing leaves before mechanical harvesting, and the use of bed leveling and raking operations have been used by most subsequent researchers and will likely form necessary operations for commercial mechanical harvesting.

To feed berries into the picking tool more efficiently than multi-forked "scoop" and "reel" type pickers, Quick (13) suggested the use of vibrating picker-teeth. Picking teeth, vibrating in the horizontal plane, could be maintained close to the soil surface at all times — a condition that cannot be attained by using "scoop" or "reel" mechanisms. It is reported that the use of a machine embodying this principle, on wide flat strawberry beds, could potentially harvest 95 percent or more of available berries.

Nelson and Kattan (10) appear to be the first to use a vacuum pick-up to assist machine feeding. If soil contamination of the harvested fruit can be held within acceptable limits, this concept will likely be used on commercial harvesting machines. Hanson (5) indicates that a harvester using the vacuum pick-up principle has been used in Michigan with satisfactory results.

DEVELOPMENT OF A HARVESTING SYSTEM

2.1 Initial and Final Conditions

Logical investigation of any system requires a clear understanding of system boundaries (16). The purpose of this research is to develop a mechanical harvesting system for strawberries. The initial (input) condition for the proposed harvesting system is defined as "existing commercially grown strawberry cultures" (Figure 1). The final (output) condition is defined as "mechanically harvested fruit suitable for processing by existing methods". System components convert the initial condition into the final condition.

2.2 System Components

Investigation shows that the mechanical harvester will form only a small part of a new harvesting system. It seems unlikely that a mechanical harvester can be designed to acceptably harvest existing varieties grown under present cultural methods; nor does it seem likely that harvester output will be acceptable to processors until subsequent operations are performed on the harvested berries.

Obviously, the proposed harvesting system cannot be developed by researchers of a single discipline. A cooperative effort by horticulturalists, fruit growers, engineers and fruit processors is required. Basically, therefore, the proposed system will have four components interrelated by appropriate feedback loops (Figure 2).

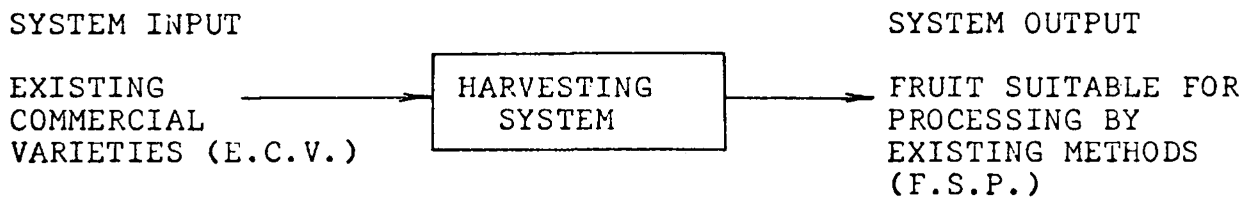


FIGURE 1 System Boundaries

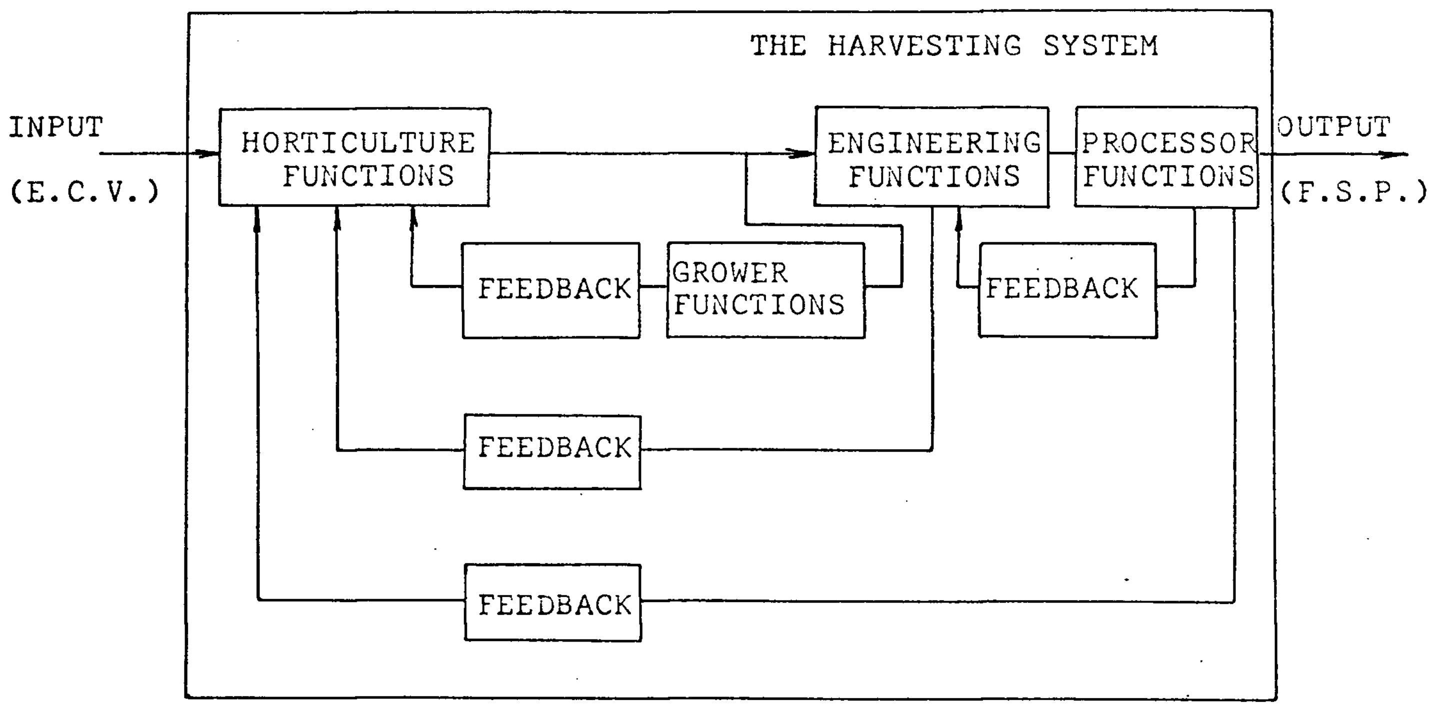


FIGURE 2 System Components

2.3 The Processor Component

Within the system, the processor must perform three basic functions on the mechanically harvested aggregate (foliage, mature fruit and greens). These are to ensure that the harvested fruit will have good processing characteristics, to sort out usable fruit from the mechanically harvested aggregate and, if required, to hull the usable fruit (Figure 3).

The mechanical harvesting strawberry culture must yield fruit which has suitable processing characteristics. Mechanically harvesting strawberries which are unacceptable to consumers is a fruitless task. Feedback information to the horticulturalist will specify the essential processing characteristics.

The mechanically harvested aggregate will, in all likelihood, contain some plant foliage, as well as green, moldy and mechanically damaged fruit. These are undesirable for most processed products and therefore must be sorted from the usable fruit. Feedback information will tell the engineers whether the level of mechanical fruit damage and the amount of plant foliage is within acceptable limits. If these are unacceptable, engineers must find a method of reducing the unwanted debris to acceptable levels. This will involve redesigning the harvesting machine and/or mechanically harvesting more suitable strawberry cultures. Other feedback information will tell horticulturalists whether the amount of

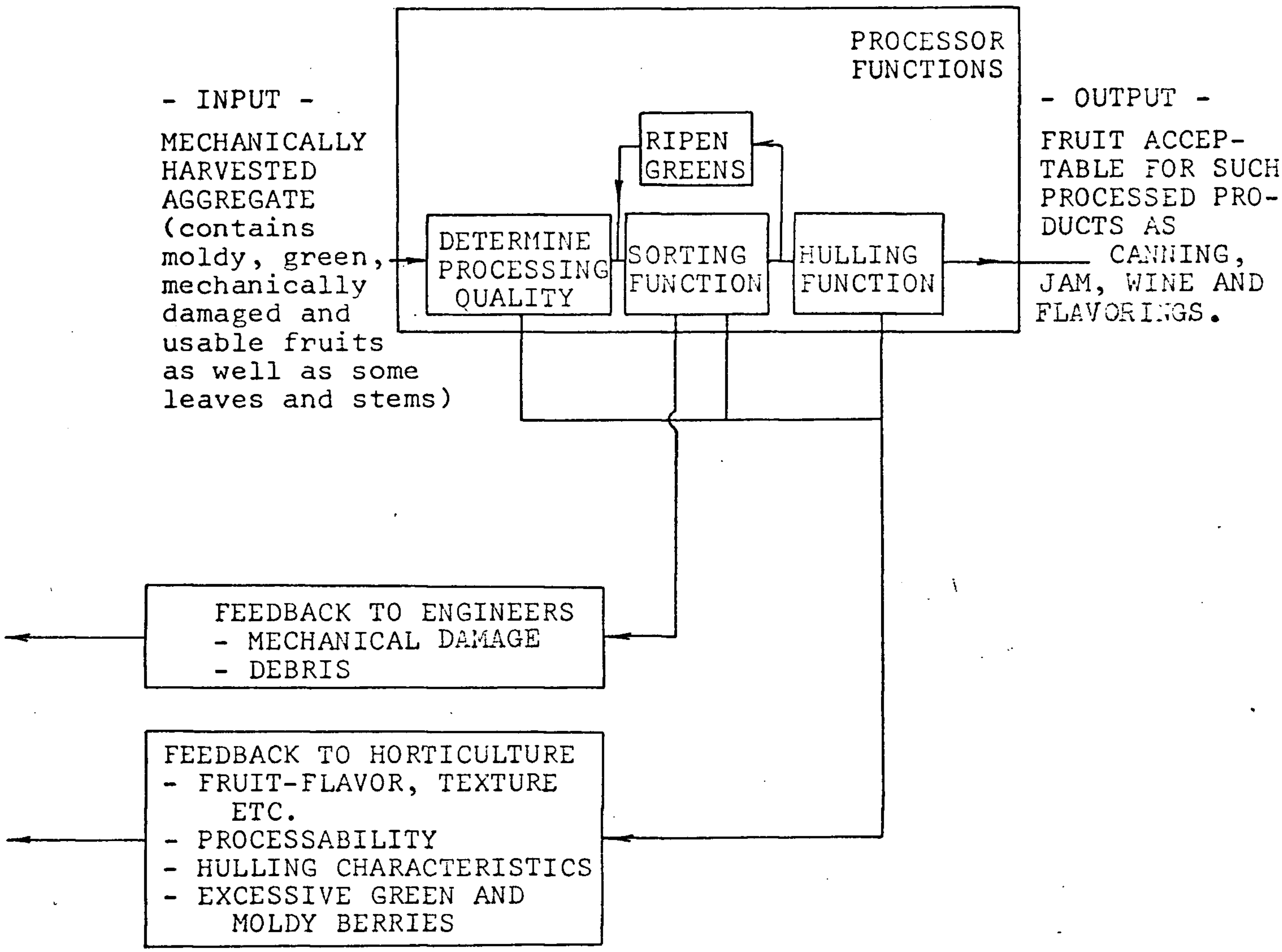


FIGURE 3 The Processor Component

green and moldy berries contained in the harvester output aggregate is within acceptable levels. If it is not, horticulturalists will have to consider the use of growth regulating chemicals, fungicides and genetic selection.

Fruit stems and hulls are undesirable for processing. The harvested fruit must either self-hull when mechanically picked (fruit retention force < stem strength) or else have hulls which can easily be mechanically detached. Feedback information to horticulturalists will indicate whether the mechanical harvesting culture has the necessary hulling characteristics.

2.4 The Engineering Component

The engineer's primary function is to design a mechanical strawberry harvesting machine. The type of machine will depend primarily upon the culture developed by the horticulturalists (the input to engineering functions). Feedback information to the horticulturalist will indicate those cultural characteristics which are desirable for mechanical harvesting (Figure 4).

All mechanical harvesters can be classified into two groups, selective harvesters and once-over harvesters. Because once-over harvesters are simpler in construction and much easier to design than selective harvesters, most mechanical harvesters used in agriculture (grain combines, tomato harvesters, grape harvesters etc.) are of the once-over type (11).

Preliminary investigation indicated that, for

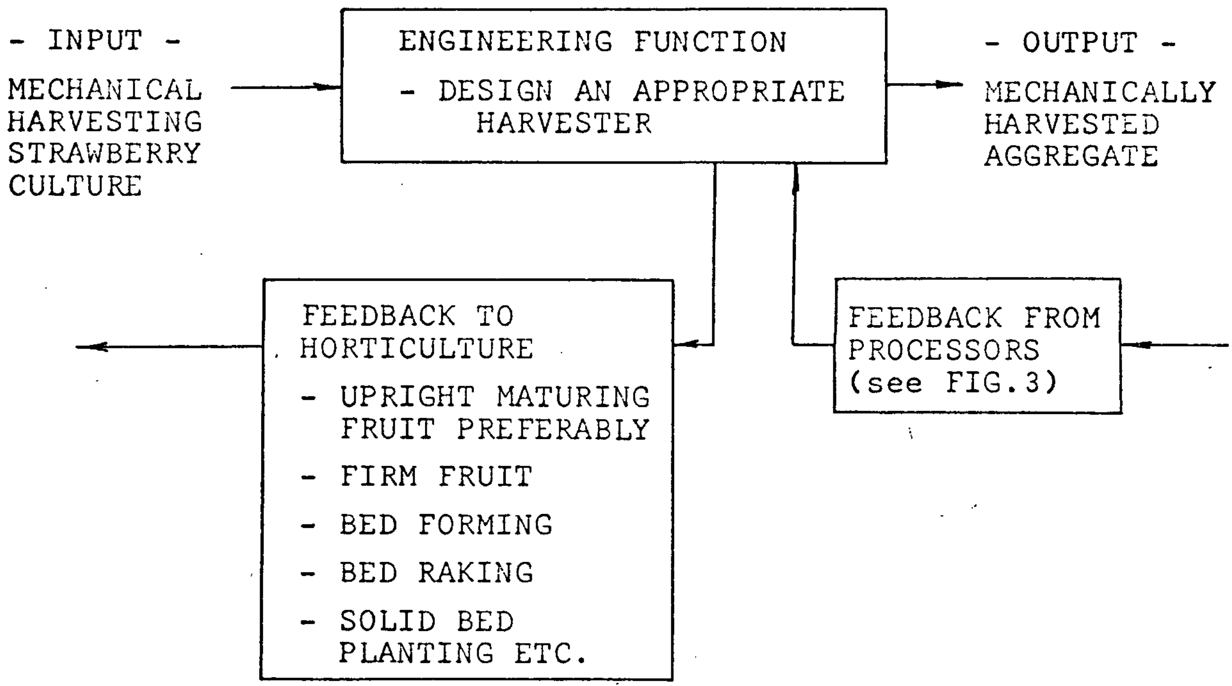


FIGURE 4 The Engineering Component

strawberries, the once-over concept is more suitable than the selective harvesting concept. Some reasons for selecting a once-over harvesting system are:

1) Selective picking mechanisms which would be capable of selectively picking only quality berries at high rates without causing excessive mechanical damage to the fruit would make a harvester excessively complicated.
2) Mechanical damage to both the plant and fruit resulting from multiple passes over the crop would be more difficult to resolve than for a single pass.
3) Genetic selection of uniformly maturing plants, judicious use of fungicides such as Captan, and sound maturity monitoring techniques will likely make selective harvesting unnecessary.

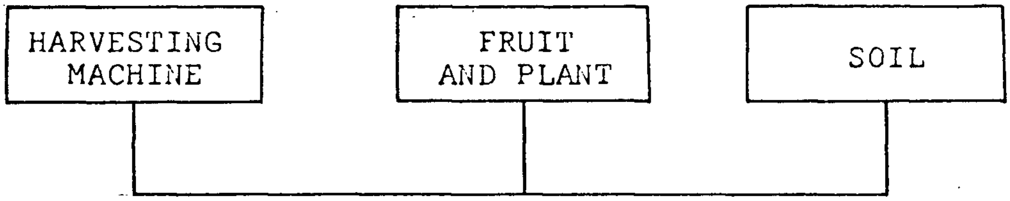
Present commercially grown strawberry varieties yield fruit which mature primarily on the ground surface. These are referred to as "surface maturing" varieties. The development of mechanical harvesters to date has been primarily directed towards harvesting these varieties. Plant breeders in Ontario and California have recently begun development of strawberry varieties which yield fruit that matures above the soil surface. These are referred to as "upright" varieties. The development of a machine for mechanically harvesting these varieties can be expected to be much easier than development of a harvester for surface maturing varieties. Since the fruit is located above the soil surface, ground contour and surface debris will not hinder operation. Greater forward speeds should be possible since picking head height control need not be as critical and better fruit quality can be expected since soil contamination is less likely to occur. For these varieties, the designer need only consider machine-plant interactions, whereas for surface maturing varieties, he must consider not only machine-plant interactions but also machine-soil and soil-plant interactions (Figure 5). Test results with a prototype mechanical daffodil header (15) indicated that a once-over harvester for upright strawberry varieties (Machine A, Figure 6) would be relatively easy to design. Less radical cultural modifications would be required to once-over mechanically harvest surface maturing varieties (Machine B, Figure 6). Most of the published results on mechanical strawberry harvesting have had this objective in mind. Cultural modifications would include solid-bed plantings and preharvest bed preparation (bed raking, forming and compacting).

2.5 The Grower Component

The mechanical harvesting culture developed by the horticulturalist will not form part of a commercially valuable system unless it is acceptable to commercial growers. The new culture must be easy to grow and give more economic returns than existing strawberry cultures (Figure 7).

2.6 The Horticultural Component

The horticultural input is probably the most important



A. INTERACTIONS FOR MECHANICALLY HARVESTING SURFACE MATURING FRUIT

B. INTERACTIONS FOR MECHANICALLY HARVESTING UPRIGHT MATURING FRUIT

FIGURE 5 Comparison Between Mechanically Harvesting Surface and Upright Setting Strawberry Fruit.

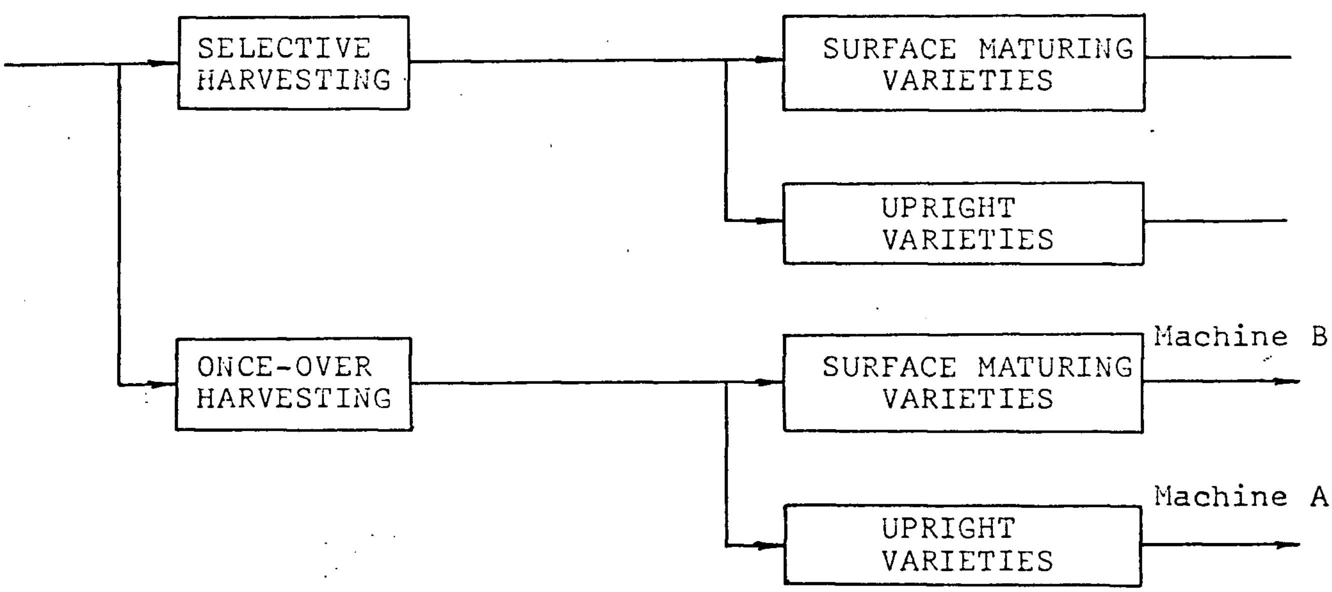


FIGURE 6 Mechanical Harvesting Alternatives

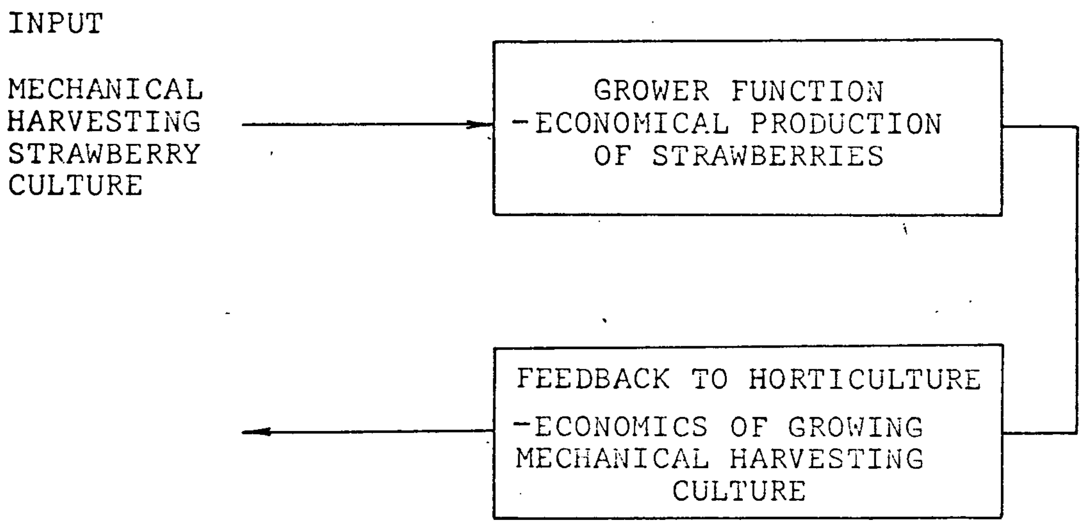


FIGURE 7 The Grower Component

and most difficult to resolve part of the proposed harvesting system. Research to date indicates that existing strawberry cultures are not well suited for mechanical harvesting. Commercial varieties and commonly employed cultural practices have been developed to optimize manual harvesting. Existing varieties and cultural methods must be modified if mechanical harvesting is to become a reality. Using feedback information from growers, engineers and processors, the horticulturalists' task is to produce a commercially valuable, strawberry culture suitable for mechanical harvesting (Figure 8).

2.7 Summary

A new system of strawberry production must be developed before commercial mechanical harvesting can become a reality. System development will be a joint task among horticulturalists, growers, engineers and processors. The mechanical harvesting machine is only one component of this system. Equally important is the development of a strawberry culture suitable for mechanical harvesting. In all likelihood, mechanically harvested fruit will be inferior in quality to hand picked fruit and therefore must be used for processing. One possibility is to manually harvest the primary (king) berries for premium fresh market prices and to mechanically harvest the remainder for the processing market.

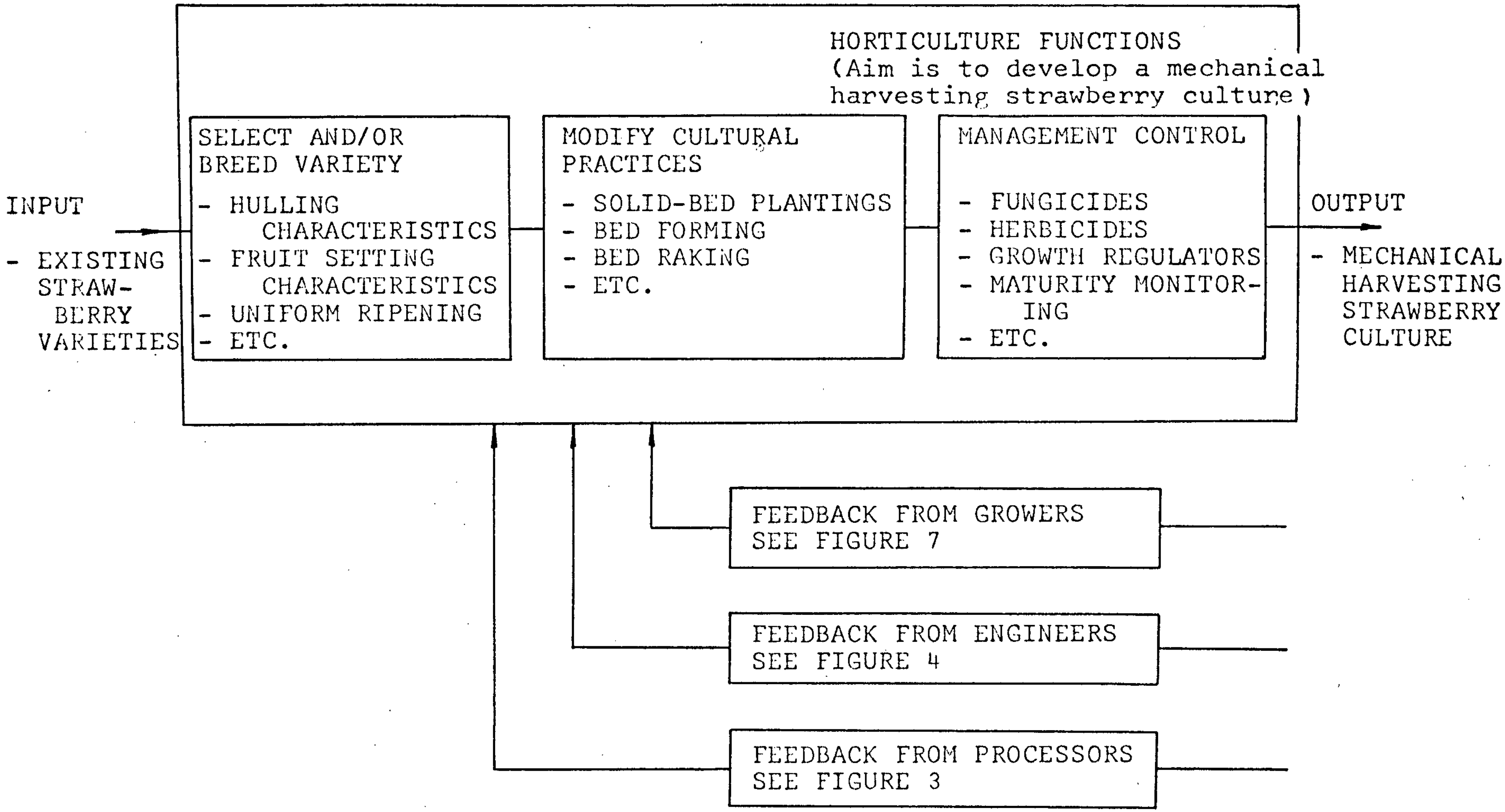


FIGURE 8 The Horticulture Component

THE MECHANICAL STRAWBERRY HARVESTER

3.1 Operational Requirements

As previously indicated, horticulturalists, growers, processors and engineers will all be required to develop the proposed mechanical strawberry harvesting system. The engineers' primary function is to build the mechanical harvester. Many problems associated with selectively harvesting strawberries do not have practical solutions. Practical and economically sound solutions to problems associated with once-over harvesting appear to be easier to find. Machine design was, therefore, directed toward development of a once-over harvester.

A machine suitable for harvesting upright varieties will be relatively simple and can be expected to possess high fruit removal efficiency. At present, however, most commercially grown strawberries are of the surface maturing type. If a mechanical harvester is to be suitable for present commercial varieties, it must be capable of harvesting surface maturing varieties. Harvester design, discussed in the following pages, is therefore directed toward development of a once-over machine for surface maturing strawberries.

3.2 The Process

A flow chart, outlining the basic operations which must be performed by a once-over mechanical strawberry harvester is shown in Figure 9. Each block in the flow chart represents a basic process function. Functions 2 to 4

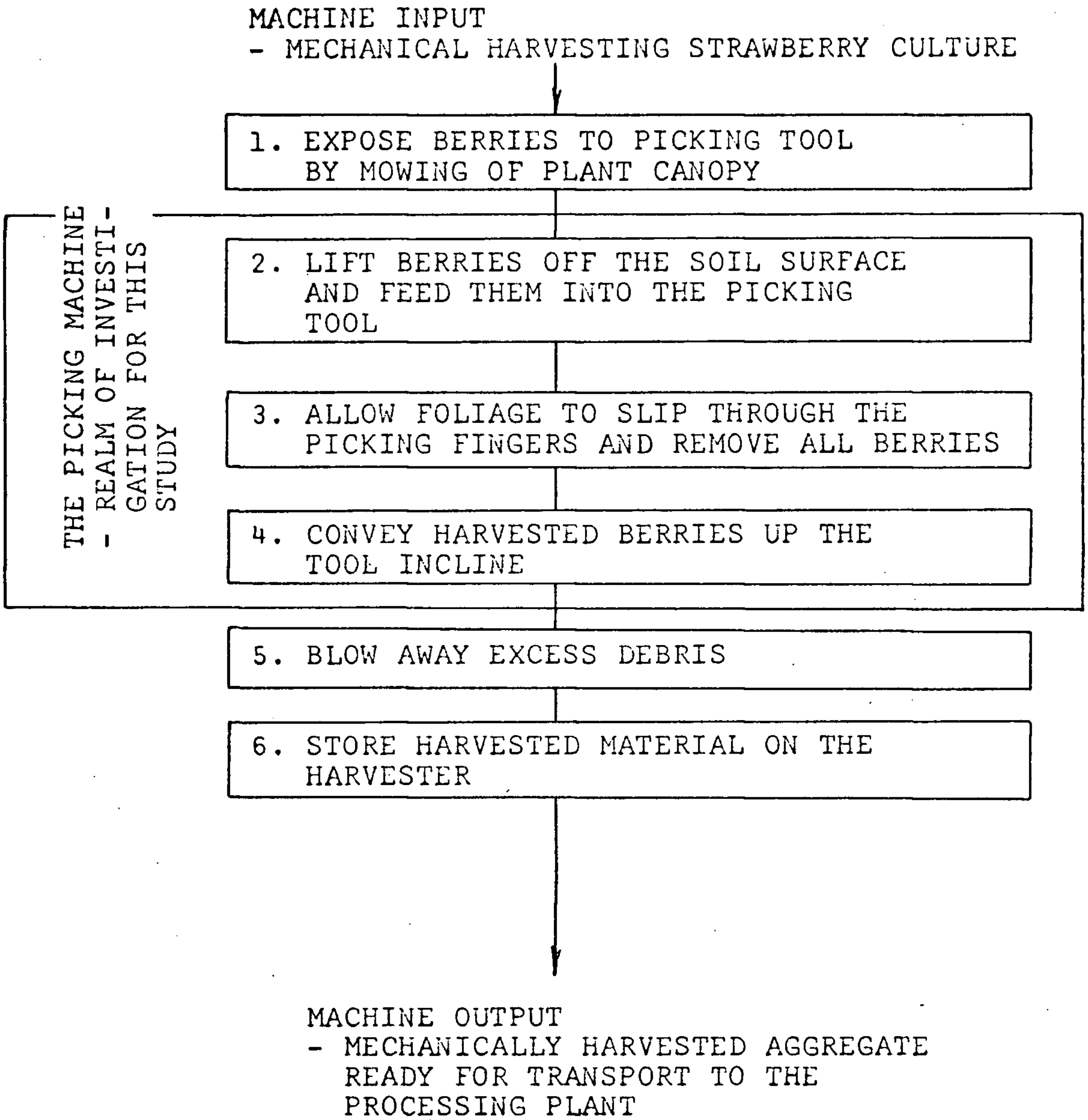


FIGURE 9 A flow chart illustrating those functions which must be performed by the proposed once-over mechanical strawberry harvester.

logically fit into one machine. The following sections outline the design and fabrication of a machine to perform these three functions. This machine will subsequently be referred to as the picking machine in order to differentiate it from the mechanical harvester which must perform all the functions outlined in Figure 9. The flow chart for the proposed picking machine is shown in Figure 10.

3.3 Tool Configuration

The proposed picking machine is schematically illustrated in Figure 11. It is comprised of two basic tools — a picking tool and a fruit conveying tool. The picking tool feeds berries between adjacent picking fingers and removes berries from the plant. The conveying tool transports harvested berries to the rear of the picking tool.

The picking tool consists of a series of fingers mounted on a common drive shaft. This shaft drives endless belts mounted on each picking finger. Fingers, spaced at less than minimum fruit diameter, are pivoted about the drive shaft, thus permitting them to follow soil surface irregularities. The front pulley on each finger is small enough to go beneath individual fruit. A pointed shoe positioned around each front pulley aids both in floatation and in feeding.

The conveying tool consists essentially of an air blower. As well as conveying harvested berries to the rear of the picking tool, the blower aids in cleaning the harvested aggregate of leaves and other debris.

INITIAL CONDITION: EXPOSED BERRIES READY FOR MECHANICAL HARVESTING

↓

1. LIFT BERRIES OFF THE SOIL SURFACE AND FEED THEM INTO THE PICKING TOOL

2. ALLOW PLANT MATERIAL TO SLIP THROUGH THE PICKING FINGERS AND REMOVE ALL BERRIES

3. CONVEY HARVESTED BERRIES UP THE PICKING TOOL INCLINE

↓

FINAL CONDITIONS: MECHANICALLY HARVESTED BERRIES IN TEMPORARY STORAGE

FIGURE 10 A Flow Chart for the Proposed Picking Machine.

3.4 Factoral Analysis of Picking Machine Functions

The overall performance of the proposed picking machine will depend upon the efficiency with which this machine performs each of its intended functions. Functional efficiency will be determined by a number of machine design parameters. These parameters will in turn be governed by relevant physical properties of the strawberry plant and fruit.

3.4.1 The feeding function

For fruit lying at random on the soil surface, the feeding operation occurs in two steps. The fruit is first picked off the soil surface and placed on the moving belt of the picking finger. The fruit then positions itself between two picking fingers so that the picking operation can occur. Obviously, for upright growing varieties, the picking tool will not have to perform the first operation.

Figure 12 illustrates the expected interaction between the front end of a floating picking finger and a strawberry. As contact is made between the shoe and the fruit, the fruit, due to its mass, momentarily remains stationary. The relative motion of the fruit with respect to the shoe at this instant causes the fruit to slide up the shoe and onto the belt. If the width of the belt is narrow compared to the space between adjacent fingers, no positioning device is required. The only requirement is that the strawberry stem is situated between two fingers.

The tool parameters which can be expected to affect

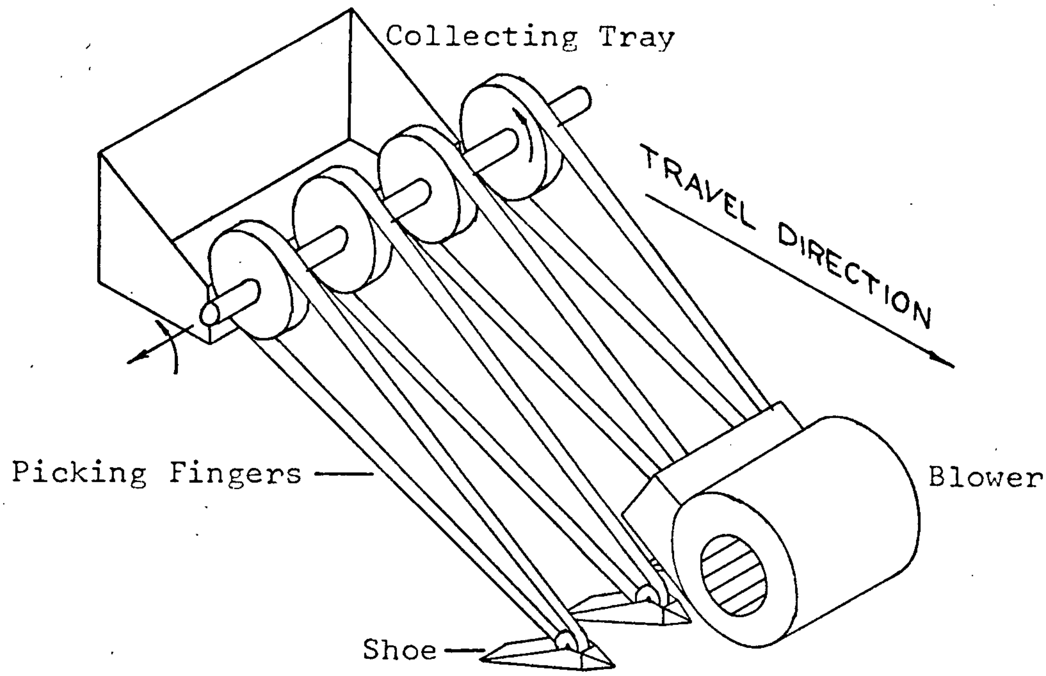


FIGURE 11 A Schematic of the Proposed Picking Machine

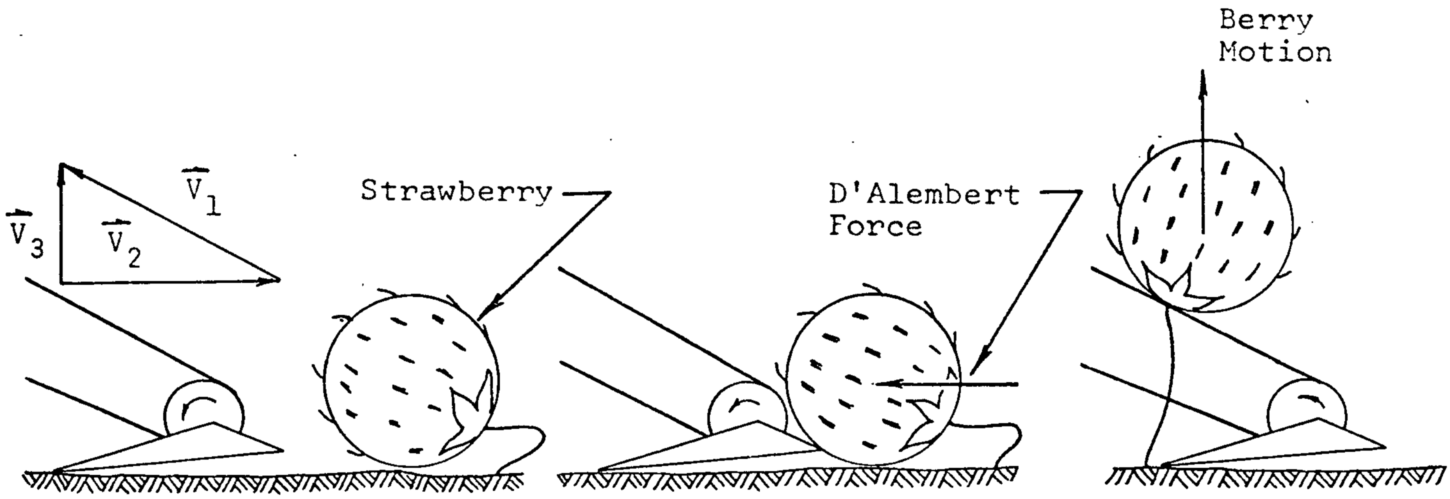


FIGURE 12 The Feeding Function

the feeding efficiency of the proposed design can be summarized by the following functional relationship.

$$P_f = f_1\ (D_f,\ S_s,\ V_2) \qquad [1]$$

where: P_f = feeding efficiency

D_f = spacing between adjacent picking fingers

S_s = shoe shape factor

V_2 = ground speed of the picking machine (fruit impact velocity)

Optimum values for the parameters on the right side of the equation [1] will be determined by relevant properties of the fruit and plant.

$$(D_f,\ S_s,\ V_2) = f_2\ (G,\ R) \qquad [2]$$

where: R = berry resistance to impact forces.

G = terrain suitability for shoe floatation.

3.4.2 <u>The picking function</u>

If picking belt velocity (Figure 13) is appropriately synchronized with the forward velocity of the prime mover (tractor), the fruit, after being placed on the picking belts, will be lifted vertically upward until stem failure occurs. When stem failure occurs, the berry is picked.

For proper synchronization of belt to tractor velocity

$$|\ \vec{V}_2\ | = |\ \vec{V}_1\ |\ \cos\theta \qquad [3]$$

where: $\vec{V}_1$ = velocity of the top surface of picking belts with respect to the machine

θ = the angle between the top belt surface and the soil surface.

The vector velocity diagram for a point on the top

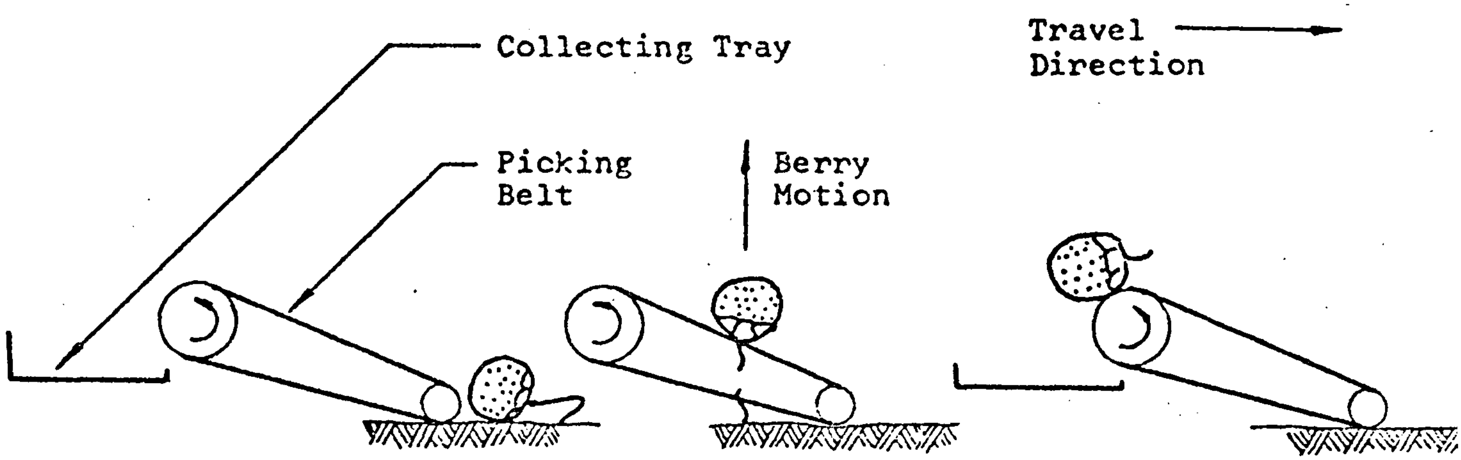
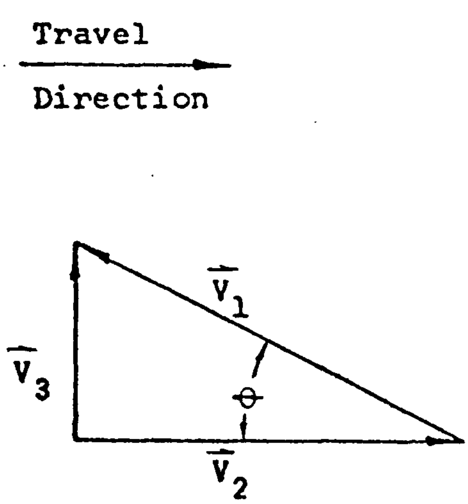


FIGURE 13 The Picking Function



$\vec{V}_1$ = velocity of the belt with respect to prime move

$\vec{V}_2$ = prime move velocity

$\vec{V}_3$ = belt velocity with respect to ground $= \vec{V}_1 + \vec{V}_2$

FIGURE 14 Vector Action of a Picking Belt

belt surface, illustrating proper synchronization is shown in Figure 14. Tool parameters affecting picking performance can be summarized by the following functional relationship:

$$P_p = f_3\ (D_f,\ L,\ \theta,\ T,\ V_3) \qquad [4]$$

where: P_p = picking efficiency

L = picking finger length

T = type of picking belt

V_3 = velocity of the upper belt surface with respect to ground ($\vec{V_3} = \vec{V_1} + \vec{V_2}$), and other symbols are as previously defined.

The machine parameters on the right side of equation [4] will be determined by appropriate physical properties of the strawberry fruit. Fingers must be spaced so that no fruit will pass between adjacent picking fingers, fingers must be capable of lifting berries higher than the longest fruit stem, berries must not be harvested in clusters and bruising damage occurring during the picking operation must be held to acceptable levels. The following functional relationship can be used to summarize the relationship between machine and plant parameters.

$$(D_f,\ L,\ \theta,\ T,\ V_3) = f_4\ (BYF,\ D_b,\ F_d,\ FRF,\ \ell) \qquad [5]$$

where: BYF = bioyield force of the compressed fruit at a loading rate equal to V_3.

D_b = base diameter of strawberry fruit

F_d = difference between the tensile strength of the fruit stem and the fruit retention force

FRF = fruit retention force

ℓ = stem length, and other symbols are as previously defined.

3.4.3 The conveying function

After berries have been fed into the picking tool, they are conveyed up the picking tool incline to the point where the picking operation occurs. Experience has shown (17) that harvested berries tend to roll down the picking tool regardless of tool inclination, θ. An air blower can be used to convey the harvested berries to the rear of the picking tool as well as to clean the harvested aggregate of excess debris. The success of the conveying function appears to be primarily a function of the length and inclination of picking fingers, the shape of the blower nozzle, and the blower face velocity.

$$P_c = f_5\ (L,\ S_n,\ \theta,\ V_b) \qquad [6]$$

where: P_c = conveying efficiency

S_n = nozzle shape factor

V_b = blower face velocity and other parameters are as previously defined.

Optimum values for these machine parameters will be determined by the terminal velocity of the fruit.

$$(L,\ S_n,\ \theta,\ V_b) = f_6\ (V_t) \qquad [7]$$

where: V_t = terminal velocity for strawberries, and other parameters are as previously defined.

3.4.4 Summary

The design parameters which will determine the overall performance of the proposed picking machine can be summarized as in equation [8].

$$P = f_7 (P_f, P_p, P_c) = f_8 (D_f, L, S_n, S_s, \theta, T, V_2, V_3, V_b) \quad [8]$$

where: P = overall efficiency of the proposed picking machine and all other parameters are as previously defined.

To experimentally determine the machine design parameters for optimum picking efficiency, a model with which each of the factors on the right side of equation [8] can be independently investigated, must be built and rigorously tested under field conditions. Estimates for many of the desired machine parameters can be obtained by analysing appropriate physical properties of the strawberry plant and fruit. The relationship among design parameters and physical properties may be summarized as in equation [9].

$$(D_f, L, S_n, S_s, \theta, T, V_2, V_3, V_b) = f_9 (BYF, D_b, F_d, FRF, G, \ell, R, V_t) \quad [9]$$

3.5 Analysis of Plant Characteristics

Some knowledge of those plant physical properties which are relevant to the proposed picking machine design must be obtained before rational model design can proceed. As with most horticultural crops, the physical properties of strawberries are dependent upon a large number of factors. Included among these are plant variety, climate and soil fertility. Obviously, precise figures defining specific strawberry physical properties cannot be obtained on the basis of a small sample taken from a given experimental plot over a single season. Information of this type; however, can give useful figures which can be used as a guide for rational bio-machine design.

3.5.1 Fruit weight and size

Some properties of the strawberry fruit and stem which are necessary to design the proposed picking machine are included in Table I. The figures in this table represent typical values for the Northwest variety of fruit grown in the Pacific Northwest. The fruit weight, berry base diameter and stem length were obtained from available literature (12). The fruit base diameter is defined as the average base diameter of the fruit and the stem length is defined as the maximum vertical height above the strawberry bed which a fruit can be lifted without removing the fruit from the plant.

It is convenient to have a representative fruit diameter when attempting to estimate some design factors such as terminal velocities and contact stresses. For this purpose, the berry was assumed to have the same density as water and to be spherically shaped. Using the measured fruit weight and the geometric formula for the volume of a sphere, the effective fruit diameter was calculated.

$$D_c = \left(\frac{6M}{\pi}\right)^{1/3} \qquad [10]$$

where: D_c = effective fruit diameter (cm)

M = strawberry volume (cm^3)

TABLE I. SOME PROPERTIES OF THE STRAWBERRY FRUIT AND ATTACHMENT SYSTEM[1]

BIOLOGICAL PARAMETER	$\bar{Y}$[2]	S.D.
Fruit Weight (gm)	12.3	4.8
Fruit Base Diameter (cm)	2.0	.57
Calculated Fruit Diameter (cm)	2.8	.4
Stem Length (cm)	14.	2.8
Fruit Retention Force (gm)	414.	92.
Tensile Strength of Main Stem (KG)	5.75	1.13
Bioyield Point (gm)	390.	80.
Tangent Modulus (gm/cm)	980.	308.
Calculated Bruising Stress (gm/cm^2)	$3.4A^{-2/3}$	NA[3].

1. All populations were assumed to be normally distributed

2. $\bar{Y}$ is the calculated sample mean and S.D. is the sample standard deviation

3. Bruising stress was calculated using the Hertz contact stress theory for uniaxial compression between two flat plates. See page 35.

4. Samples of mature fruit were used to obtain all biological parameters.

3.5.2 Fruit retention force and tensile strength of main stems

Fruit retention force is define as the tensile force required to remove the fruit from the plant. Fruit detachment can occur either at some point along the stem or at the petiole-fruit interface. For a sample of mature Northwest fruit taken during the 1968 harvest season (12), the mean and standard deviation were 414 ± 92 grams. This value is close to that found for a sample of mature Redcoat fruit taken in Ontario during 1971 where the sample mean and standard deviation were 500 ± 100 grams (17). Hoag and Hunt (6) in 1963 found a retention force range from a minimum of 266 grams for Sure Crop to a maximum of 1155 grams for Vermillion.

The extent of fruit bruising during the picking operation, using the proposed design, will be related to the fruit retention force. The higher this force, the greater the expected fruit damage. The proposed picking tool is designed to apply sufficient tensile force to individual fruit to cause failure at some point along the stem. Failure will, of course, occur at the weakest point. Ideally, the failure location will be at the petiole-fruit interface. Processors will then not be required to perform a hulling operation on the harvested fruit. For self-hulling to occur consistently, the fruit retention force must be much less than the tensile strength of either secondary or main stems. Experimentation with the Northwest variety has shown that consistent self-hulling cannot be expected.

Machines to hull strawberries with certain types of hull structures will soon be commercially available (3, 5, 7). These machines will not hull berries joined together in clusters. If the proposed picking tool cannot harvest berries individually, accessory equipment will have to be designed to break up clusters. No data were available for the Northwest variety; however, data collected on the Red Coat variety (Figure 15) in 1971 (17) indicated that the proposed picking tool will be capable of harvesting the berries of some varieties individually. Subsequent information obtained in 1972 showed that Northwest berries are among these.

3.5.3 Yield characteristics of the strawberry fruit

The following analysis was undertaken to gain some insight into factors that cause fruit bruising. Such information can be used to qualitatively design picking belt types and belt loading configurations which could be expected to minimize bruising damage. For purposes of this study, some assumptions which would not be justified for more precise work, were made. Rather than using a statistical approach to define pertinent populations and using these to calculate pertinent parameters and expected distributions, only the sample means were used for calculations.

A typical force-deformation curve obtained when strawberries are loaded under uniaxial compression at .5 cm/min between two flat plates is illustrated in Figure 16. The curve shape indicates that this fruit is a viscoelastic

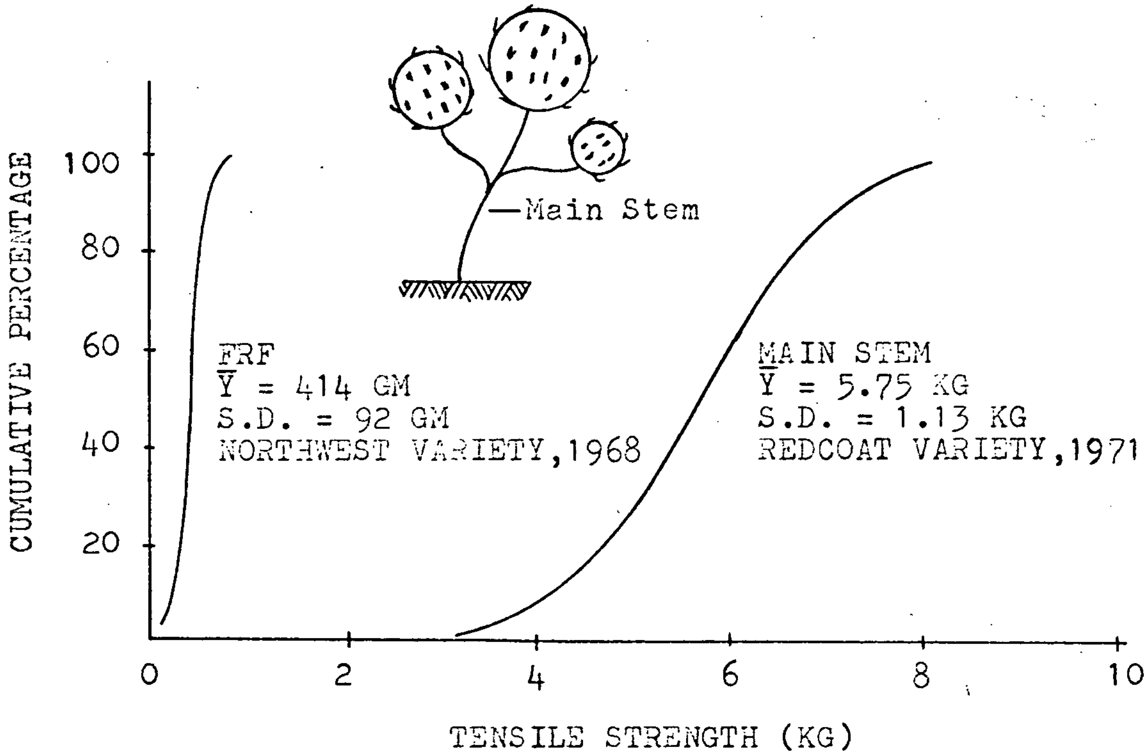


FIGURE 15 Strength Comparison Between the Main Stem and the Fruit Retention Force (FRF).

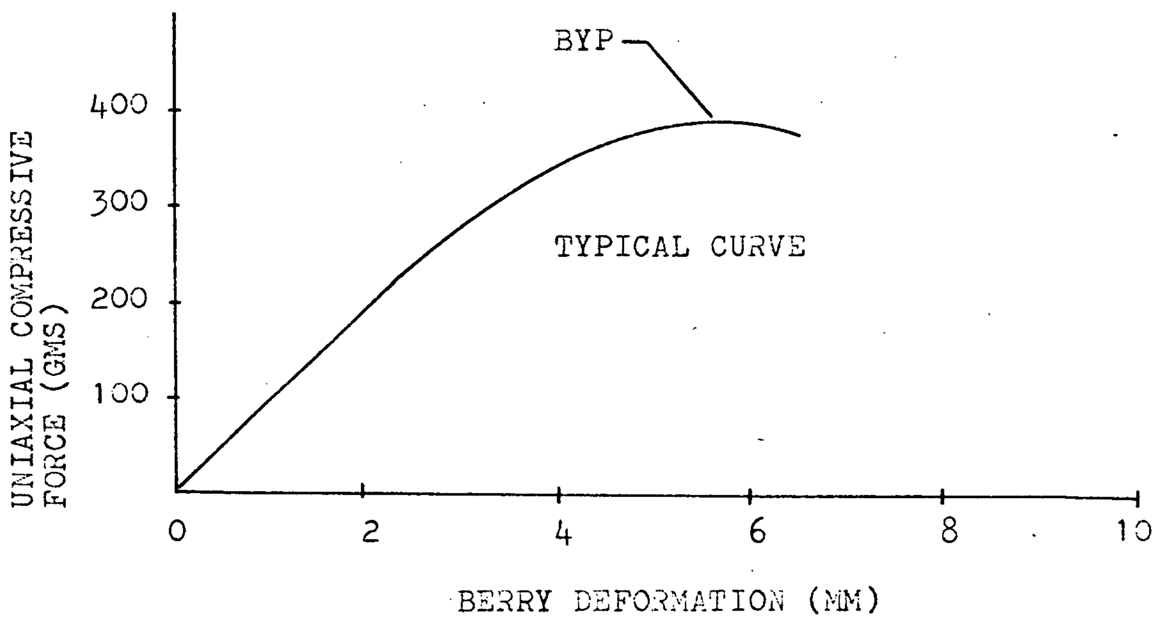
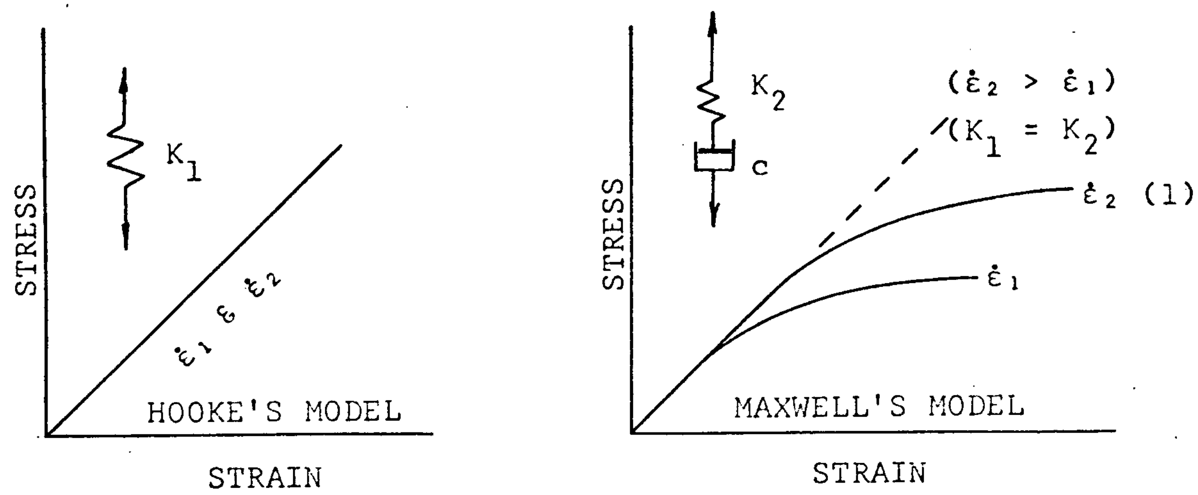


FIGURE 16 Typical Force-Deformation Curve for Strawberries Subjected to Uniaxial Compression Between Two Flat Plates at .5 cm/min.

material and can be studied with the aid of a Maxwell rheological model (Figure 17). No information was available for fruit loaded at speeds comparable to those produced by the proposed picking tool during the picking operation; however, Maxwell's model predicts that under this condition both the linear limit and the bioyield point for the stressed fruit will be greater than those obtained at .5 cm/min. A fairly safe assumption is that under typical field loading speeds, the linear limit for stressed berries will be greater than the bioyield force obtained when berries are stressed at .5 cm/min and that no bruising will occur when the bioyield force at .5 cm/min is applied at the higher loading speed (Figure 18). For purposes of this study, it was therefore assumed that, at field loading speed, bruise inception occurs at the bioyield force for berries loaded at .5 cm/min and that berries behave elastically up to that point (point A, Figure 18).

The bioyield force for strawberries is a measure of the compressive force required to cause cell rupture in the loaded specimen; however, the bioyield force for different loading configurations will differ (Figure 19) due to the contact stress phenomenon. In order to relate the bioyield force for berries loaded under uniaxial compression between two flat plates to the bioyield force for berries compressed on picking belts during the picking operation, the contact stress problem must be investigated.



(1) $\dot{\varepsilon}_1$, and $\dot{\varepsilon}_2$ are two different strain rates.

Note that for biological materials exhibiting a Maxwell type response, the bioyield point will increase with increased strain rates and that the initial portion of the Maxwell response for high strain rates resembles Hookean response.

FIGURE 17 The Maxwell and Hooke Models Illustrating Typical Stress-Strain Response

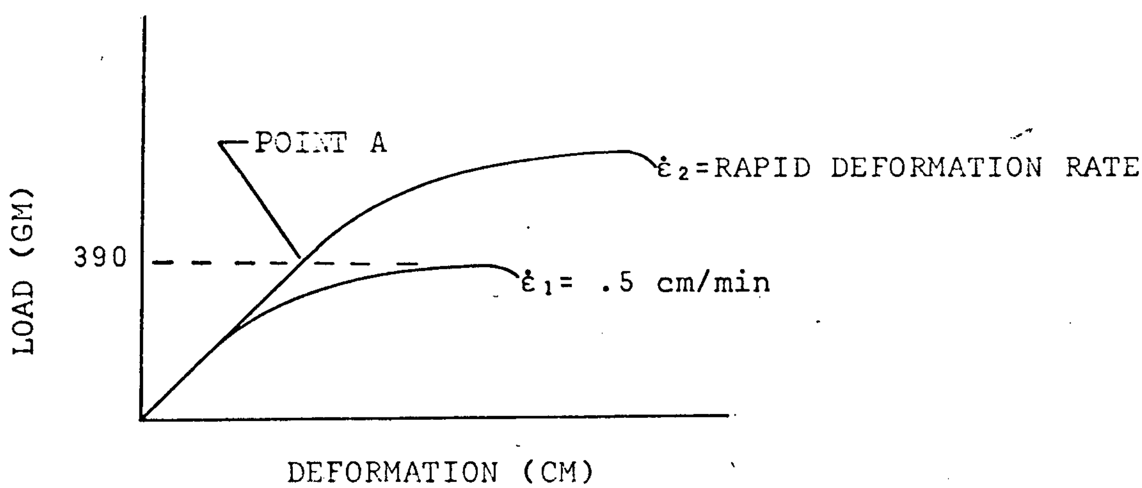


FIGURE 18 Assumed Response of Whole Berries to Rapid Deformation.

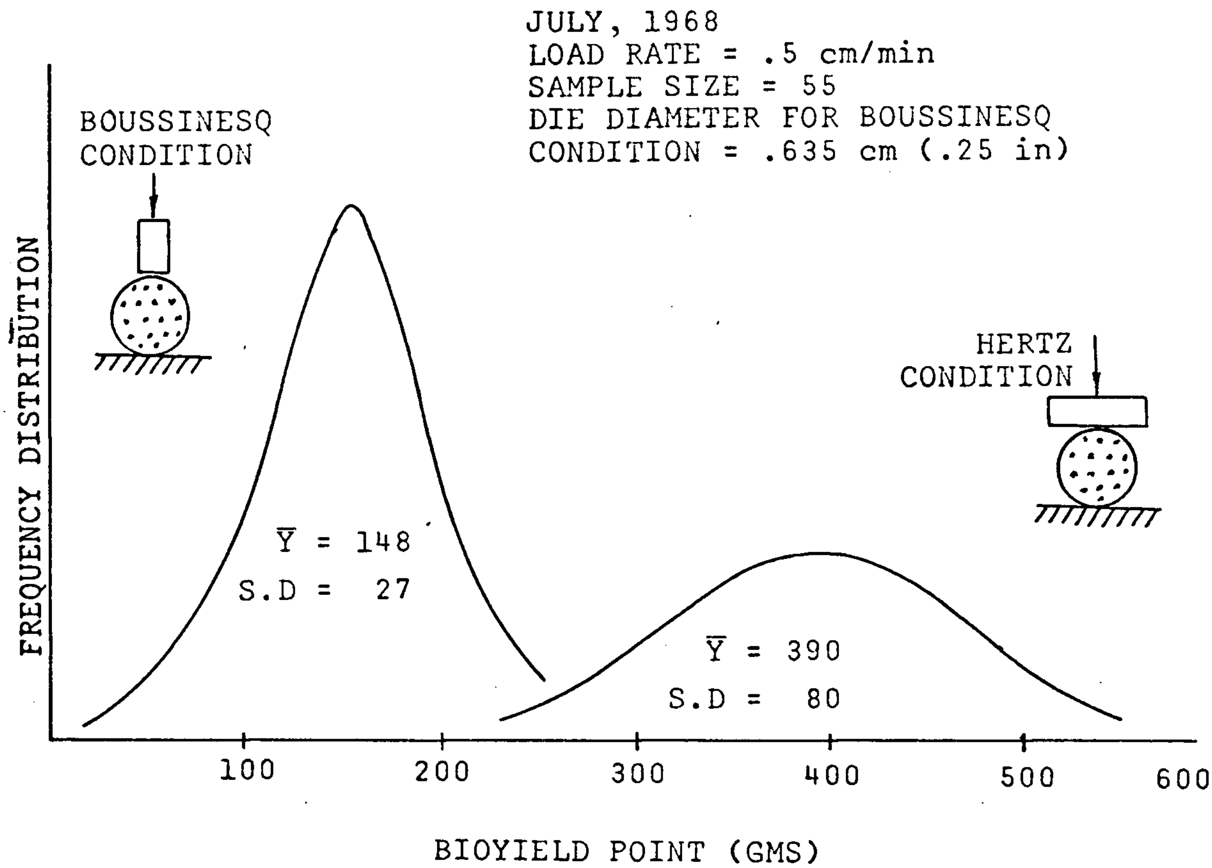


FIGURE 19 Comparison of BYF for Hertz and Boussinesq Conditions on Northwest Strawberries.

The Hertz contact stress theory can be applied to both the flat plate and picking belt conditions. The maximum contact stress between a spherical body and a flat plate can be calculated using equation [11] (4,9).

$$S_{max} = 0.918 \left(\frac{F_h}{A^2 d^2}\right)^{1/3} \qquad [11]$$

where: $$A = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \qquad [12]$$

S_{max} = maximum contact stress as estimated by the Hertz equation

F_h = compression force between a spherical body and a flat plate.

d = sphere diameter

μ_1, E_1 = Poisson's ratio and Young's modulus respectively for sphere.

μ_2, E_2 = Poisson's ratio and Young's modulus respectively for the plate

By substituting the bioyield force and fruit diameter, D_c, into equation [11], the fruit bruising stress can be estimated as

$$S_b = 3.4\, A_p^{-2/3} \qquad [13]$$

where: $$A_p \approx \frac{1-\mu_s^2}{E_s} \qquad [14]$$

S_b = estimated fruit bruising stress

E_s = Young's modulus for strawberries

μ_s = Poisson's ratio for strawberries

3.6 Mathematical Analysis for Some Machine Parameters

The proposed picking machine must perform, in sequence, each of the three functions outlined in Figure 10. Overall performance will depend upon a number of machine parameters as shown in equation [8]. In the following section, an attempt is made to estimate values for many of these in a logical way.

3.6.1 Picking finger spacing

When the plant canopy has been mowed off, the optimum finger spacing is a function of berry base diameter only.

$$D_f = f_{10}\,(D_b) \qquad [15]$$

where: D_f = spacing between adjacent picking fingers

D_b = base diameter of strawberry fruit (Figure 20)

Assuming that a machine loss of 10 percent (by number) is acceptable, fingers should be spaced at:

$$D_f = D_m - 1.28 \text{ S.D.} \qquad [16]$$

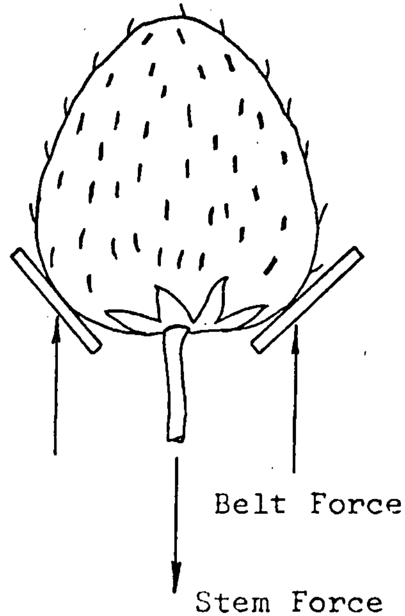
where: D_m = mean berry base diameter

S.D. = standard deviation

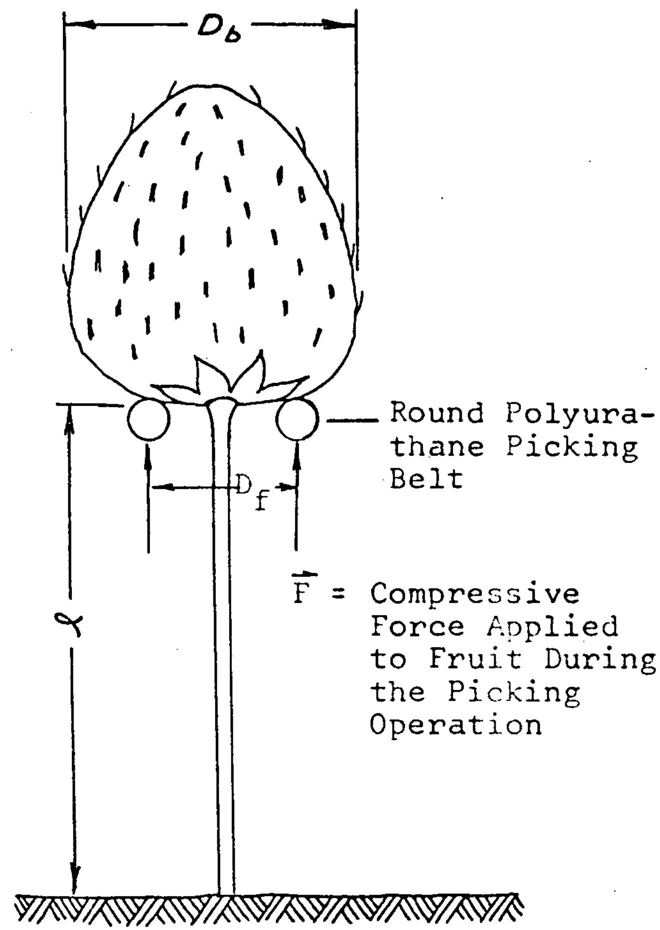
A sample of mature Northwest berries taken in 1971 (8) had base diameters of 2.0 $\pm$ .57 cm. Substituting these values into equation [16], finger spacing can be estimated as 1.27 cm (0.5 in).

3.6.2 Picking finger length

In order to remove a berry from the plant by use of the proposed picking machine, picking fingers must be capable of lifting the berry to a height greater than its stem length.



THEORETICAL NO BRUISING CONFIGURATION
- use flat belts (e.g. Dixylon D-O type) at an angle to reduce contact stresses.



FRUIT LOADING CONFIGURATION FOR 1972 TEST MODEL

FIGURE 20 Loading Configuration During the Picking Operation

For this to be true,

$$\ell < L \sin \theta \qquad [17]$$

where: ℓ = stem length

L = picking finger length

θ = tool inclination

A sample of Redcoat berries taken in 1971 (17) had stem lengths of 14.0 ± 2.8 cm. Assuming a normal population, approximately 98 percent of these berries had stem lengths less than or equal to 19.6 cm (7.7 in). Substituting this value for the lifting height, ℓ, into equation [17] and selecting a minimum tool inclination of 30 degrees, picking fingers must be at least 39.2 cm (15.4 in) long in order to pick 98 percent of berries. To ensure that finger length would not limit picking efficiency, picking fingers for the Northwest variety were made 19 inches long.

3.6.3 The picking belt

To simplify the design and construction of the 1972 field model, the picking belts were made from .53 cm (.21 in) diameter round polyurethane belting.

The picking belts exert a compressive force on the fruit during the picking operation as shown in Figure 20. Using the Hertz contact stress theory (9) for a belt diameter of .53 cm and a fruit diameter of 2.8 cm, and assuming that $E_b >> E_s$ the maximum contact stress can be estimated as

$$S_{max} = .94\, A_b^{-2/3}\, F_r^{1/3} \qquad [18]$$

where: $A_b = \frac{1-\mu_s^2}{E_s} = A_p$

S_{max} = Maximum contact stress as estimated by the Hertz equation

E_b = Young's modulus for a polyurethane picking belt

F_r = Compressive force exerted on a berry by a picking belt during fruit removal and other parameters are as previously defined.

Substituting the maximum allowable stress from equation [13] into equation [18], the maximum force that a picking belt can exert on berries without causing bruises, was estimated as 47 grams.

Since each berry is held by two picking belts, the maximum force which the belts can exert on a berry during the picking operation, without bruising, is approximately 100 grams. This estimated force is approximately two standard deviations less than the mean fruit retention force measured for the Northwest variety in 1968. Although initial calculations indicated the possibility of bruise damage, the previously described belts were used in model fabrication to aid in design simplicity. If the fruit bruising level is unacceptable, different picking belts and loading configurations must be considered. A loading configuration which can be expected to eliminate bruising during the picking operation is illustrated in Figure 20. To build a prototype with this loading configuration would, however, be quite difficult.

3.6.4 The fruit conveying tool

The floating (terminal) velocity of a spherically shaped particle in air (1) is:

$$V_f = \left[\frac{4gP_p d_p}{3f_d\ P_a} \right]^{1/2} \qquad [19]$$

where:
V_f = floating or terminal velocity
g = gravitational constant
f_d = drag coefficient
d_p = particle diameter
P_p = particle density
P_a = air density

Assuming that the calculated fruit diameter (D_c) can be used to estimate the terminal velocity, substitution of the appropriate values into equation [19] indicates that 98 percent of berries will have terminal velocities less than 5600 ft/min. The required conveying velocity is a function of both the picking tool inclination and the terminal velocity of the berry.

$$V_c = V_t \sin \theta \qquad [20]$$

where:
V_c = conveying velocity
V_t = terminal velocity
θ = tool inclination

Assuming that the maximum tool angle under field conditions will be 45 degrees and using equation [20], the required conveying velocity can be estimated at 4000 ft/min. As shown in Figure 21, blower air velocities decrease with distance

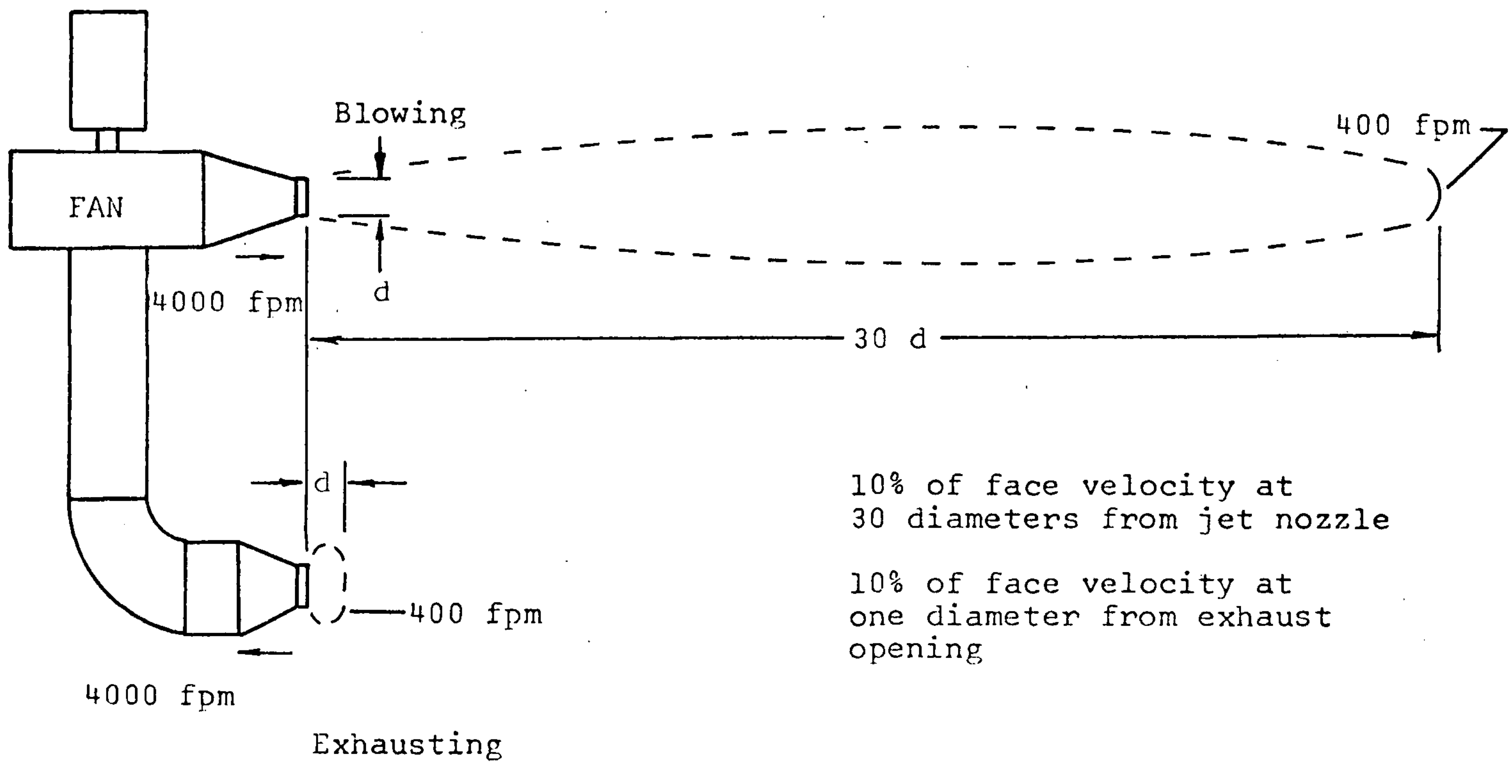


FIGURE 21 Zone of Influence for Blowers

from the nozzle exist (1). A factor must therefore be included in the design nozzle exit velocity to compensate for energy dissipation. The value of the compensation factor will depend upon the shape of the nozzle and the distance that the blower will be required to reach.

$$V_b = (f_{L,S})(V_c) \qquad [21]$$

where: V_b = required blower face velocity

$f_{L,S}$ = a factor dependent upon the picking finger length and nozzle shape.

3.7 The Test Model

The proposed design was first tested by use of a very simple model during the 1971 harvest season at the H.R.I.O. research station at Vineland, Ontario. Although mechanical difficulties prevented extensive factorial studies with this machine, limited field test results were encouraging. On the basis of the 1971 tests a second test model was constructed at the University of British Columbia in 1972. This machine corrected apparent deficiencies in the original model.

The model (Figures 22 to 29) was mounted on a Case 444 hydrostatically driven garden tractor to give continuous model speed variability, at full torque, in the 0-2 mph range. Picking tool inclination could be continuously varied in the 20-45 degree range by altering model height. Picking belt speeds could either be synchronized with the model ground speed (Figure 27) or be varied by use of the independent engine drive (Figure 26). Each finger was designed to "float" on

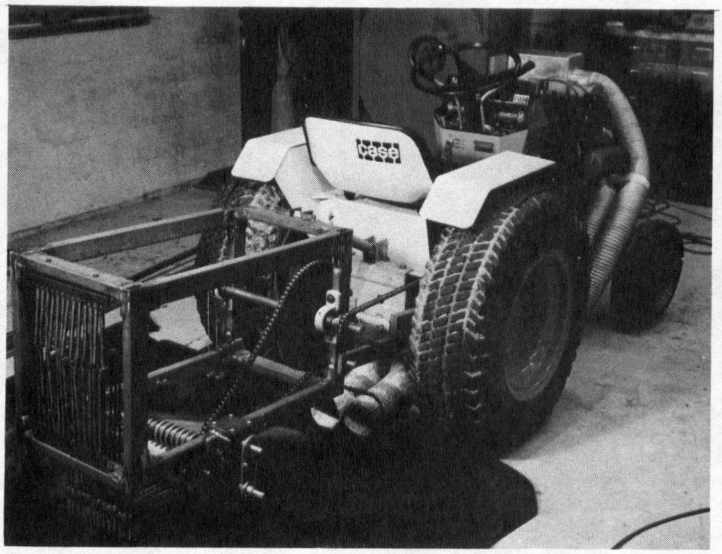


FIGURE 22 The Test Model

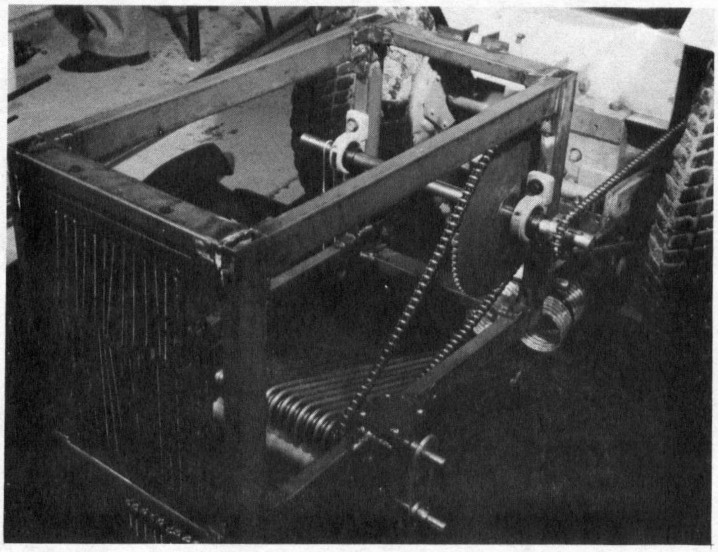


FIGURE 23 Close-Up of Test Model

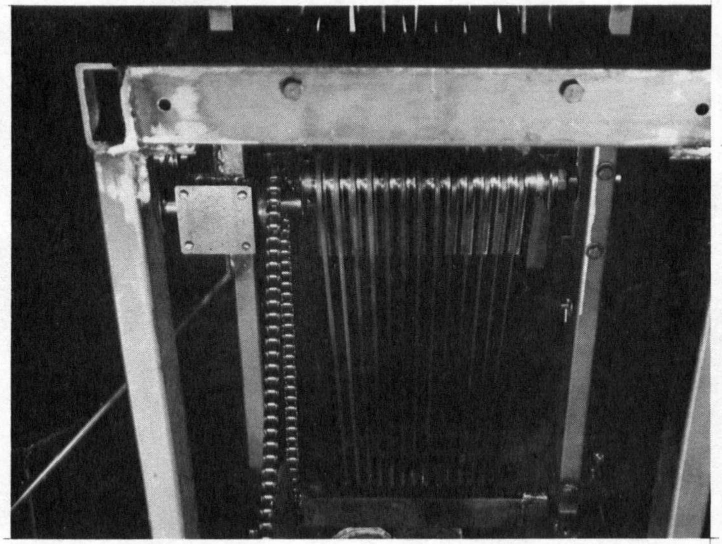


FIGURE 24 Top View of Picking Fingers

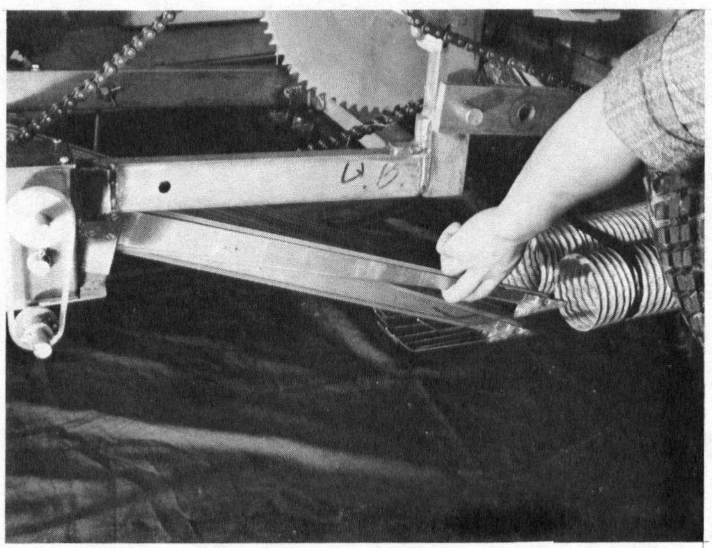


FIGURE 25 View Illustrating Floatability of Individual Picking Fingers.

FIGURE 26 Illustration of Engine Drive Mechanism

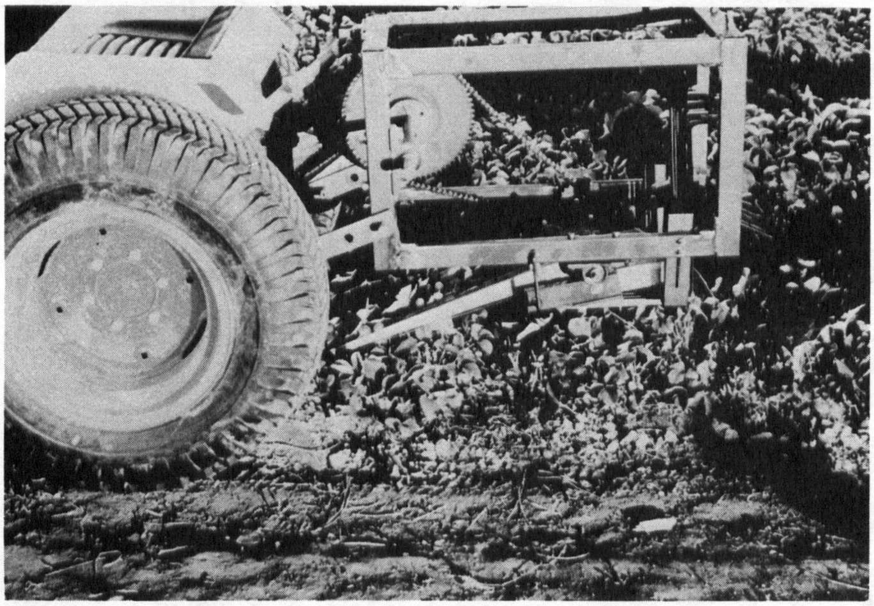


FIGURE 27 Illustration of Ground Drive Mechanism

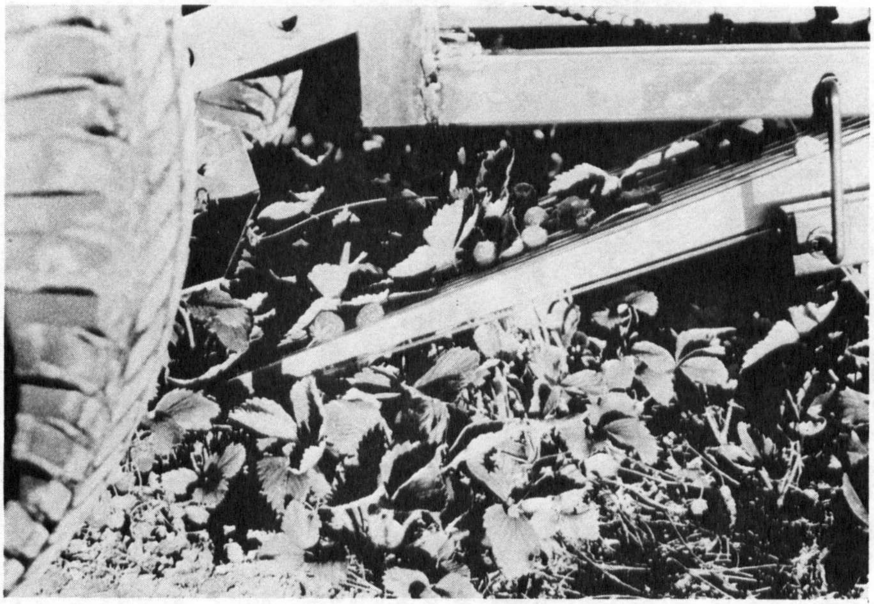


FIGURE 28 Side View of the Picking Machine in Operation

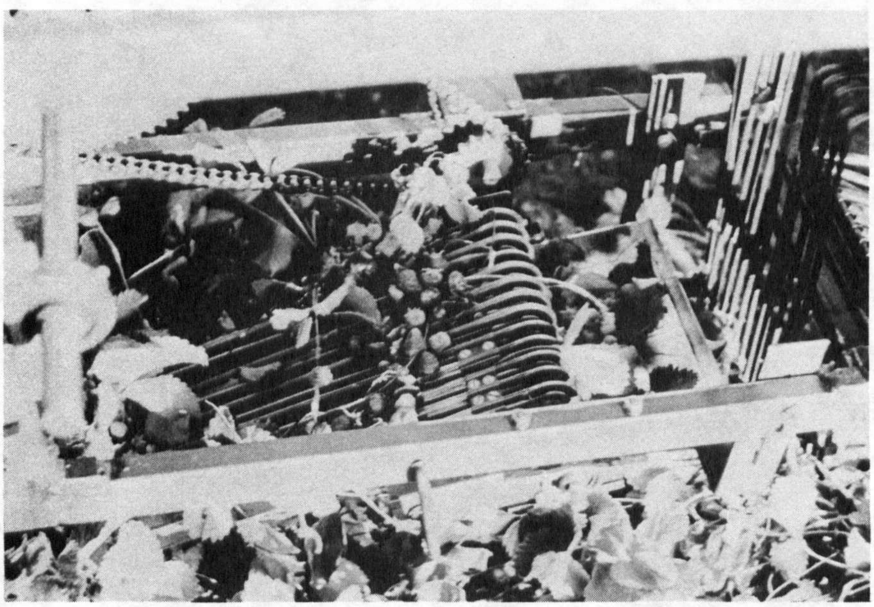


FIGURE 29 Top View of the Picking Machine in Operation

on the soil surface (Figure 25) and a variable output blower was used to assist fruit movement up the picking tool incline and to remove some debris. In addition, adjustable shoes were used on the picking finger tips to assist fruit feeding and finger floatation.

3.8 Model Evaluation

The model was tested under field conditions on a commercial planting in the Fraser Valley of British Columbia during the 1972 harvest season. This planting had considerable frost damage and beds were not prepared in any way for mechanical harvesting.

Although the picking fingers floated well when tested up to speeds of about 2 mph on a lawn, they were not effective under the field conditions where testing was done. Fingers tended to dig into ridges formed by hoeing and cultivating operations. These fingers will not float under conditions where there are abrupt surface irregularities. Dead runners and leaves also tended to prevent proper floatation. Testing was subsequently done with fingers set at about 1 inch above the ridges.

The theoretical calculations indicated that the picking belts used on the model would bruise good quality fruit during the picking operation; however, field tests showed that these fruits were not noticeably damaged in most cases. Mechanical damage was primarily confined to overripe fruit which were unsuitable for processing prior to mechanical harvesting. Green fruit was not damaged and could likely be artificially ripened at the processing plant. Figures 30 and 31 illustrate samples of berries picked by the test model. Picking machine output for two runs is shown in Table II.

For the optimum pick, approximately 60 percent of berries were considered to be of good processing quality. Use of genetic selection, growth regulators and fungicides to obtain a more uniformly mature crop would increase the percentage of quality berries harvested by this machine. The yield of usable berries can be significantly increased by use of solid-bed rather than matted row plantings. Ricketson (14) reports that about 10 to 15 tons of usable berries per acre can be obtained with a once-over pick of Vibrant and Redcoat strawberries in a solid-bed planting.

Mechanical fruit damage was found to be relatively independent of picking belt speed; however, it was noted that fast belt speeds tended to clear material through the picking tool better than slow speeds. Ground synchronization was not essential and in fact may not even be desirable.

Except for some mechanical deficiencies which can be readily solved, this concept appears to have only one inherent drawback. The feeding function did not work effectively in unprepared fields. As indicated previously, upright setting fruit would overcome this problem. Levelling and smoothing of the strawberry beds in the spring is essential for proper feeding in the Northwest variety.

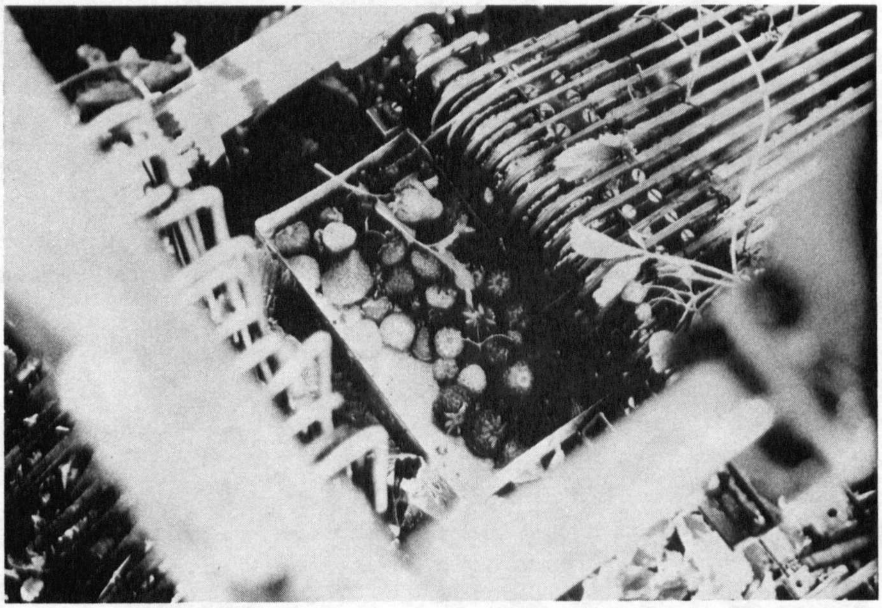


FIGURE 30 Typical Picking Machine Output

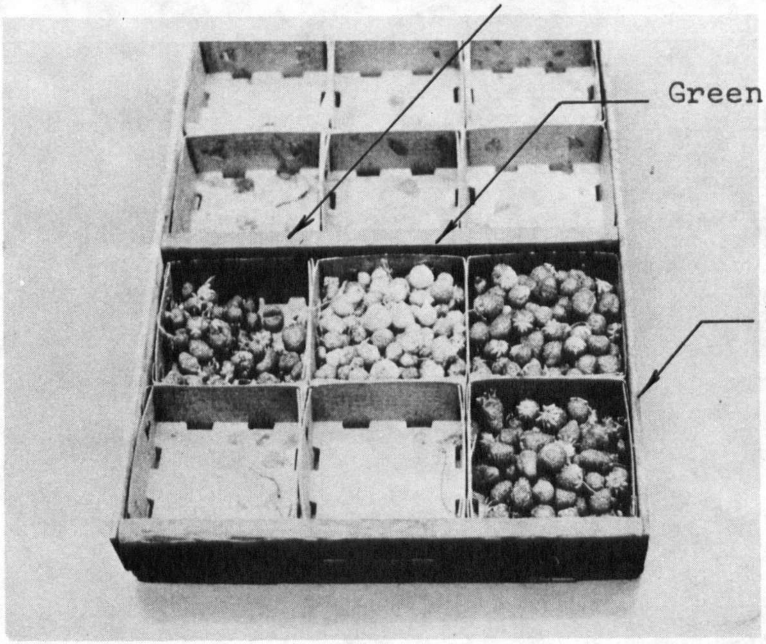


FIGURE 31 Machine Output Separated into Three Categories

TABLE II TEST RESULTS

Date	Green Berries	Usable Berries	Overripe and/or Mechanically Damaged Berries[1]
July 1	30%	55%	15%[2]
July 8	20%	60%	20%

1. The number of mechanically damaged berries which were of good processing quality prior to mechanical harvesting was not significant. Mechanical damage was primarily confined to overripe fruit.

2. Differences between the test results for July 1 and July 8 can be attributed to gradual ripening of the mechanical harvesting culture as the season progresses. To improve overall mechanical harvesting efficiency, uniformly ripening cultures are essential.

Mechanically picking daffodil seed pods will be similar to harvesting upright setting fruit. A machine designed and tested to perform this operation (15) indicated that over 90 percent of seed pods can be mechanically detached at speeds in excess of 2 mph without causing noticeable plant damage (Figures 32 and 33). It is believed that a similar machine could harvest upright setting fruit equally well.

For harvesting surface maturing varieties, a vacuum type pick-up should be considered to assist the feeding function. To investigate the feasibility of a vacuum pick-up, a preliminary theoretical study and laboratory experimentation were undertaken. Results, however, were inconclusive.

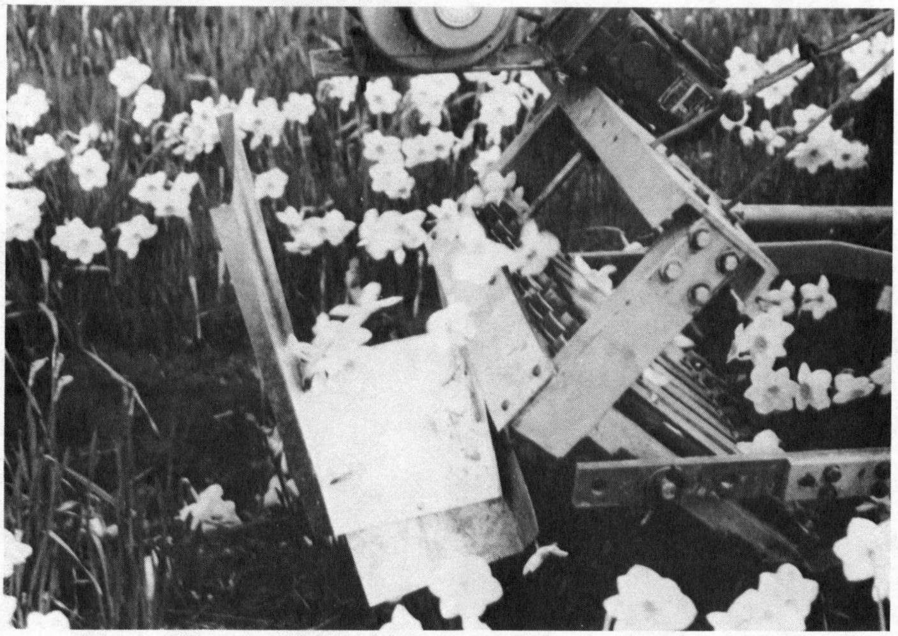


FIGURE 32 Close-Up View of Prototype During Field Tests

FIGURE 33 A Partially Mechanically Headed Daffodil Field

CONCLUSIONS

Potentially, all berries fed into a machine using the proposed concept can be picked with very little damage to fruit; however, the feeding mechanism will have to be improved to realize good overall machine efficiency.

The "floating" fingers worked well on lawn type conditions; however, problems arose when these fingers were used on unprepared strawberry beds. Preharvest field preparation such as bed raking, levelling and compacting should therefore be considered. To eliminate ridges which are undesirable for the proposed machine and to increase potential yields, solid-bed plantings should also be considered.

Mechanically harvested Northwest berries generally had hulls attached to the fruit. Mechanical hulling methods and/or selection of varieties with better hulling characteristics should be considered.

Field testing of the model indicated that fast picking belt speeds tend to clear material through the machine better than ground synchronized belt speeds. No noticeable difference in fruit mechanical damage was observed. Future models should therefore use an independent motor drive to operate the picking belts.

For surface maturing strawberries, a vacuum pick-up device should be considered to assist the feeding operation. Theoretical investigation led to inconclusive results, therefore, field experiments must be undertaken to determine the feasibility of vacuum pick-up devices.

Work with the mechanical daffodil header, indicated that a simple, efficient machine could likely be designed for upright setting strawberries. Horticulturalists should therefore direct some effort toward development of such varieties.

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