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# The Potato Operation:
# Computer vision for agricultural robotics

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## ABSTRACT

Each year at harvest time millions of seed potatoes are checked for the presence of viruses, by means of an Elisa test. The Potato Operation aims at automatizing the potato manipulation and pulp sampling procedure, starting from bunches of harvested potatoes and ending with the deposit of potato pulp into Elisa containers. Automatizing these manipulations addresses several issues, linking robotic and computer vision.

The paper reports on the current status of this project. It first summarizes the robotic aspects, which consist of locating a potato in a bunch, grasping it, positioning it into the camera field of view, pumping the pulp sample and depositing it into a container.

The computer vision aspects are then detailed. They concern locating particular potatoes in a bunch, and finding the position of the best germ where the drill has to sample the pulp. The emphasis is put on the germ location problem. A general overview of the approach is given, which combines the processing of both frontal and silhouette views of the potato, together with movements of the robot arm (active vision). Frontal and silhouette analysis algorithms are then presented. Results are shown, that confirm the feasibility of the approach.

## 1. OVERVIEW AND CONSTRAINTS

### 1.1. Overview

This article presents a general overview of the Potato Operation[1,2,3,4,5,6,7] in its current status. The whole project belongs to the domain of agricultural robotics[8,9,10,11,12], or agrotics. It aims at automatizing pulp sampling of potatoes used as seeds. With respect to industrial applications, the Potato Operation project will lead to the realization of a prototype.

At harvest time (autumn), randomly selected potatoes are tested for the detection of possible viral diseases. The detection is performed using an Elisa test[13]. Such statistical detection is essential in order to prevent propagation of these viral diseases, which can decrease productivity by up to an order of magnitude. The whole process is currently being performed by hand for hundred of thousand of potatoes each year. At the Swiss Federal Agricultural Station in Changins, approximately 10’000 potatoes are handled per day during the two months testing period. The present project aims at automatizing the manipulation and sampling procedure,

starting from bunches of potatoes that have been brought to the laboratory, and ending with the deposit of potato pulp into appropriate containers where it will be analyzed with the Elisa test. The project neither deals with the harvesting itself, nor with the Elisa procedure.

The manipulation and sampling procedure consists of grasping a potato from a bunch, then extracting and handling the pulp. Pulp extraction can be decomposed into detecting a large germ in the potato, then guiding a drill nearby and puncturing the surface in order to acquire some pulp. This pulp is then dropped into an appropriate container for further analysis.

Automatizing all these manipulations implies many problems, that we divide into two main categories: those linked with robotics and those with computer vision. The robotic problem consists of locating a potato in a bunch, grasp it, positioning it into the camera field of view, pumping the pulp sample and depositing it into a container. The vision problem concerns locating particular potatoes in a bunch, finding the position (best germ) where the drill has to sample the pulp (Fig.1).

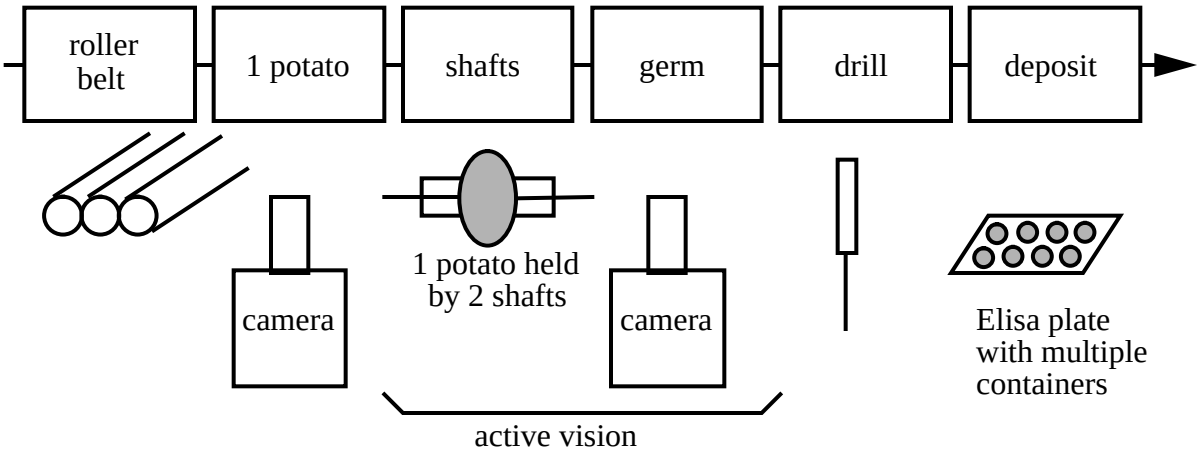



Fig.1: General overview. Potatoes arrive on a roller belt; they are disambiguated, then grasped by two shafts (the potato can rotate around an axis approximately equal to its axis of inertia); the germ where to dig the drill in is found by computer vision; the pulp is deposited into one container of the Elisa plate (plate size 128 x 86mm, 8 x 12 containers). Active vision, combining robot movement with image analysis, is used.

### 1.2. Constraints

The puncture of flesh must be done on one of the biggest germ or most important group of germs, which are usually located near one end of the potato called the crown. This is the location where viral activity is the most important. Detecting the germs is a non-trivial task, since germs as well as potatoes have highly variable shapes and colors; as an example, there are 22 recorded potato varieties in Switzerland (Fig.2). Also, the potato skin has many defects such as specular reflections and pimples (Fig.2). The germs may have lengths of up to 50mm, and are very rarely straight; long germs are usually not isolated.

The sampling of pulp is done with an extractor (Tecan Plant Sap Extractor 400®[14]), currently being used for such tests in agronomic centers. The extractor has to be led into the sampling zone (Fig.3), and its drill be guided into this zone with an appropriate angle. This dip angle $\rho$ between the drill and the local normal to the potato surface is in the range $10^\circ \leq \rho \leq 40^\circ$. The drill should remain within 10mm of the surface, since viral concentration decreases exponentially from the skin level.

At the present time, the speed of operation (by hand at the Swiss Federal Agricultural Station in Changins) is of the order of 300 to 400 potatoes per hour, that is approximately 10 seconds per object. Approximately 10'000 sampling operations are done per day by a team of two to three persons. The tolerated error rate (i.e. pulp sampled from an incorrect location) should not exceed 5%, and should ideally be within the range 1% to 2%. In addition, in order to be usable, the whole system should have an autonomy of about 4 hours.

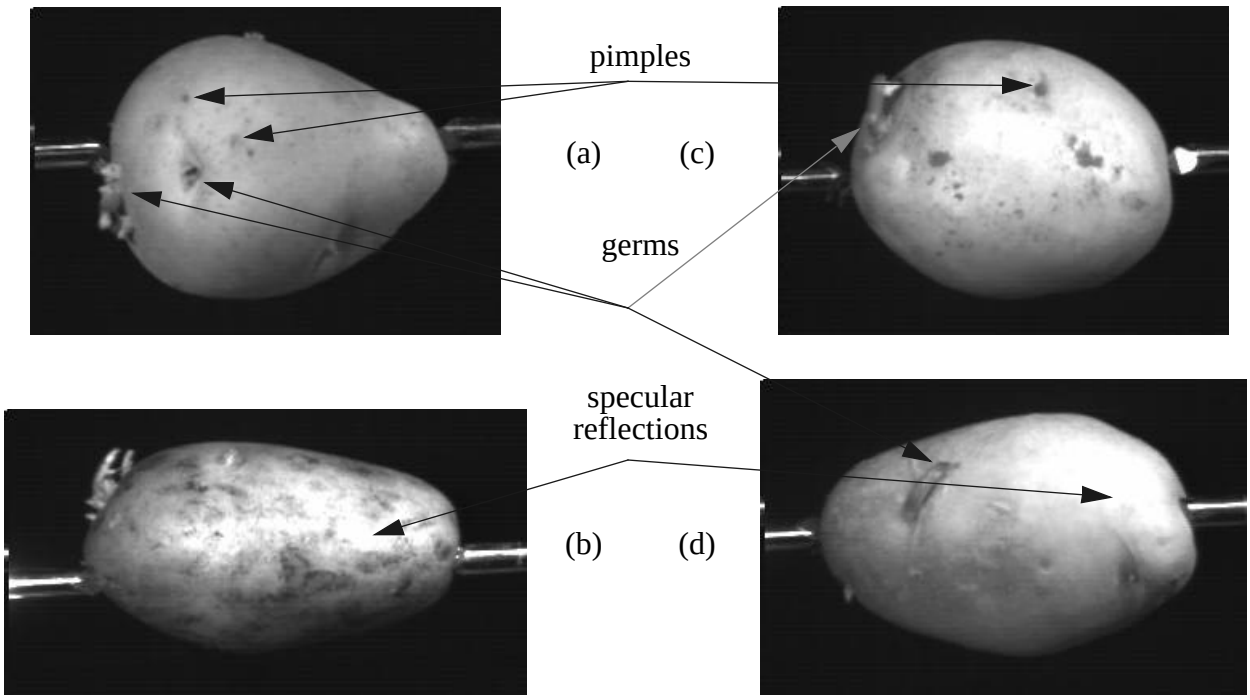



Fig.2: Typical potatoes from four different varieties: (a) Colmo; (b) Ostara; (c) Sirtema; (d) Palma. Some skin defects are indicated; the axes of the shafts are clearly visible.

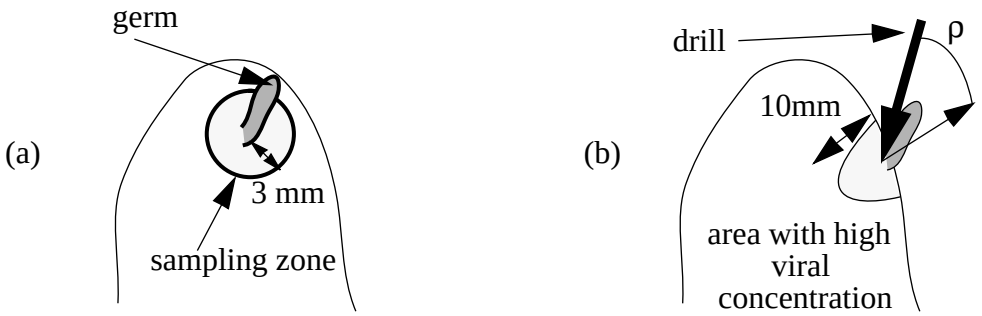



Fig.3: Constraints for the pulp sampling; (a) sampling zone, circular area of approximately 3mm around the base of the germ; (b) dip angle and drilling. The drill must puncture under the selected germ, with a dip angle $\rho$, $10^{\circ} \leq \rho \leq 40^{\circ}$.

## 2. ROBOTIC ASPECTS

### 2.1. Overview

This part of the system design is mostly being studied at the Institute of Microtechnology, Swiss Federal Institute of Technology in Lausanne, Switzerland (see acknowledgments). It is summarized here; details can be found in reference[7]. It is however useful to report on those robotic aspects since they are deeply linked with the vision aspects and must be developed concurrently.

The robotic problems are subdivided into the following main points:

- prehension of the potato from a bulk, in order to position it into the camera field of view. More precisely, under the assumption that the potato can be approximated by a 3D ellipsoid, the axis of rotation (shafts) must be as close as possible to the axis of this ellipsoid;
- active vision[15] subsystem, which links vision algorithms together with potato movements in order to locate the intervention point within the sampling zone (this is described in section 3.);
- guiding of the drill and drilling into the potato onto the germ or the group of germs that have been detected by the active vision subsystem;
- deposit of the pulp sample into an appropriate container.

The number of degrees of freedom of the robotic setup has not been entirely determined; it will probably be four or five. This will depend on the result of the current investigations[7], aiming at designing an inexpensive and rugged apparatus that could be used in different environments and countries.

### 2.2. Grasping of the potato (prehension)

The aim of this first step is to bring the axis of rotation of the shafts as close as possible to the axis of the ellipsoid that approximates the potato.

Bunches of potatoes will be deposited on an apparatus consisting of a vibrating conveyor belt composed of rollers linked together. The potatoes will therefore be approximately oriented along their main inertia axis. They will then be separated either mechanically, or using simple vision algorithms such as described in [10,11] (the same camera as the one use for germ location can be used). A 2D ellipse fitted to the silhouette of the potato can help in adjusting the axis of the shafts.

Alternatively, potatoes could be detected directly from the bulk using a range data sensor[16], which would provide an approximate knowledge of the surface of the heap; the more accessible potato would then be located. Such approach however would require an extra sensor, together with a more complex prehension system.

### 2.3. Guiding of the drill and drilling

After location of the germ, the drill has to be guided to the intervention point. This requires knowledge of the 3D coordinate of this point; also, this implies determination of the approximate local normal to the surface. It is not mandatory that the drill be guided besides the germ(s); going through is admissible.

### 2.4. Deposit of the samples

Each sampling yields approximately 20 microliters of ground pulp. The drill will then finally deposit this pulp sample into a container on an Elisa plate, whose position is known. There exist mechanical devices that provide automatic handling of such plates. Associated problems have to be considered, such as cluttering of the drill with pulp, and removal from the drill of previous pulp samples (decontamination). Once all containers in a plate are full, the viral tests will be performed automatically.

## 3. COMPUTER VISION ASPECTS

### 3.1. Active vision for germ localisation

This section 3. describes the problem of locating the germ(s) of interest once the potato has been grasped, assuming that the axes of rotation and of the ellipsoid are the same. Generally speaking, the problem is non trivial since the objects to analyze have highly variable shapes. Obviously, it is desired that the method be fast and robust; it should be fairly reliable, in particular with respect to the different varieties of potatoes.

The aims of the vision algorithms are to provide:

- an estimate of the 3D coordinates $(x_g, y_g, z_g)$ of the junction point between a "good germ" and the potato. This is the point where the drill will puncture the surface;
- an estimate of the local normal to the surface, yielding the directing cosines $(\cos\alpha, \cos\beta, \cos\gamma)$ of the dip angle of the drill.

The principle of the interaction between the mechanical movements of the potato and the measurements made by computer vision are described below (§3.1.1 to §3.1.4; see also Fig.4).

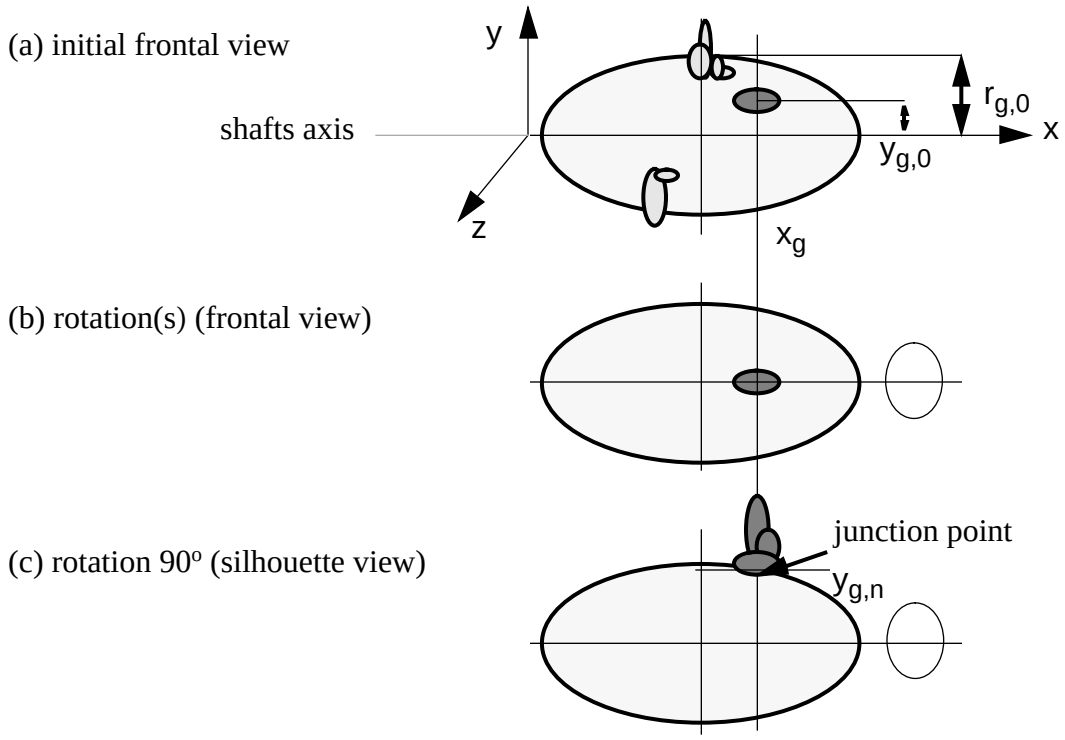



Fig.4: Sequence of measurements and potato rotations required to obtain the 3D estimates of the intervention point and the local normal (frontal view $\{x, y\}$ ). Steps (a) and (b) require a frontal analysis of the potato image, step (c) a silhouette analysis.

#### 3.1.1 Initial frontal view

The whole potato is first analyzed in order to find as many germs as possible by means of the frontal analysis (described in §3.3.). A first ellipse is then fitted to the outline silhouette of the potato:

$$\frac{(x - x_C)^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{1}$$

with $a$ being half of its major axis, $b$ half of its minor axis, $(x_C, 0)$ its center. The center of gravity of the germ closest to one end of the ellipse (crown) is kept as the point where the drill will dig in. In case no such germ is found, the potato is rotated by 120°; at most two such rotations are needed. This yields the coordinate values $(x_{g,0}, y_{g,0})$, where $x_{g,0}$ is the first estimate of $x_g$. An initial estimate $r_{g,0}$ of the "radius" $r_g$ (Fig.5) at the junction point is:

$$r_{g,0} = b \tag{2}$$

### 3.1.2 Rotations

The aim is now to bring the point of interest such that $y_g = 0$, so that its projection lies on the axis of rotation. Therefore, by a 90° rotation, it will be possible to bring this point of interest on the silhouette of the potato ($z_g = 0$) and consequently know its 3 coordinates. The initial rotation is (Fig.5):

$$\alpha_0 = \text{asin}(y_{g,0} / r_{g,0}) \tag{3}$$

The new center of gravity $(x_{g,1}, y_{g,1})$ of the germ can again be determined by frontal analysis; if

$$|y_{g,1}| > \varepsilon \tag{4}$$

where $\varepsilon$ is a given tolerance (typically 1mm), a new approximation for $r_g$ and a new angle of rotation are estimated:

$$\Delta r_{g,0} = \frac{y_{g,1}}{\tan \alpha_0} \tag{5}$$

$$r_{g,1} = r_{g,0} - \Delta r_{g,0} \tag{6}$$

$$\alpha_1 = \text{atan} \frac{y_{g,1}}{r_{g,1}} \tag{7}$$

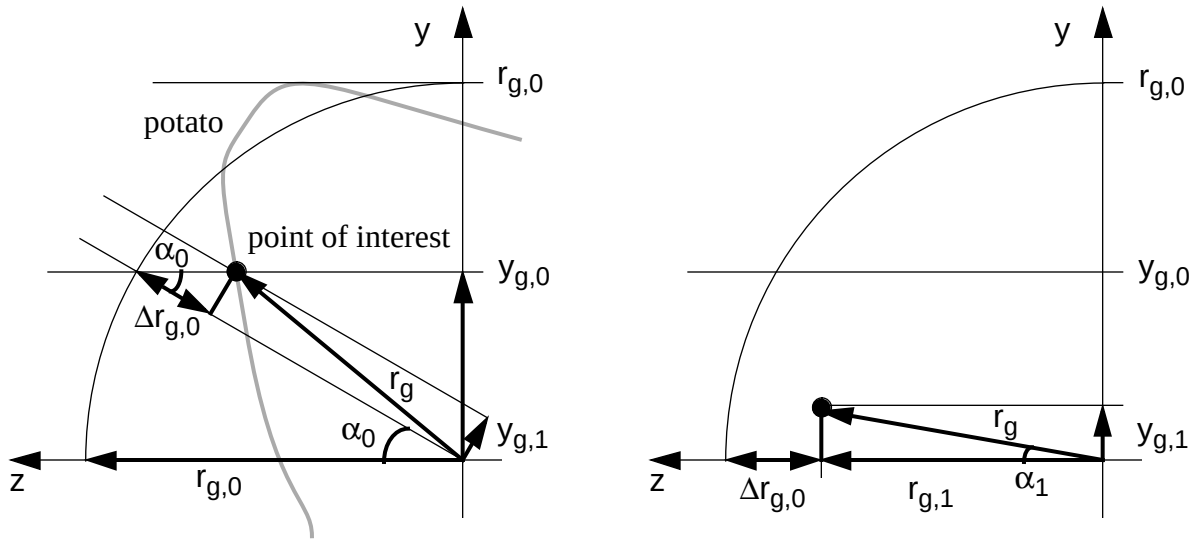



Fig.5: Slice view $\{y, z\}$ of the potato; (a) initial situation; (b) after first rotation of angle $\alpha_0$.

After rotation of $\alpha_1$, the result should be correct enough. However, if the axis of rotation is not exactly the same as the major axis of the ellipse, it might be necessary to iterate the procedure $K$ more times (without however having to recompute the ellipse). After rotation of angle $\alpha_{i-1}$ and estimation of $y_{g,i}$:

$$\Delta r_{g,i-1} = \frac{y_{g,i}}{\tan\alpha_{i-1}} \tag{8}$$

$$r_{g,i} = r_{g,i-1} - \Delta r_{g,i-1} \tag{9}$$

$$\alpha_i = \operatorname{atan}\frac{y_{g,i}}{r_{g,i}} \tag{10}$$

### 3.1.3 Rotation of 90°

The potato is then rotated by 90°; the germ should now be approximately on the silhouette. By means of the silhouette analysis (described in §3.4.), the junction point is determined, with coordinates:

$$(x_{g,n}, y_{g,n}) \tag{11}$$

The final 3D coordinates of the point of interest are therefore:

$$\begin{aligned} x_g &= x_{g,n}, \text{ or } x_g = \frac{1}{n}\sum x_{g,i} \\ y_g &= y_{g,n} \\ z_g &= 0 \end{aligned} \tag{12}$$

It is possible to iterate the whole procedure if:

$$|y_{g,n} - r_{g,K}| > \varepsilon . \tag{13}$$

### 3.1.4 Determination of the normal

In order to determine the direction of the normal at $(x_g, y_g, z_g)$, a second ellipse of center $(x_\Omega, 0)$ and axes $(c, d)$ is fitted to the silhouette of the potato:

$$\frac{(x-x_\Omega)^2}{c^2} + \frac{y^2}{d^2} = 1 \quad \Leftrightarrow \quad \frac{x'^2}{c^2} + \frac{y^2}{d^2} = 1 \text{ with the coordinate change } x' = x - x_\Omega \tag{14}$$

The angle of the local normal at $(x'_g, y_g)$ (with $x'_g = x_g - x_\Omega$) is then:

$$\rho = \operatorname{atan}\left(\frac{c^2}{d^2}\cdot\frac{y_g}{x'_g}\right) \tag{15}$$

The directing cosines of the drill are finally:

$$\cos\alpha = \cos\rho, \quad \cos\beta = \sin\rho, \quad \cos\gamma = 0 \tag{16}$$

An alternative to this second ellipse fit would be to approximate locally the potato contour by a cubic spline, and then determine the local normal to this curve.

The following subsections first discuss lighting problems, then describe the computer vision algorithms used to perform the necessary measurements by means of the frontal and silhouette analyses.

### 3.2. Lighting

Various lighting schemes are being experimented in order to maximize the contrast between germs and potato and consequently ease detection. The more natural and easiest scheme to implement consists in using standard white light sources. However, such lighting generates specular reflections on the potato skin and several simultaneous sources are therefore necessary[5,6].

It has been considered to use the fluorescence properties of the germs[3]. This approach relies on the fact that the germ is the only part which evolves (grows) all the time; such evolution is characterized by the presence of flavines, which have a specific fluorescence. The aim is therefore to detect germs from their fluorescence, on the basis of spectral measurements. When illuminating the potato with a source at wavelength $\lambda_{exc}$, a fluorescence is observed at wavelength $\lambda_{em}$ for germs and, if not hidden by skin, for the pulp as well. Although germs and pulp cannot be distinguished on this basis since they show the same response, under normal circumstances (potato without scars) the pulp is hidden by the skin. The major problem of this approach is the weakness of the fluorescence signal. Preliminary experiments are however promising and tests are currently conducted in order to find the most appropriate wavelengths in order to obtain maximal fluorescence.

Another approach, currently under investigation, is thermography[7]. After having heated the whole potato, germs accumulate more heat and therefore can be detected using an infra-red camera. This approach however requires a fairly costly infra-red sensor.

A rather different lighting scheme has also been investigated, based on the controlled usage of simultaneous sources[5,6]. The main ideas of this method are, on the one hand to detect the shadows produced by the germs, and on the other hand to work with several light sources simultaneously in order to enhance the detection. Each light source produces a different set of shadows; combining the shadows produced by all light sources might help in locating the germs, since these shadows are the only patterns that significantly vary between the views.

### 3.3. Analysis of frontal views

This subsection describes the processing steps used for locating germs on the frontal view. The problem is more complex than with the silhouette view (below in §3.4.), since in the frontal case all germs within the boundary of the potato are desired, while in the silhouette case only the outer germs are researched. Therefore, in the first case, full grey-level processing is mandatory since no single threshold can discriminate germs from skin; in the second case, the outer germs are highly contrasted with respect to the background and binary processing can be used.

The grey-level images are denoted by $g(i,j)$, where $g \in [0\ldots255]$ is the grey level at pixel $(i,j)$. Two approaches have been experimented. They both rely on the fact that germs are regions with high “activity”. The first approach, less successful, attempted at classifying contour segments as either “germ” or “no-germ” on the basis of a measure combining segment length, curvature, and compacity of an inertia ellipse fitted to the segment[4]. This method, at least employed alone, was found not to be reliable enough for practical use.

The second and current approach is as follows:

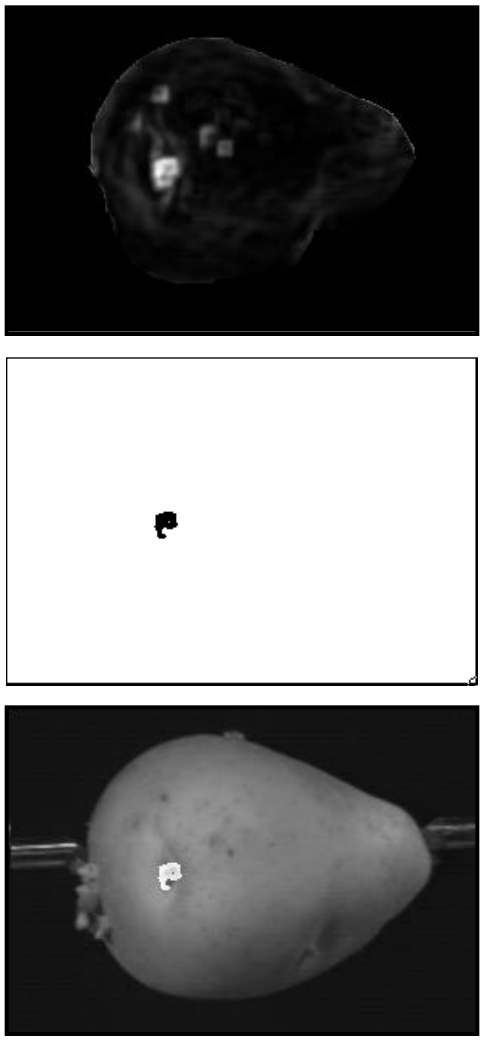
- estimation of the local image energy by means of the windowed standard deviation. A typical window size is NxN = 5 x 5 for images typically of the order of 256 x 256 pixels:

$$\mu_g(i,j) = \frac{1}{N^2}\sum\sum g(i,j)$$

$$\sigma_g(i,j) = \sqrt{\frac{1}{N^2}\sum\sum(g(i,j)-\mu_g(i,j))^2} \quad (17)$$

- thresholding of this activity image. This operation is straightforward, since the energy histogram is clearly unimodal with a peak in the first 5 to 10% of the dynamic range; the threshold is currently selected at 50% of this dynamic range. This yields the regions of interest (Fig.6);
- within each region, determination of the center of gravity of the edges that are obtained by Deriche's approach (recursive implementation of oriented filters)[17] and peak-following[18];
- selection of the center of gravity closest to one end of the ellipse fitted to the potato (c.f. §3.1.). This yields the initial point $(x_{g,0}, y_{g,0})$.

The subsequent estimates of the germ position $(x_{g,i}, y_{g,i})$, $i = 1 \ldots K$, required by the frontal algorithm (Eq.(3) to Eq.(10)), are obtained in a similar manner.



(a)

(b)

(c)

Fig.6: Steps of the frontal analysis for a potato of the Colmo variety, 294 x 204 pixels (Fig.2.a); (a) local energy image obtained by a 5 x 5 windowed standard deviation; (b) region(s) of interest; (c) superimposition of the region(s) of interest on original image.

### 3.4. Analysis of silhouette views

This subsection describes the processing steps used for locating germs on the silhouette view. The sequence of operations is as follows:

- thresholding of $g(i,j)$, providing a binary image $b(i,j)$ where 0 corresponds to the background and

possible shadow of the potato, and 1 to the potato, germs and shafts. The threshold is easy to determine since the first local minimum of the histogram always provide a good discrimination (Fig.7.a, Fig.7.b);

- morphological opening, followed by exclusive-oring (XOR) with the thresholded image. This provides binary regions representing outer germ(s), shafts, and fragments of the potato silhouette (Fig.7.c);
- elimination of those fragments which correspond to the potato silhouette (Fig.7.d). The discrimination is done using their area $A$ and elongation $p^2/A$, $A$ and the approximate perimeter $p$ being obtained by:

$$A = \sum_{\text{region}} b(i, j) \tag{18}$$

$$p = \sum_{b(i,j) \text{ has } >0 \text{ neighbour } =0} b(i, j) \tag{19}$$

A schematic scatter plot in the space $(A, p^2/A)$ is shown on Fig.8. Each point corresponds to one fragment; the threshold line separates between fragments corresponding to germs and fragments corresponding to the silhouette. The position of this line is predetermined using a series of training potatoes;

- elimination of the regions corresponding to the shafts. Since these shafts are longer than the image, the corresponding regions are those that are connected to the image border (Fig.7.e);
- as with the frontal analysis, determination within each region of $b(i, j)$ of the center of gravity of the edges of $g(i, j)$ obtained by application of Deriche operator and peak-following. This yields the desired point $(x_{g,n}, y_{g,n})$ from Eq. (11) (Fig.7.f).

In summary, these frontal and silhouette analyses combined with the active vision scheme as described above provide the 3D coordinates of the intervention point.

## 4. CONCLUSION

This article has given a general overview of the Potato operation. Its robotics and computer vision aspects have been discussed. The general guidelines for developing a working system have been indicated. Emphasis was given to the description of proposed solutions to the computer vision problem, in particular concerning the germs detection question. From a computer vision point of view, the major difficulty stems from the necessity of dealing with natural shapes. The proposed solution, by combining computer vision with mechanical movements, overcomes this difficulty.

The work reported in this document is still ongoing; the results obtained however indicate that the project is feasible. In view of the global needs for a better worldwide food supply, the potential usefulness of such a project and its interdisciplinary nature makes it a very interesting and challenging endeavour.

## 5. ACKNOWLEDGEMENTS

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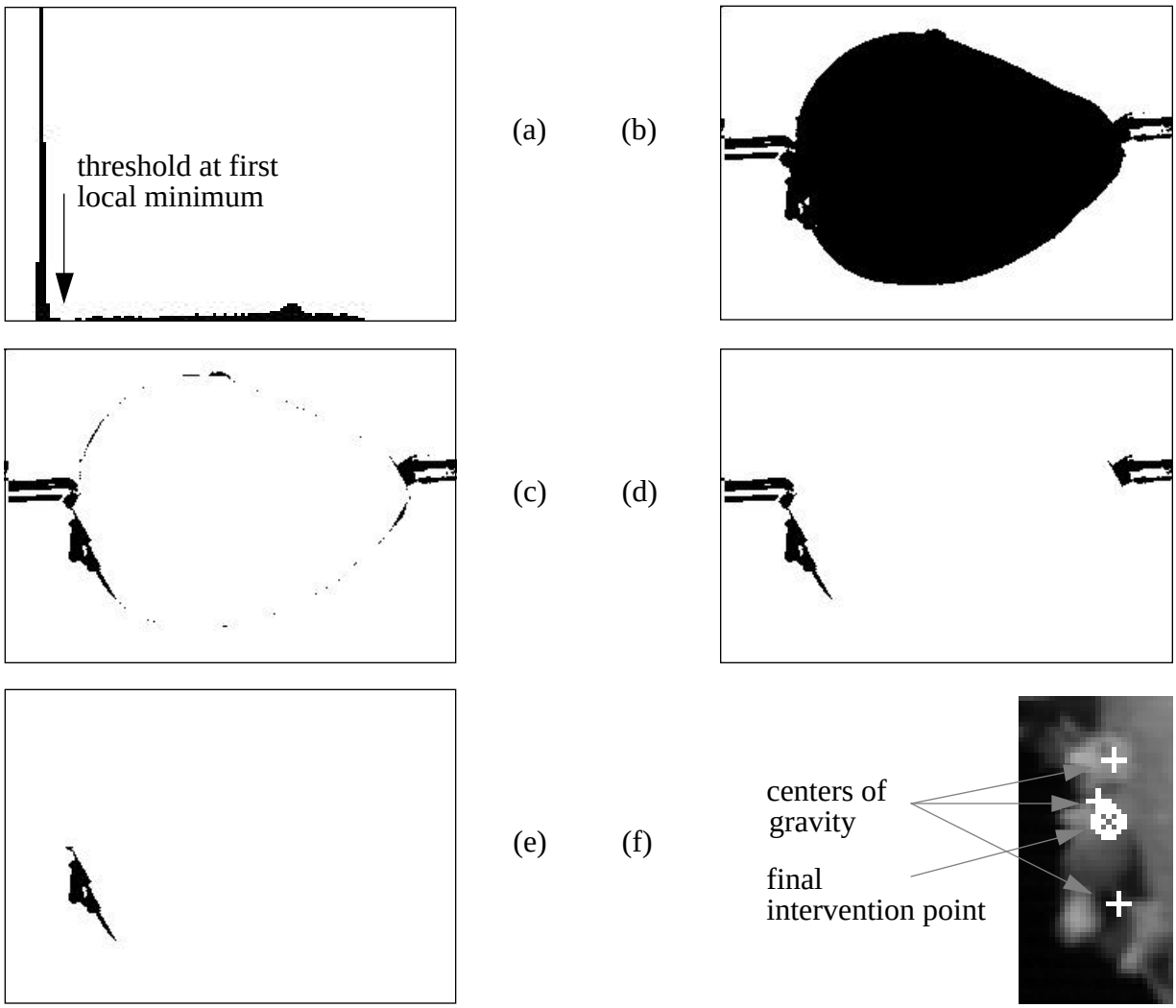


Fig.7: Silhouette processing of a potato of the Colmo variety (Fig.2.a). Steps: (a) grey level histogram (256 levels); (b) binary image, with potato, germs, shafts; (c) after morphological opening and exclusive-or; (d) after elimination of the potato silhouette; (e) after elimination of the shafts; (f) determination of the final intervention point, with indication of centers of gravity of the contour segments.

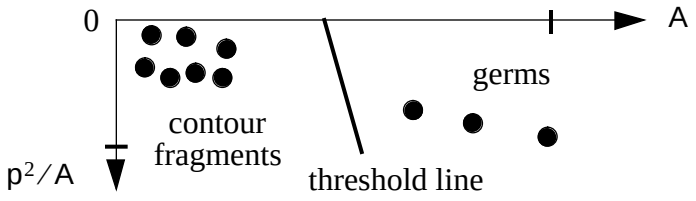


Fig.8: Schematic scatter plot in space $(A, p^2/A)$. Each point corresponds to one fragment; the threshold line separates between germ and silhouette fragments.

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