NEW POWER-LEDS BASED ILLUMINATION SYSTEM FOR FERTILIZER GRANULE MOTION ESTIMATION

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ABSTRACT

Environmental problems have become more and more pressing in the past twenty years, with fertiliser use being one main contributor to environmental imbalance. Understanding the spreading process from the vane to the soil contributes essential information about fertiliser use. Progress in imaging devices and image processing has resulted in the availability of new technologies to use when describing the behaviour of fertiliser granules during ejection from centrifugal spreaders. The high-speed of the granules at the ejection - around 40 m/s – requires such high-speed acquisition system to be used. Therefore a has been developed based on the combination of a standard digital camera and a stroboscopic illumination with photographic flashes. To avoid non consistent illumination and weak lifespan of the flashes, improvements of the lighting system has been done by using 3W power-leds located 1m height around the digital camera and controlled by a FPGA card specifically dedicated to our application. To provide homogeneous and powerful lighting (≥ 1500 lux) on a large surface (i.e. $1m^2$), the power-leds have to be regrouped and arranged in a hexagonal configuration. The power-leds can be used in a static or a dynamic mode. Used in a static mode, they provide a continuous lighting, and they have to be associated with a high-speed camera to allow the granule displacement to be measured. Used in dynamic phase, to reproduce stroboscopic effect, a standard low-cost camera is only required. The acquisition provides multi-exposured images and a specific image processing method is required. The image processing method has been improved by the development of a multi-phase method based on a cross-correlation algorithm which guarantees sub-pixel accuracy ranging between 0.1 and 0.4 pixels.

Keywords: High-speed images, Power-leds illumination, Fertilizer granules, Motion estimation

CONTEXT AND OBJECTIVES

Environmental problems have become more and more pressing in the past twenty years particularly with the fertilization operation, one main contributor to environmental imbalance. The understanding of the global centrifugal spreading process, most commonly used in Europe, can contribute to provide essential information about fertiliser granule deposition on the soil. The current system requires a tedious and laborious process: in-field setup of collection trays, removing collected material from each tray, weighing the contents, entering the weight data into a computer program, and printing the output. In addition, the farmers do not generally verify the correct adjustment of the spreader, which skews the data.

Distribution of granules in the soil could also be predicted using a ballistic flight model and several fertilizer characteristic's determination such as velocities and directions of the granules at the ejection.

Since 15 years, and due to improvement about image and signal acquisition and processing, optical systems have been developed, to determine some granule parameters, especially granulometry (Grift and Hofstee, 1997), trajectories (Cointault et al., 2002) or the horizontal mass flow distribution around the disc (Dutzi, 2002; Miller and Parkin, 2005). Particularly, high-speed imaging devices have been developed using either high-speed camera and led-based illumination (Vangeyte and Sonck, 2005) or classical digital camera coupled to stroboscopic flashes (Cointault et al., 2003) and combined to image processing based on motion estimation methods (Hijazi et al., 2008). They differ one from the other in terms of image processing, field of view of the camera and illumination approaches (flashes or leds). In all cases, the quality of images is not sufficient to determine accurately the trajectories of the granules because of a degradation of the illumination with time or a too small field of view.

This paper presents a full study of the new stroboscope system based on power-leds, technology greatly improved since the last five years, which appears as a reliable substitute for our flashes.

The high-speed imaging system conceived is first presented and the illumination by flashes is described. The second part deals with improvements of the lighting system using power-leds. Examples of granule images obtained are presented in a third part together with the new image processing developed, before to propose prospective works and to conclude about this research.

HIGH-SPEED IMAGING SYSTEM AND ITS ILLUMINATION PART

Due to the relatively high speed (from 25 $m.s^{-1}$ to 40 $m.s^{-1}$) of the fertiliser granules, we believed that a high-speed imaging system would be a good alternative in order to determine the granule trajectories. Due to the poor resolution of the resulting images at that time, the results were not significant. High-speed cameras with sufficient resolution were scarce and much too expensive to be used in agricultural practise.

We then developed alternatives to high-speed cameras (Cointault and Vangeyte, 2005), by combining a high-resolution monochrome CCD camera with strobe systems based on flashes or leds (Figure 1).

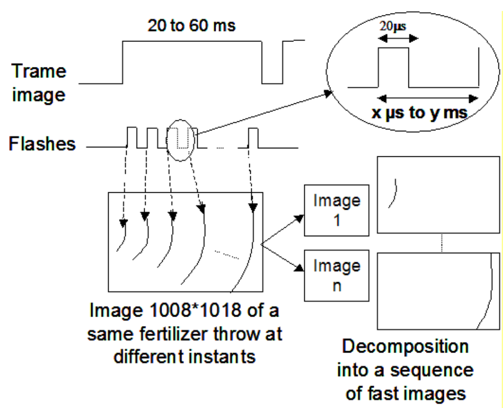

Figure 1. Principle of the high-speed imaging device and example of typical multiexposure image obtained.

The motion estimation combined a theoretical model of the granule distribution and MRFs (Markov Random Fields) method, based on the determination of optical flow characteristics on the images. The results for granule velocities were close to velocities which were visually evaluated from examination of the image, and similar to the results obtained with motion blurred images (Villette et al., 2007). However, this system cannot be installed currently on an actual spreader, owing principally to the:

- relative high cost and lack of robustness of the flash system
- non consistent illumination
- weak lifespan of the flashes

In response to these challenges, power-leds appear as an interesting alternative to photographic flashes as this technology is well known now and provides sufficient illumination with high robustness and lifespan. Our main goals are then to propose different solutions for the definition of a new lighting system for fertilizer granule motion estimation:

- A high-speed camera coupled to power-leds direct illumination with a higher cost than the below solution (to use the system as a control one for spreader settings)
- A low-cost multiexposure approach with device based on a power-leds stroboscop and a standard high resolution camera (to install the system directly on a spreader)

The last approach optimizes the multiexposure imaging system by first developing a robust and easy to use power-leds based stroboscope and combining it with a new motion estimation method based on cross-correlation (Hijazi et al., 2009). The advantages of this approach are that it provides sub-pixel accuracy in the velocity calculation, which allows us to decrease the resolution of the standard camera and thus use low-cost digital cameras. The estimation of the velocity is validated by comparing the measured velocities to the known velocities of the grains on simulated images. The estimated velocities are compared to the known velocities of the grains on images created by specially developed simulation software.

Our main objective is thus to propose a long-term unique device capable of characterising the fertiliser, to establish a typology of products (behaviour, friction resistance, ejection characteristics, etc.), and finally to install it on a spreader for online fertiliser regulation.

IMPROVEMENTS OF THE CURRENT ILLUMINATION DEVICE

Accurate scene illumination requires a lighting system with the following characteristics: high luminosity power, robustness, automated control and low cost. The stroboscopes share the same principle as photographic flashes. A condenser unloads through a transformer, which produces a luminous flash. The duration and intensity of the flash depend on the characteristics of the electronics used. Degradation of the electronic components limits the duration of the flashes to around 10,000 flashes. The recycling time of the classical stroboscope is difficult to modify and limits the frequency. The combination of frequency and illumination necessary for our application cannot be obtained with the existing stroboscopes.

Other tests have shown that four 200 watt spotlights furnish around 5 000 lux at the level of the spinning disk (distance is 20 cm between the spotlights and the luxmeter). With these lighting conditions and the camera located at 1m height, images of the fertiliser granules are overexposed. Around 1 500 lux are sufficient to provide clear images when the power-leds are used.

Power-leds appear to be a good alternative to the illumination systems mentioned above. We began our experiments with white power-leds because they have been greatly improved over the last five years and are relatively inexpensive. This system is piloted by an FPGA card, allowing easy modifications of the illumination configurations into several modes, i.e., sequence or single flash with different parameters such as illumination time, inter-flash time and eventually inter-sequence flash. Figure 2 illustrates the entire system along with the stroboscope functioning sequence.

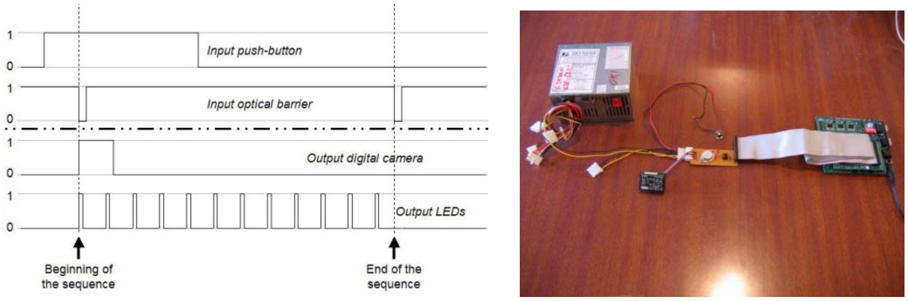

Figure 2. The whole stroboscopic command and functioning sequence.

The output can be set from one to 32 flashes. We used eight flashes, the number used in the previous stroboscopic setup. Image acquisition is synchronised with the granular flow: the passage of the vane triggers an external sensor to take the picture. The power-leds must be positioned uniformly around the camera lens to fulfill two demands: sufficient and homogeneous illumination. AgroSup Dijon has completed a preliminary study characterising the illumination distribution of power-leds (Jaton and Biryukov, personal communication, 2008).

For StardLed power-leds with the following characteristics: 80° of angle of view, 3 W, 7000 K, the illumination (E) provided can be approximated by a polynomial equation of 7th order:

$$E_i = \sum_{j=1}^{7} \left(k_j \times d_i^{(7-j)} \right) \quad (1)$$

where E_i the illumination from a point i and k_j is the coefficient of the jth term of polynomial equation.

If *Xc* and *Yc* are the coordinates (in cm) of the projection of the lighting source on the field of view and *Xi* and *Yi*, the coordinates of the point *i*, the distance between the two points is:

$$d_i = \sqrt{(Xc - X_i)^2 + (Yc - Y_i)^2} \quad (2)$$

If the lighting source is composed of n power-leds, we introduce a coefficient *n* which gives this equation:

$$E_i = n_{LED} \times \sum_{j=1}^{7} \left(k_j \times d_i^{(7-j)} \right) \quad (3)$$

When combining the above equations (2) and (3), we obtain the illumination of the point i according to the coordinates and the location of the lighting source:

$$E_i = n \times \sum_{j=1}^{7} \left(k_j \times \sqrt{(Xc - X_i)^2 + (Yc - Y_i)^2}^{(7-j)} \right) \quad (4)$$

Figure 3 shows the spatial curve of the illumination for each point of the field of view.

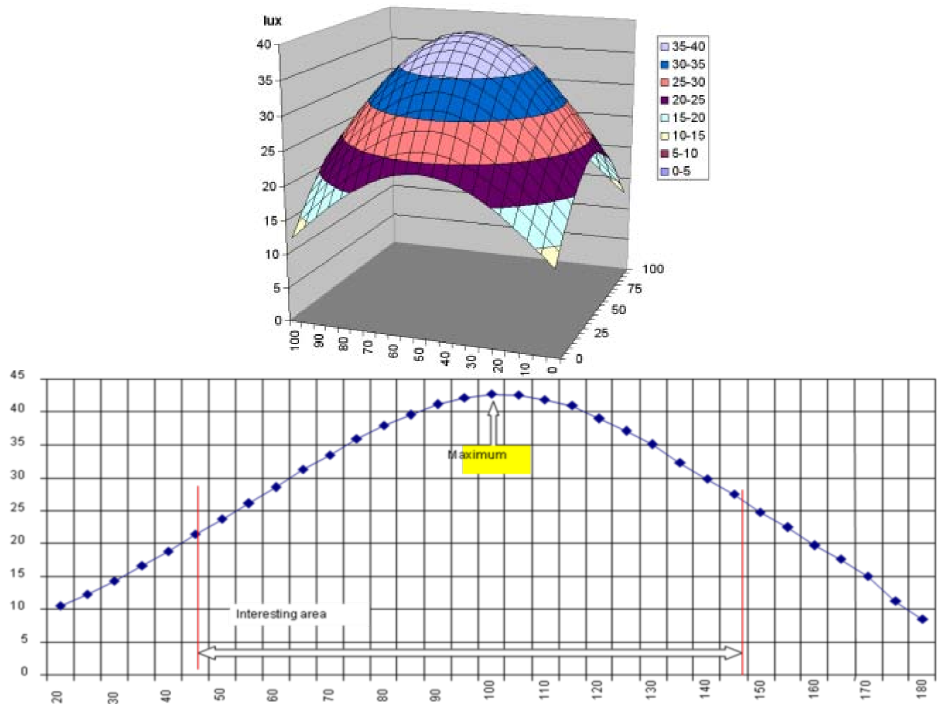

Figure 3. Illumination in Lux of one single 3W power-led located at the centre of the field of view.

If several lighting sources are placed above the field of view, each source creates an illumination E_{pi} for a point i. The entire field of illumination is then described by equation (5).

$$E_{\Sigma i} = \sum_{p=1}^{P} E_{pi} = \sum_{p=1}^{P}\left[n_p \times \sum_{j=1}^{7}\left(k_j \times \sqrt{\left(Xc_p - X_i\right)^2 + \left(Yc_p - Y_i\right)^2}^{\,(7-j)} \right)\right] \quad (5)$$

where Xc_p and Yc_p are the coordinates of each power-led and P, the number of lighting sources.

Figure 4 shows the resulting illumination for two 3W power-leds separated by 110 cm and proves that the illuminations of two lighting sources can be added together to foresee in sufficient luminosity

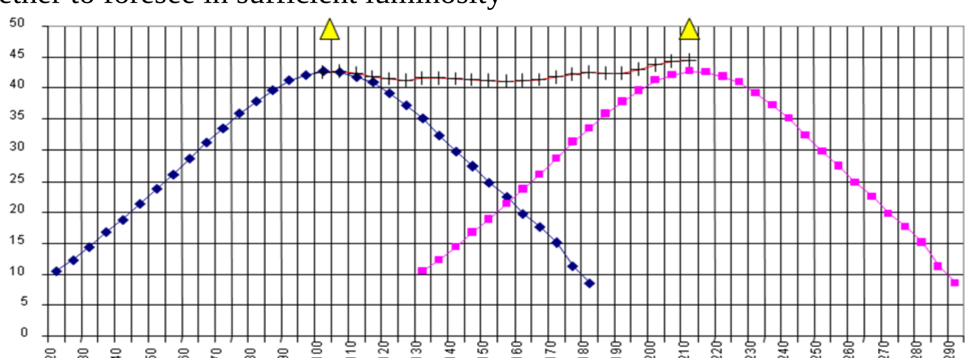

Figure 4. Illuminations in lux obtained for two power-leds separated by 110 cm.

The second fundamental point concerns the homogeneousness of the illumination. The resulting illumination of the system depends on the characterisation of the luminosity of each the power-led. All motion estimation methods rely on homogeneous illumination, but particularly those using optical flow information. We calculated the mean illumination of a grid of power-leds on a surface of 1m². The theoretical spread angle of the granules is 180° but, in practice, the spread angle of interest is only 120°. The lighting sources thus have to illuminate a scene corresponding to this angle.

In a second study, we proved empirically that two different arrangements (both of which take the height of the camera into account) appear to be the best solutions for our application (Figure 5).

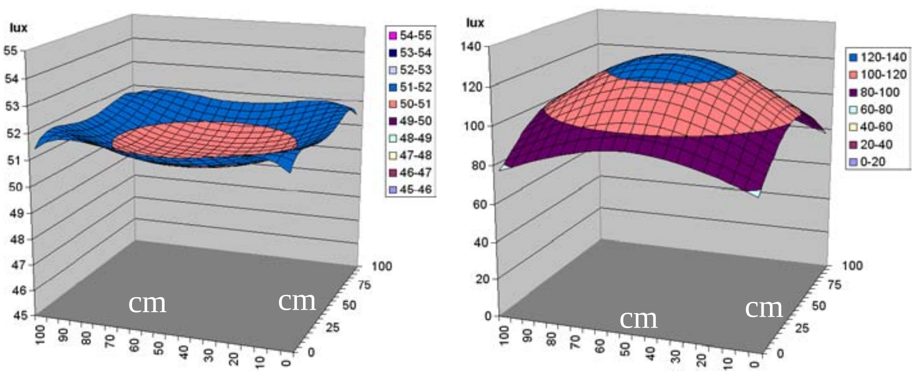

Figure 5. Best illumination of the field of view with four power-leds located on a square (left) or six power-leds located on a hexagon (right).

The lighting arrangement does not depend on any particular spreader, since it is placed one metre above the spreader.

Arranging the power-leds to form a square creates a more homogeneous illumination than the hexagonal arrangement. However, the maximum value of the average illumination (51.18 lux) is the half of the value for an arrangement in a hexagon (105 lux). Therefore, to obtain around 1 500 lux illumination at the necessary 1m height we decided to use a modified hexagonal arrangement with several power-leds on each corner as shown in figure 6. Eight power-leds are positioned at each corner of a hexagon inscribed within a circle with a radius of 70 cm were necessary to give constant illumination inside 1 square meter.

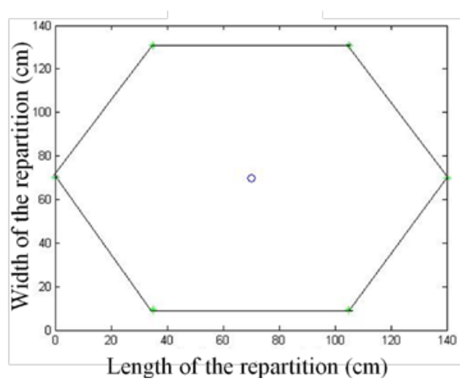

Figure 6. New hexagonal arrangement with eight power-leds at each location.

In that case, the average illumination is of 600 lux with 48 3W power-leds (Figure 7).

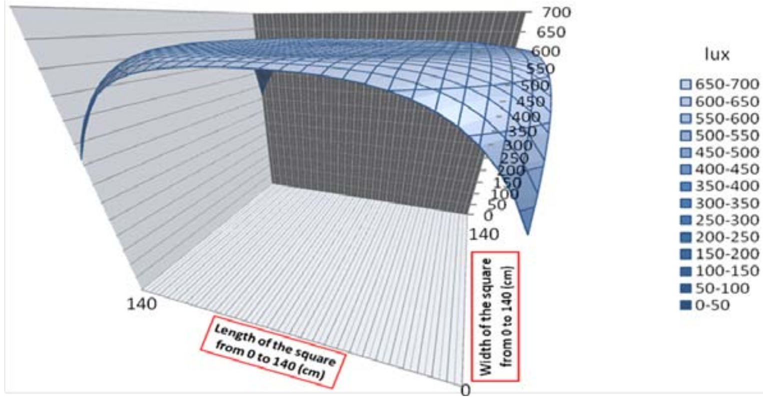

Figure 7. Illumination (in lux) for 48 3W power-leds uniformly arranged on a hexagon inscribed in a circle with a radius of 70 cm.

This value does not reach the 1 500 lux required to illuminate 1m² at 1m height. But the average illumination depends on the number of power-leds for each edge. If 10 power-leds are used per edge, the whole 60 power-leds provide an average illumination of 800 lux.

Therefore, we propose the following configuration as a trade-off between complexity and performance: hexagonal distribution with each corner regrouping 12 power-leds to illuminate 0.25 m^2 at 1m height.

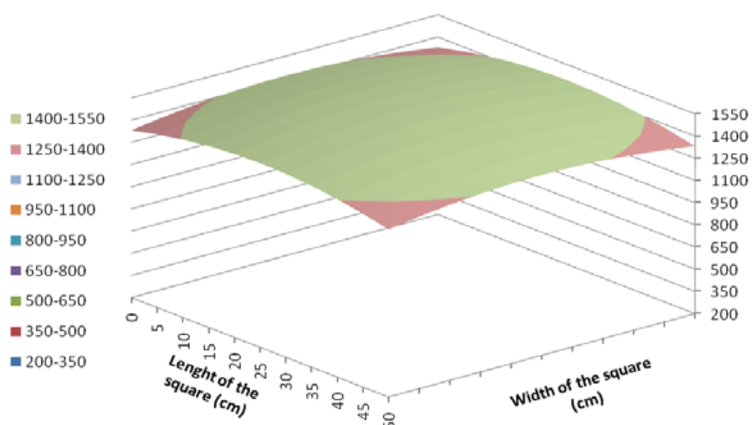

Figure 8. Illumination (in lux) for 72 3W power-leds uniformly arranged on a hexagon inscribed in a circle with a radius of 25 cm.

In this configuration, the illumination appears constant for all the square area and provides the lighting value necessary to accurately visualize the fertilizer granules. Although we have modified the location of the illumination system, we can consider that a field of view of 0.25 m² is sufficient to apply our motion estimation method and give enough information on the fertilizer granule behavior at the ejection.

RESULTS AND DISCUSSION

For the test of our power-leds device, we used a 1m² box allowing to reproduce the field of view of $1m^2$ for granule ejection.

According to the final imaging system we wanted to develop, the power-leds have been tested in static and dynamic configuration to obtain respectively for a continuous and stroboscopic lighting. With in all cases the use of a high-speed camera conceived by EyeNetics.

Tests of the power-leds in static

Two different tests have been done with a continuous lighting generated by the power-leds. Firstly, we have manually checked the received lighting with a Lux-meter. Different parameters, such as the number of power-leds, the shape configuration have been considered. The measurements exactly match the simulation tests presented in the previous section. Secondly, a high-speed camera is used to obtain short time delay images. As detailed in Vangeyte and Sonck (2005), a pair of images enables motion vector fields to be determined. Obviously, the received lighting depends of the camera sensor sensibility and the image frequency image (i.e. the exposure time). We focus on our application requirements; the exposure time should be consequently ranged between 5 ms and 10 µs depending on the fertilizer and the spreader features. The high-speed camera set-up is fixed at its maximum around 19 000 frames/s with an exposure time equals to 52 µs. At this frame rate, the image quality enables motion to be extracted with the expected 1 500 lux.

Finally, the tests done in static with our power-leds and high-speed camera provide interesting results and prove that the use of high-speed camera combined with power-leds is possible to replace photographic flashes. However, this solution is again too expensive compared to the price of standard centrifugal spreader and one of our objective is to use the power-leds directly in a stroboscopic configuration.

Tests of the power-leds in dynamic

The tests done in static are very satisfying and sufficient to prove the utility of an illumination with power-leds correctly arranged. Nevertheless, we have to know if 3W power-leds offer sufficient lighting at 1 m height when they are used very rapidly in a stroboscopic approach.

The power-leds are controlled with rectangular waves (duty cycle equals to 50 %). The high-speed camera enables the study of the power-leds lighting in function to the rectangular wave frequency. The static tests provide directly the reference frames. With the best available set-up, our camera provides around 19 000 frames/s, therefore we decided to limit the wave's frequency at 1 KHz (10 frames per cycle). High-speed acquisitions prove that switch duty cycle is respected (5 frames for each phase), moreover the illumination is not modified in comparison with the static mode obtained with the same exposure time. Therefore the previous hexagonal configuration with 72 power-leds can be used for the stroboscopic approach. The feasibility of such stroboscopic approach using power-led is prove nevertheless extra tests with higher frame rate would provide the system's limitation. Moreover, to validate this approach, we are currently developing a prototype that should be directly fixed on the spreader to produce fertilizer granule image sequences.

In any case, the illumination device which will be finally chosen would allow us to obtain fertilizer granule images, so as to estimate the granule trajectories, granulometry and angular distribution. The following paragraph present then briefly the new motion estimation method we developed for the trajectory determination.

Granule velocity determination with cross-correlation method

Motion study through image processing can be broken down into three main activities: detection, analysis and estimation. Estimation requires evaluating different parameters such as types of movement detected, techniques developed, size of the detected objects, length of the displacements, management of the illumination problem, and tests done (as a synthesis or on actual images).

In centrifugal spreading, the distribution of the fertiliser granules on the ground results from two successive steps: first, the ejection, and then the ballistic flight of the granules. We have spent the last ten years characterising the ejection parameters of the fertiliser granules using image acquisition and processing. The motion of the granule is one of the most important parameters, particularly the velocities of the granules after leaving the spinning disc. To evaluate these velocities, several motion estimation methods can be used. The following characteristics of the fertilizer granules and their motion need to be taken into account: size of the granules (5 mm), motion discontinuity, effect of the centrifugal force, and others. The fertiliser granules make very large displacements in pixels/image as compared to the displacements generally estimated with classical motion estimation methods. The fertiliser displacement cannot be detected directly by such methods as Markov Random Fields (Cointault et al., 2003), block matching, or optical flow measurement (Barron and Thacker, 2005), even if we obtain a vector field describing the displacement of each point between two successive images. Indeed, the maximum displacement which can be detected is very small (< 3 pixels/image). This can lead to some errors in our application.

Due to the necessity of estimating local motion, a possibility was to use Gabor filters, or to use a combination of spatio-frequential methods. These filters, used in triad of controlled filters, have the double advantage to eliminate the modelling and minimisation steps of the MRFs. Unfortunately, Hijazi et al. (2008) proved that this method does not accurately measure the displacements.

The second possibility was using cross-correlation techniques, because they are considered as reference methods for motion estimation. The cross-correlation method can be used in signal processing as well as image processing. In signal processing, cross-correlation is used to measure the similarity of two waveforms. In image processing, it has applications in pattern recognition, single particle analysis, PIV (Particle Image Velocimetry) (Coudert and Westerweel, 2000) (Foucaut et al., 2003) and others. Processing images using the cross-correlation method is based on the correlation between a same block in successive images. The similarity between blocks is given by the difference between luminosities of the blocks using the Sum of Absolute Difference (SAD).

Different variations of cross-correlation algorithms (CCA) have been used, such as calculating the difference to replace multiplication, the mean squared error, the absolute error, or the median squared error (Traver and Pla, 2005). A normalised cross-correlation algorithm (NCCA) (Nillius and Eklundh, 2002) obtains better results by using the local mean value and the local variance value. Since the images of fertiliser granules are subject to noise and variation of luminosity, the use of NCCA algorithm is more appropriate to our study.

Since the new stroboscopic device is under development, we tested the different motion estimation methods on multiexposure images obtained with the old high speed imaging system. When comparing results on velocity vector fields obtained from different image processing methods, Hijazi et al. (2009) concluded that combining theoretical granule distribution modelling with MRFs or a two step cross-correlation, are two techniques that obtain the best results (Figure 9).

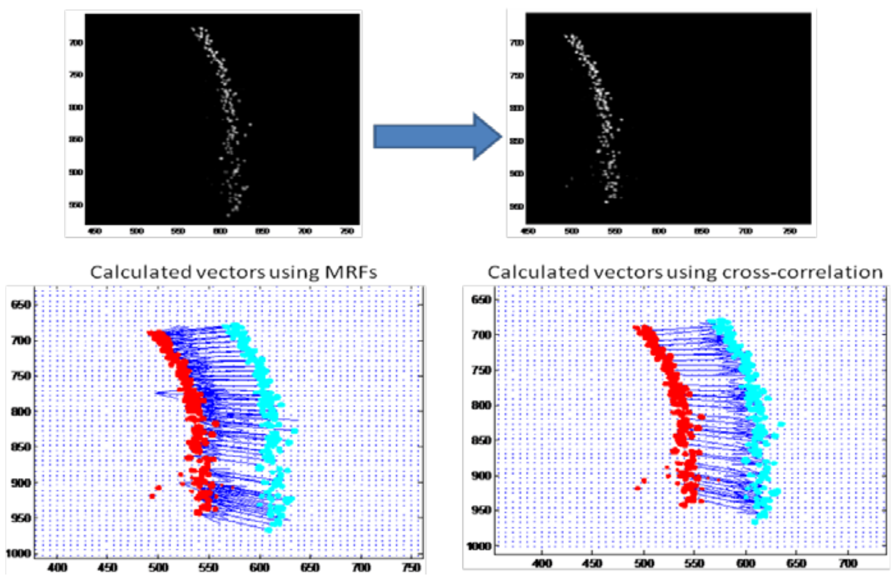

Figure 9. Velocity vector fields obtained with MRFs (bottom left) and cross-correlation (bottom right) techniques, between two successive throws (up right and left).

When examined visually, even when the displayed velocity vectors are not for the same pixels, the estimations using both techniques seem to give the same results. However, the MRF method is highly time-consuming and the modelling used for the initialisation of the velocity vector field needs an accurate determination of different spreader parameters such as the centre of the spinning disc, the length of the vanes (in pixels), and other parameters. These parameters can create errors on the motion estimation. Furthermore, this technique is highly influenced by changes in illumination between the images. The cross-correlation method is thus the best solution.

The first column of Table 1 presents the following information:

- The number of the successive throws (“T7 and T8” and respectively “T5 and T6”) in order to obtain a sufficient number of granules per throw, the motion estimation of the displacements is always done from the throw n° 5 to the throw n°8. For the other throws, the granules are too much concentrated.

- The delay between each flash, which indicates the value of the displacement to detect: for t=25 mm and a flash delay of 2.048 ms, we have a displacement of *77 pixels (or mm) / image*; for t=45 mm and a flash delay of 2.048 ms, we have a displacement of *63 pixels (or mm) / image*
- “A” corresponds to the type of fertilizer (Ammonium nitrate)
- “V800” corresponds to the rotational speed of the spinning disc (800 rpm)
- “Pl” and “Pm” correspond to the length of the vanes (325 mm or 275 mm)
- “t=25 mm” and “t=45mm” correspond to the aperture of the hopper trap and define the fertilizer mass flow (0.6 kg/s => 125 kg/ha or 1.4 kg/s => 290 kg/ha)

The last column gives the accuracy of the particle speed. Ninety percent of the detected particle speeds have a accuracy inferior to this value. With our camera and our lens located at a height of 1m, 1 pixel corresponds to 1 mm.

Table 1. Comparison of velocities obtained with cross-correlation and MRFs, based on simulated images for throws T7 and T8.

Velocity between T7 and T8 2.048ms A ; V800 ; Pl ; t = 25 mm		Mean velocity modulus (pixel)	Mean error (pixel)	Error max (pixel)	Standard deviation	accuracy 90% (pixel)
Cross-correlation	Horizontal	76.509	0.064839	0.330551	0.059355	**0.13392**
	Vertical		0.065808	0.277008	0.050016	**0.12189**
MRFs	Horizontal	74.855	2.062399	7.966087	1.805508	**4.54770**
	Vertical		5.172972	11.957868	3.008836	**9.03480**

The table clearly shows that the cross-correlation method very precisely determines the fertilizer granule velocities with an average error of 0.1 pixel or less, and 90% of the granule velocity with a rate of error less than 0.4 pixel.

The main advantages of the cross-correlation technique can be broken down into the four following points:

- Only two successive images are needed and the distance between these two images theoretically makes no difference. ;
- This is a semi-local motion estimation method and the two-step strategy developed is ideal for particle motion; (for our application?)
- It provides sub-pixel accuracy, which allows for a decrease in the resolution of the camera used. This opens the possibility of using classical high-speed cameras. For example, a precision of 0.2 pixel can allow us to divide the resolution of the camera by 5 in each dimension. Moreover, it can let us use higher focal lens which will avoid image calibration due to distortion.

The sub-pixel accuracy obtained with the cross-correlation method is a function of different image processing parameters: size of the searching window and number of the zones used for the dissociation of a fertilizer throw. We are currently investigating their influence on the accuracy of the velocity measurement.

The motion estimation method based on cross-correlation has been used successfully on fertilizer granule images. The velocity vector obtained is more accurate, in all cases, than with other methods such as MRF. Additionally, this method does not require precise control of the luminosity.

A final perspective is providing a mobile low-cost measurement system. The sub-pixel accuracy enables a system based on a low-resolution camera sensor (typically lower than 640x480 pixels) to be considered. Such camera associated with the proposed power-leds stroboscope can be considered as the first step of for low-cost embedded measurement solution in a spreading context.

CONCLUSION

In the current agronomic context of optimization of the input in the field, the understanding of the mineral fertilization becomes essential. The centrifugal spreading process, most commonly used in Europe, rolls over of many research since 15 years particularly with the development of image processing and acquisition.

In this paper we described one of these research using high-speed imaging system and specific illumination based on stroboscopic approach. The replacement of photographic flashes with power-leds allowed to propose a new and more robust lighting system to be combined with standard or high-speed cameras.

We determined the number of power-leds required to obtain sufficient and homogeneous illumination at 1m height, the height where we placed the camera. We also determined by modelling that a hexagon is the best configuration to provide adequate illumination for our purposes, and we proposed an alternative to between number of power-leds and field of view by using the illumination system to observe only 0.25 m².

We also adapted a new motion estimation method based on cross-correlation technique to estimate the specific motion of the granules. The results on images are very satisfying. The use of a two-step estimation was the best way to estimate motion of fertiliser granules. The sub-pixel accuracy we obtained with cross-correlation method as compared with the MRFs method is sufficient to decrease the resolution of the camera enough to use a standard low-cost high speed camera. This last conclusion is fundamental if the imaging system is attached to existing centrifugal spreaders. The next step will be to test a low-resolution high-speed camera and to estimate the fertilizer velocities.

This study is the first part of a more global project on the development of 3D image processing techniques and 3D image acquisition systems in order to characterize intrinsic parameters of fertilizer granules (trajectories, mean ejection angles, granulometry, and angular distribution) and spreaders (3D tracking of single or multiple granules, mass flow of ejected granules, and so on).

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