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Active infrared thermography as a tool for quality control in the food industry

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Abstract Active infrared thermography is a technique which can visualize differences in the thermal properties of the objects under inspection. It is an interesting alternative to existing methods in various fields of quality control in foodstuff. Possible applications include the detection of foreign bodies in almonds and potatoes and the detection of bruises in apples. This chapter explains the principles of active thermography, gives typical examples and discusses the options and limits of the technique as wells as some aspects of infrared image processing.

1 Introduction

Consumers of food expect high quality and low prices at the same time. Consequently, automated techniques for quality control in the food industry are essential and still gain in importance. While well-established methods based on image processing in the visible part of the electromagnetic spectrum exist, little use is made today of the differences in thermal properties such as thermal capacity and thermal conductivity of foodstuff. These differences can be made visible by means of active infrared thermography. In such a way, thermography can help to solve some problems e.g. in the detection of foreign bodies in food. Potatoes coming from the producer, for example, can contain a lot of foreign bodies such as wood, bones, objects from plastic and even golf balls. Many of these can be separated by means of heavy media separation: Potatoes sink in normal water, any object with lower density than potatoes will swim and can be removed. In salt water, on the other hand, the potatoes will swim, and objects with a higher density can be separated. However, wooden objects, bones, and also the golf balls cannot be removed in this way. Furthermore, they also look very much like potatoes, so that conventional image processing is difficult or impossible. As will be shown below, these objects can be detected using active infrared thermography.

2 Principles of infrared imaging

The basis of infrared thermography is the fact that every object having a temperature above absolute zero emits electromagnetic radiation which is called thermal or Planck radiation. At a given wavelength the radiated power density (for a so-called black body) depends on the temperature only so that the temperature can be calculated by measuring the radiated power density. The dependence of the power density on temperature and wavelength is given by the famous Planck equation:

$$M_\lambda^0 = \frac{C_1 \lambda^{-5}}{\exp(\frac{C_2}{\lambda}) - 1}$$

In this equation, M_λ^0 is the power density per wavelength interval emitted by an ideal (“black”) radiator (unit: W/m^3), whereas λ stands for the wavelength and T for the absolute temperature. The constants C_1 und C_2 contain only natural constants such as h (Planck’s constant), c (speed of light) und k_B (Boltzmann’s constant):

$$C_1 = 2\pi hc^2$$

$$C_2 = \frac{hc}{k_B}$$

For room temperature, the emissivity curve peaks around 10μm (see Fig. 12.1). A large number of cameras exist on the market which are sensible to infrared radiation in this wavelength range. Basically, there are two groups of cameras. In the first type, the so-called uncooled or bolometer cameras, the infrared radiation is focussed on an array of small silicon plates. The resulting increase in temperature is detected by means of the increasing electrical resistance. In the second

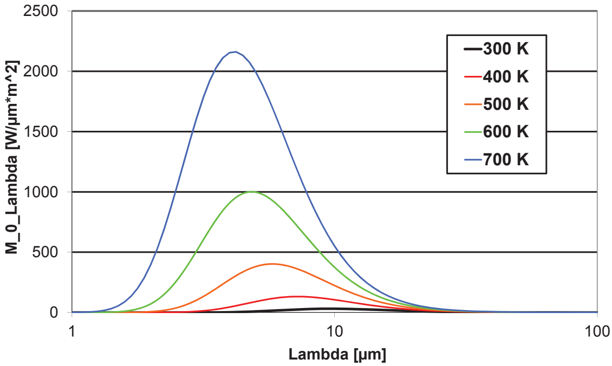

Figure 12.1: Power density radiated by a black radiator between 300 K and 700 K.

group of cameras, mostly called cooled cameras, the infrared photons create electron-hole pairs in semiconductors such as HgCdTe or InSb. These detectors have to be cooled to temperatures around 90K in order to avoid excessive thermal noise. Typical pixel numbers are 640 x 512 for both camera types. The temperature sensitivity is given by the so-called noise equivalent temperature difference which is in the range of 50mK for uncooled and 15mK for cooled cameras. It is often said that infrared cameras image the surface temperature of objects. This is not exactly true since Planck's formula as written above is valid only for the ideal black radiator. Any real object radiates at a given temperature less power than the black radiator This is mathematically described by a multiplicative constant called ϵ which is between 0 and 1 by definition:

$$M_\lambda^\epsilon = \epsilon(\lambda) M_\lambda^0$$

While polished metals can have very low emissivity values (Al: 0.03), most organic materials have emissivities close to one.

3 Active infrared thermography

The idea of thermography for quality control in foodstuff is to generate temperature differences between "good" and "bad" regions which can

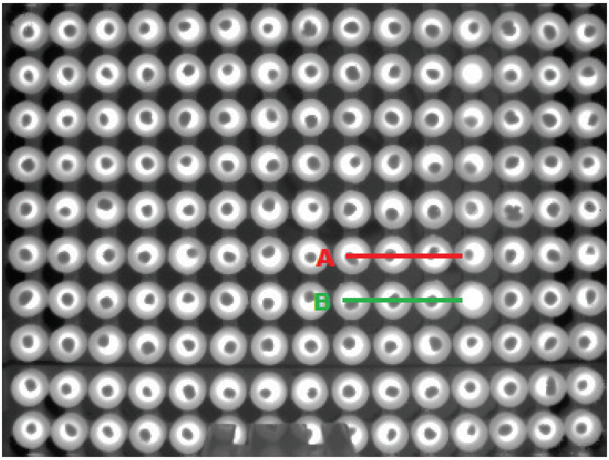

Figure 12.2: Thermal image of caramel cups (light grey) filled with hot chocolate (white) and nuts (dark). A: half nut. B: mising nut.

subsequently be detected by infrared imaging. The flow of heat in solid matter is described by Fourier's law:

$$\nabla Q = \nabla(\nabla \kappa T)) = \rho C_{sp} \frac{\partial T}{\partial t} - q$$

where Q is the heat flow, κ the thermal conductivity, ρ the mass density, C_{sp} the specific heat capacity, and q the internally generated heat. In order to have $\nabla T \neq 0$, one needs either internally generated heat (q$\neq$ 0) or a change of temperature in time ($\partial T/\partial t \neq 0$), or both. Only the second case is of practical importance in quality control of foodstuff since there are normally no internal heat sources. A change of temperature in time can simply be achieved by letting cool down some foodstuff which was heated in a preceding production step (passive heat flow thermography). A typical example for passive heat flow thermography is presented in Fig. 12.2, showing the top view of an array of caramel cups (light grey) filled with ot chocolate (white) and hazelnuts (dark). Missing nuts (B) and half nuts (A) can be clearly detected.

A second and more important way to achieve a change of temperature in time is to apply a transient heat pulse to the foodstuff. An

Figure 12.3: Photographic (left) and infrared (right) image of almonds with stones as foreign bodies.

easy way to this is to let the foodstuff pass an infrared heater on a conveyor belt. This corresponds to a single rectangular heat pulse. Since infrared cameras are very sensitive, a temperature increase of a few degree Kelvin is sufficient. In order to better understand the underlying physics, let us first consider the homogeneous thermal excitation of an infinite half plane by a sinusoidally (with frequency ω) modulated heat source. In this case we get a sinusoidal, but exponentially damped thermal wave [1]. Its amplitude is described by

$$T(z,t) = \frac{Q}{2\sqrt{\rho C_{sp}\kappa\omega}} \exp(\frac{z}{\mu})$$

where

$$\mu = \sqrt{\frac{2\kappa}{\rho C_{sp}\omega}}$$

is the damping factor, also called penetration depth, Q the external heat flow, and z the distance from the surface. It can be seen that a thermal contrast can arise when there is a difference in $\rho C_{sp}\kappa$. The contrast and the penetration depth increase with decreasing ω. Following Fourier, rectangular pulses can decomposed in a series of sinusoidal waves. The lowest efficiently excited frequency is inversely proportional to the pulse length. Consequently, the penetration depth under rectangular excitation can be tailored to a desired value by adjusting the

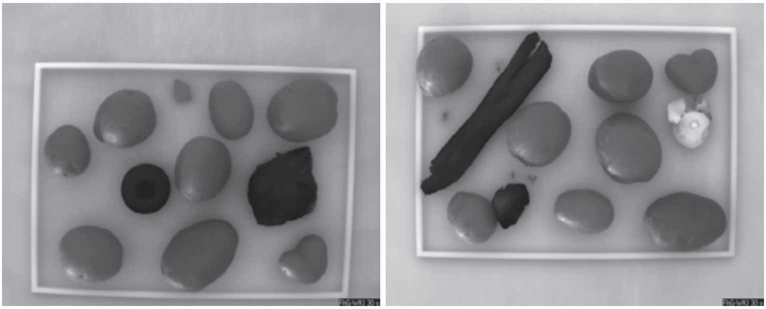

Figure 12.4: Infrared images of potatoes with different foreign bodies including golf ball and pumice stone (left) as well as peices of wood and bone (right).

pulse length. A typical result of this technique can be seen in Fig. 12.3 which shows almonds with stones as foreign bodies. In the infrared image (right) these appear darker because of their higher thermal capacity.

4 Application: Detection of foreign bodies in potatoes

Figure 12.4 shows infrared images of potatoes and foreign bodies taken with active thermography. Interestingly, the grey values of the potatoes are all the same, independent of their size. The reason is that the penetration depth was chosen in such a way that it is much smaller than the smallest dimension of the potatoes. Thus, the heat front is confined a region close to the surface, and size effects do not appear. The foreign bodies can be clearly identified by their differing grey values. A piece of bone (right part of the right image) appears brighter since it has a rather low thermal capacity. The thermal capacities of a golf ball and a pumice stone (left image) are higher than those of the potatoes, consequently they appear darker. The same is true for a wet piece of wood (left part of the left image). The presented images are already the result of some image preprocessing routines. First of all, the pixels of infrared detectors have very different response curves so that a so-called non-uniformity correction has to be carried out. To this end, two reference images of a homogeneous area are taken at different temperatures. By assuming linear response curves, correction factors for most pixels can

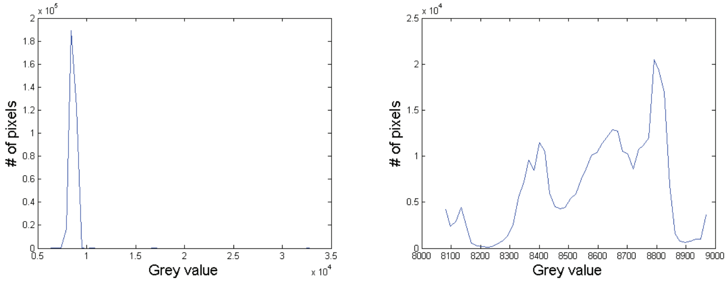

Figure 12.5: Histogram of the left image in 12.4 before (left) and after (right) outlier removal.

be calculated. However, some pixels cannot be corrected in this way since they do not give any signal at all (dead pixels) or have very non-linear or unstable response curves. These pixels have to be removed because they could lead to wrong results in further processing steps. A possible way to do this is to identify them manually, register them in a look-up table and replace their values by those of a good neighbour pixel. In case the bad pixels do not form too big cluster, a median filter is an alternative solution. Even after bad pixel correction, the histogram of a typical infrared image like the left image in Fig. 12.4 looks like the left histogram in Fig. 12.5: It is dominated by outliers whereas the actual signal is confined to a small grey value range. A good method to remove the outliers is to clip the histogram at the lowest and highest 1 percent of the grey values (right histogram in Fig. 12.5). For a segmentation of the foreign bodies one can in principle use the histogram and set a grey value threshold. However, the potatoes and also the foreign bodies can have various temperatures, depending on the storage conditions. Consequently, a fixed grey value threshold will not work, and an adaptive calculation of the threshold is necessary. There are several ways to do this. Fortunately, foreign bodies are rare. Thus, one can simply take images of the potato stream and calculate the histograms. This will normally have two peaks: those of the potatoes, and those of the conveyor belt. It helps when the grey value of the conveyor belt is close to that of the potatoes or at least between the grey values of the "dark" and the "bright" foreign bodies. When a third peak appears in

Figure 12.6: Apple with bruise.

the histogram, some action has to be taken. Alternatively, one could take two images, one before the thermal excitation and one afterwards. The grey value difference between both images depends only on the heating power and the speed of the belt. However, this requires two of the rather expensive infrared cameras.

5 Application: Detection of bruises in apples

Another promising application of this principle is the recognition of bruises in apples. When the apple tissue is damaged by the application of a certain force, subsequent chemical processes lead within several hours to brown spots on the apple surface which many customers do not accept. These spots can easily be detected by conventional image processing. Fresh bruises, however, are not visible. But the damaged tissue has a different thermal conductivity than sound tissue (see Fig. 12.6), so that even fresh bruises can be detected by thermography. This is demonstrated in Fig. 12.7. Three apples were subjected to forces of 20N, 40N, and 60N, respectively, on an area with 1cm diameter. The left part of the picture shows the apples before thermal excitation, whereas the right image was taken after thermal excitation. The bruises can clearly be detected, and different pressures apparently cause different patterns in the infrared image.

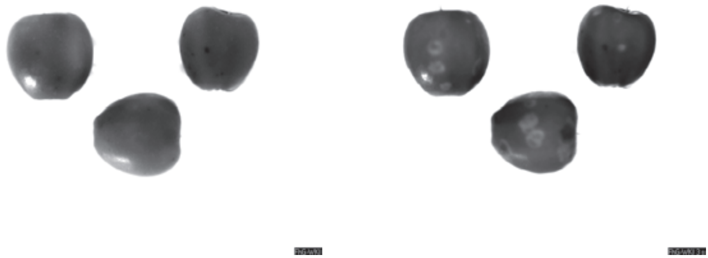

Figure 12.7: Infrared images of apples with bruises caused by defined pressure before (left) and after thermal excitation.

6 Summary

It was shown that active infrared thermography is a versatile tool for quality control in foodstuff since it can visualize differences in thermal capacity and/or thermal conductivity and thus opens the way to utilize physical properties not used before. Thermal excitation can be achieved by simply installing an infrared heater over a conveyor belt. Significant changes to the production line are not necessary. Furthermore, no safety concerns as in x-ray technologies exist. Typical applications include the detection of foreign bodies in almonds and potatoes and of bruises in apples. Whereas many algorithms of conventional image processing can be adapted for the use in thermography, infrared images have some peculiarities which have to betaken into account.

References

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