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Parallel session 3: Robotics and process control

PS3.03 Use of image analysis Ultrasound and CT in grading and processing of pig carcasses 58.00

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I. INTRODUCTION

The imaging modalities of ultrasound and computer tomography are long established disciplines in the medical field. These applications are characterized by a subjective interpretation of image details performed by highly trained specialists. This is rarely the situation for application of imaging systems in meat production in which automatic software performs the image analysis often at very high line speeds.

II. ULTRASONIC GRADING

A. Technology basics (generating the image) The physical foundation of ultrasonic imaging is described extensively in several medical imaging reference books [1,2] and will not be given here in greater detail. However, basic topics relevant for application in the meat industry are reviewed here. When describing sound propagation in different tissues, the concept of impedance is advantageous to consider. Physical impedance can be understood as the persistence of the tissue to support the propagation of the elastic sound waves, i.e. the acoustical implication of the general cause/effect theme: the impedance is the causal relation between imposed pressure and the resulting (volume) velocity. Sound propagation in tissue like fat and meat relies on the acoustic impedance as the impedance reflects the sound velocity (V) and the density (D) of the material through the expression Z=V*D. The higher the density, the more difficult for the sound pressure to accelerate the molecules of the medium. Using this definition reveals that gasses have low levels of impedance due to very low density in the range of 0.0013g/cm3 and a sound velocity of 344 m/s (air at atm. pressure) compared with water with a density of 1 g/cm3 and a sound velocity of 1490 m/s. I.e. Zwater = 1.490*106 kg/m2/s, Zair = 0.4*103 kg/m2/s. Water can be used as a simplified acoustical model for fat and muscle tissues. When a sound wave travels through water of a constant temperature, it propagates until it reaches a boundary (or all energy is absorbed by conversion into heat). The boundary (wall) has very high acoustic impedance, due to its high density and high sound. In analogy to audible acoustics most of the sound is reflected by the boundary. Similarly, sound is propagating from air to water due to the large difference in impedance of the two media. The reflected sound intensity Ir is related to the initial intensity I0 by the expression: (1)

In general, the smaller the difference in acoustic impedance between two materials, the smaller the reflected sound intensity, in the limit: the boundary between two materials with exactly the same impedance value appears “invisible” to the sound propagation. By inserting a thin layer of a third material between two materials of equal impedance, quite a different acoustic scenario is set up. As for a thin sheet of plastic (with high acoustic impedance) placed in the air, a reflection of a certain ratio of incoming sound intensity is observed. The propagation of ultrasound is similar.

Consider a short sound pulse propagating through a homogeneous media like water in a small tank (Fig.1). At a certain distance from the transmitter, a thin (compared to the wavelength) diaphragm of plastic is inserted, perpendicular to the direction of sound propagation. Some of the sound energy is reflected by the diaphragm and will arrive at the position of the transmitter with a delay depending on the distance to the reflector and the speed of sound in water. Thus, the delay is independent of the reflected intensity, but a function of distance and sound velocity only. The reflected intensity is determined by (1). Knowing the speed velocity in water, a simple time delay measurement is transformed into a distance scale. Note the ambiguity in case of an unknown velocity and position, an ambiguity that will appear important later. Soft tissues like meat, muscle and fat exhibit a sound velocity and density comparable to water.

Table 1 shows typical values as slightly differing figures are cited in the literature pointing out one important thing about these tissues: the exact value of the two parameters vary with a range of parameters like temperature, fibre direction, intramuscular fat content etc. Consider a simplified model of the subcutaneous fat tissue that borders directly to a muscle tissue. Using (1) with the figures in the table above leads to a reflected intensity level of approx. 1.5% of the incoming sound intensity, a substantially lower level than an air/water transition. Comparably the air/water boundary reflects 99.88% of the incoming sound intensity. These figures illustrate the importance of ensuring a proper contact between transducer and the tissue of interest.

B. Application in the meat industry In practice, such a system is used for (non invasive) measuring the thickness of the subcutaneous fat layer in living pigs. The system consists of a sound transmitter/receiver and a time gating mean to convert the reflection delay into the fat layer thickness. For breeding purposes (selection programmes) one or more discrete anatomical points are selected to be representative for the subcutaneous fat layer of the entire animal [3]. A continuous version of the discrete system above can be used to measure the thickness along a specific track in the length of the entire back of a pig carcass. An example of a measured sagittal thickness profile is shown in Fig. 2a. Repeating the continuous thickness profile along several parallel sagittal tracks can be used to describe a complete “fat coat” of the main part of the pig back as shown in Fig 2b. An automatic version of the continuous system is used to make on-line measurements of the back fat on pig carcasses in Danish slaughterhouses. The system has been calibrated to a manually dissected lean meat percentage (LMP) of pig carcasses in an experiment including 53 carcasses using the EU reference method [4]. The sample was a sub sample of a larger sample of 297 carcasses, both representing the Danish pig population. All carcasses were measured approx. 20 min. after bleeding with the AutoFOM system. The 16 transducers of the AutoFOM system provide the fat coat of the carcass. From the fat coat, 5 descriptive features are extracted and used as input to a PLS model to estimate the total LMP of the carcass. The procedure is described in more detail in [5]. The predictive performance of the AutoFOM system expressed as a RMSEP value was estimated to be in the 1.5-1.6 range.

C. Concluding remarks on ultrasound The main challenge in interpreting the signals in the ultrasonic grading system is the ambiguity mentioned above: when neither the acoustic impedance (type of tissue) nor the reflection distance is known, the reflected signal is difficult to relate to an exact fat thickness. Anatomical features can solve the ambiguity problem in some parts of the carcass, namely in the vicinity of the longissimus dorsi muscle. In some carcasses with low levels of intermuscular fat, the longissimus muscle can be taken as a homogeneous tissue. For that reason, the interpretation can assume that no reflection of the ultrasonic intensity occurs from within the muscle. The assumption leads to identification of the fat/muscle boundary thereby leading to determination of the subcutaneous fat thickness. In some other anatomical parts like the belly, this assumption fails, leaving the ambiguity problem quite challenging. In these regions, the reflection from thin membranes between equal tissues complicates the interpretation of the reflection signal further. Emerging ultrasound techniques, like elasticity imaging [6], seems to overcome the ambiguity problem. A recent review of such ultrasonic methods applied in the field of meat science can be found in [6]. However, anatomical relations between the fat coat and other quality traits facilitate modelling the quality of other parts of the carcass, eg. the fore part and the ham. It is important, however, to note that such models are generally sensitive to genetic changes in the population of interest.

III. COMPUTER TOMOGRAPHY

A. Technology basics

Computer tomography is an imaging modality based on attenuation of X-ray energy often in the 80-140 kV range. Several reference books exist on the technique [7, 8], thus, mainly details relevant to clarifying the difference from ultrasonic imaging will be highlighted here. Consider an X-ray tube generating a fan of monochrome rays illuminating a linear array of detector elements. Inserting an object in the centre between source and detector will cause attenuation of some of the x-rays determined by the size, thickness and composition of the inserted tissue object.

From each detector element a measure of the attenuation along one specific ray of the fan beam accumulated through the object can be found. The intensity (Ie) arriving at the detector element can be expressed as: (2) The object thickness is d, and the radiation intensity is I0. The parameter μ is denoting the (linear) attenuation coefficient of the tissue volume element along the radiation path. In the simple case of a homogeneous tissue, the integration in (2) simplifies to the product of attenuation coefficient and tissue thickness (μd). In meat products μ often varies with position and (2) expands to the integration of any local distribution of μ(x,y) along its entirety in the direction of the e-th detector element. By using the simple line integration of (2), an ambiguity arises in case of unknown tissues of unknown thickness. Any tissue volume element along the propagation path contributes to the linear integration in (2). At the detector, every local value of μ is masked by this ambiguity. In Fig. 3 above, a number of local attenuation values are present within an object of interest. A radiograph can be formed by exposure from a parallel x-ray beam, and the received intensity on three detector elements is found by simple summation. The three detector signals are not sufficient to determine the nine local attenuation coefficients. The ambiguity can be considered as an underdetermined set of mathematical equations for determination of the local value of $\mu(x,y)$. To overcome this, the detector array and the x-ray source are rotated at a small angle and the next set of projections is measurable at the three detector elements, thus, they can be taken as an additional set of equations. In a modern CT scanner as much as 1500 projections are made, each measured with a detector array consisting of more than 1000 discrete elements forming a large set of equations to solve the local value of $\mu(x,y)$ anywhere in the tissue object. The solution to the set of equations can be shown in a 2D frame, reconstructed from all the projections, conventionally referred to as a tomogram. The tomogram is not a radiographic image but an illustration of the solution to a very large mathematical problem. By contrast the projections can be taken as simple line-radiographies. The tomogram represents the value of $\mu(x,y)$ from a large number of volume elements, say 512 by 512 voxels, a thin slice of the object. The attenuation values of tissues relevant for the meat science application are shown in table 2, expressed at the so-called Hounsfield Scale. Comparing the tissue attenuation value with the corresponding value of water leads directly to the Hounsfield Scale by the relation: CT value = $1000*(\mu T - \mu water)/\mu water$. The attenuation coefficient μ is determined by the physical density and elemental composition of a material. Light elements like H, O and C contain small absorption compared with heavier elements like Ca and P containing a much higher absorption at x-ray energies [9]. As a rule of thumb, by comparing to the values of water it can be said that a tissue lighter than water assume negative Hounsfield Units and the heavier tissues are found at positive HU values. The heavier, the higher the HU rating. Displaying the tomogram on a grey scale of say 256 levels one has to decide on a look-up-table to transform data between the Hounsfield scale and the grey scale showing the image features. It is important to note that the HU value is directly linked to the absorption values whereas the grey scale can be chosen to optimize a specific detail of interest. A suitable transformation (LUT) for meat/fat analysis is to assign HU levels lower than -127 to black and higher than +127 to white. This leaves fat and meat tissues clearly discernable with bony structures as uniform white and light plastic (supporting trays) and air as uniform black.

B. Applications in the meat industry

Now, consider a 3D object scanned by multiple "slices" as described above. The slice thickness is set by the scanning protocol and can assume from a fraction of an mm up to 10mm. Setting of this parameter is often adjusted to the spatial variation of the tissue features of interest. For grading purposes, frequently 5 or 10mm slice thickness is used. By consecutive movement of the object perpendicular to the slice, a distance equal to the thickness and by repeating the projection procedure it is possible to record the density of any voxel within the object volume. On the computer it is consequently possible to build a complete 3D model of the tissue object represented by any local density distribution. From a grading perspective the tissue distribution can be taken to be discrete with three bins only: fat, meat and bone. Conventionally, the assessment of tissue into the three bins is performed by manual dissection. CT scanning enables the computer to do the assessment. Several assessment strategies have been published [10] and some even evaluated with respect to robustness: sensitivity to protocol parameters like reconstruction algorithm, x-ray current, slice thickness and x-ray energy [11]. The analysis approach of CT data for grading can be divided into two groups: a) The spectral calibration of the density distribution (in Hounsfield Units) using the manual assessment (dissection) as reference employing multivariate methods or b) volume grading methods based on determination of the volume of the three tissue classes, fat, meat and bone calibrated to the total (scale) weight of the product. The latter group of methods seems to surpass the spectral methods regarding robustness [11].

One other advantage included in the volume grading approach is the capability to estimate the weight of any part of a scanned volume. From the scanned volume of half a carcass it is feasible to estimate the weight of the tri sectioning parts or any other jointing of interest [12, 13].

In [14] a methodology for quantification of the biological variation of bone structures is formulated. The approach can be of interest as a design tool in development of boning equipment to verify the variability of any relevant fix point. Furthermore, a specific joint can be described relative to the fix points, thus defining the space of variation for the cutting tools of the boning machine.

Breeding programmes [15] for domestic animals can benefit from CT scanning of the candidates to reveal much more detailed information about quality traits of the selected breeding individuals. Furthermore disposal for certain diseases can be predicted from detailed scanning of skeletal features.

III. CONCLUDING REMARKS

Non-destructive measurements are expected to develop new application areas within meat production. Especially X-ray systems seem to expand from simple foreign body detection systems into a more versatile product quality gauge [16]. Parameters as weight, missing product homogeneity, size and fat content are gradually enabled with increasing computer power and availability of more and lower X-ray energies.

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Use of Image Analysis

Ultrasound and CT in grading and processing of pig carcasses

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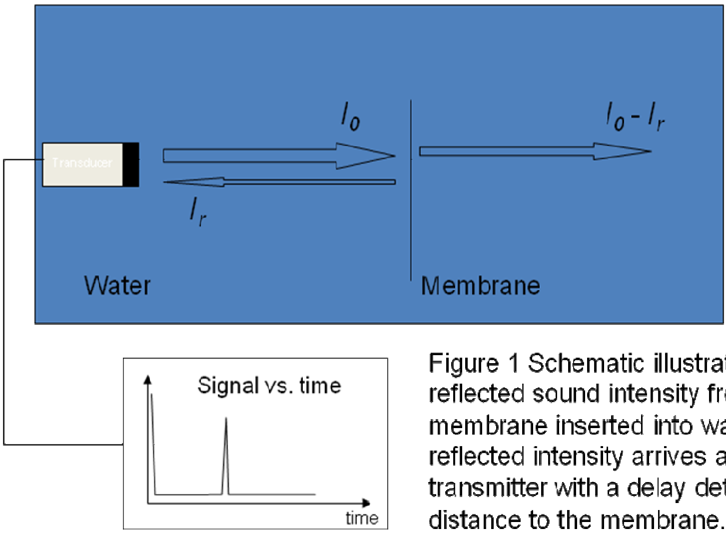

Figure 1 Schematic illustration of the reflected sound intensity from a thin membrane inserted into water. The reflected intensity arrives at the transmitter with a delay determined by the distance to the membrane.

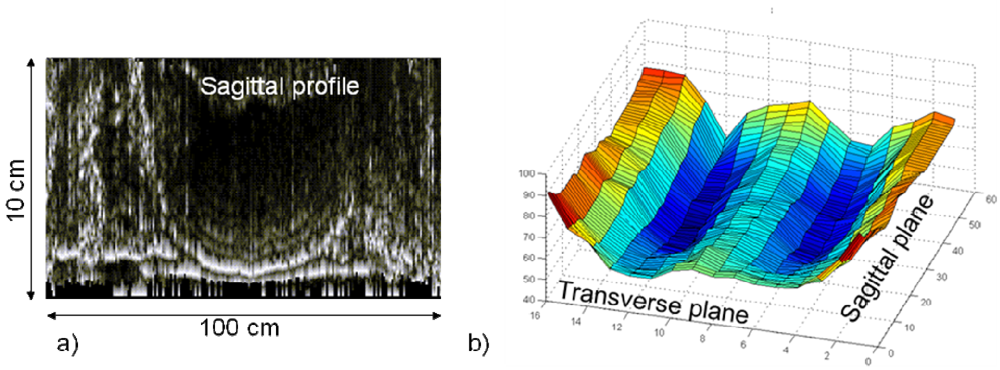

Figure 2. a) Sagittal ultrasonic reflection profile from a pig carcass. Measured along the Longissimus Dorsi muscle. b) A “thickness map” of the subcutaneous back fat layer of a pig. The blue regions are the thin fat thickness above the two loin muscles.

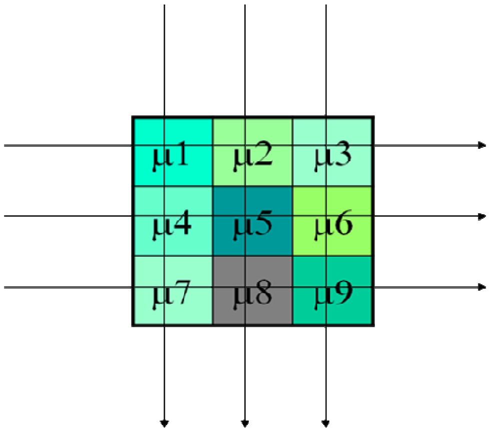

Figure 3. Schematic illustration of a heterogeneous object (with nine attenuation coefficients) measured with a parallel X-ray beam with a three-element detector. The integration on each detector contains an ambiguity resulting from the line integration of (2).

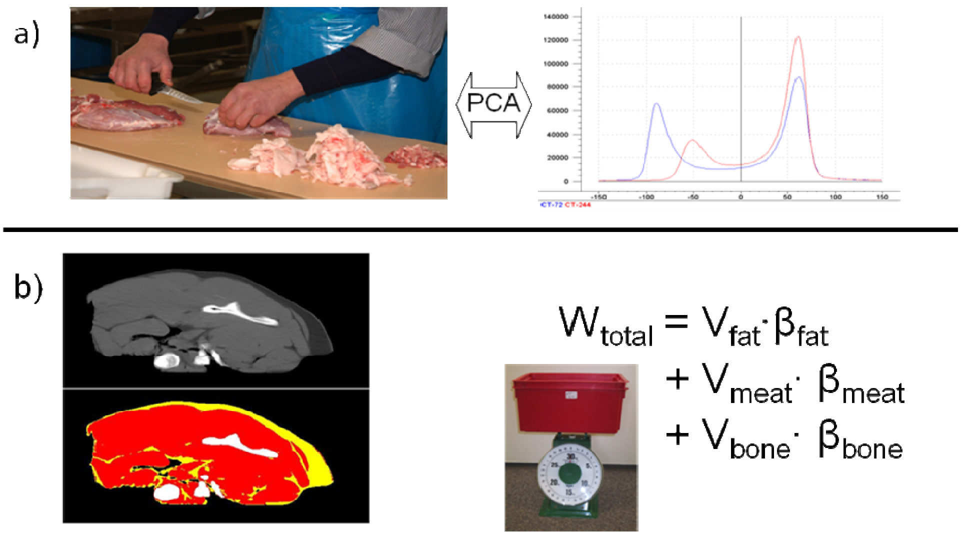

Figure 4. a) Spectral Calibration: The same sample of carcasses is CT scanned and manually dissected. The Hounsfield spectra are calibrated to the manually determined LMP using multivariate methods. b) Volume Grading: The carcass is CT scanned and weighed on a scale. From the tomograms the total volume of fat, meat and bone is measured and compared to the scale weight. By this comparison, the three average tissue densities (β_i) are estimated.

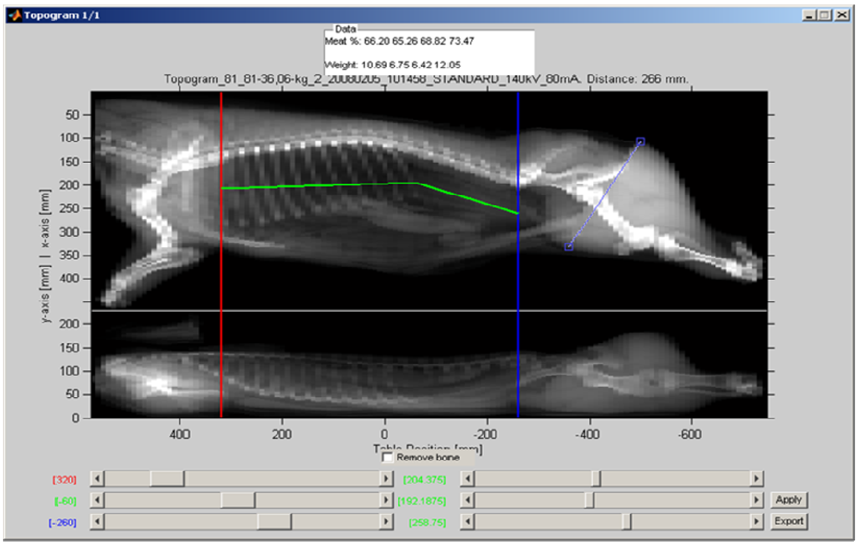

Figure 5. An example of a four-sectioning of half a carcass exploiting the benefit of the volume grading approach. The programme estimates the weight and meat content of the four main cuts of the carcass. The sliders can change position, thus defining alternative jointing settings. The program also provides a distance tool.

Tables & Formulas

Table 1. Acoustical (typical) parameters for meat tissues and air

	Speed of sound	Tissue density	Acoustic impedance
Air	344 m/s	0.0013 g/cm³	0.4*10³ kg/m²s
Fat	1450 m/s	952 g/cm³	1.38*10⁶ kg/m²s
Muscle	1540 m/s	1070 g/cm³	1.65*10⁶ kg/m²s

Table2. Attenuation of meat tissues, water and air expressed on the Hounsfield Scale

Tissue	Air	Meat	Fat	Water	Bone
HU[1]	-1000	20 - 100	-100 - -20	0	200 - 2000

$$\frac{I_r}{I_o} = \frac{\left(Z_{water} - Z_{air}\right)^2}{\left(Z_{water} + Z_{air}\right)^2} \qquad (1)$$

$$I_e = I_0 e^{-\int_0^d \mu ds} \qquad (2)$$