On-Line Sizing and Velocity Measurement of Particles in Pneumatic Pipelines through Digital Imaging

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Abstract. This paper presents a new solution to the on-line continuous measurement of particle size and particle velocity within a dilute gas/solid pneumatic pipeline, using low-cost opto-electronic components and imaging hardware. A low-cost, single CCD colour digital camera is used with high power light emitting diodes (LEDs) of different wavelengths, which are driven with very narrow pulses during each camera frame. These resulting frames consist of multiple images of the same particle at different instances in time, by correlating these images it is possible to calculate the size and velocity for each individual particle to high accuracy as the blur due to the finite exposure time can be calculated and removed. As multiple images are taken of the same particle it is possible to extrapolate other information, including acceleration, rotation and direction of movement. The results from this research are very promising and the technique may provide a satisfactory solution to the long standing industrial measurement problem. This system is specifically developed for the measurement of particle sizes in the range of 10µm to 1,000µm, but the technique can be applied equally well to particles outside these limits.

1. Introduction
The accurate continuous sizing and velocity measurement of particulates within pneumatic pipelines are required in many industrial sectors. Traditionally, off-line sizing methods have been used, where samples of particles are taken from a process and then analysed in a laboratory. Since such methods have many drawbacks, research has been ongoing for on-line solutions for many years where the analysis is undertaken during process operation. By monitoring particulate statistics in real-time it will be possible to control flow, sizing and other parameters dynamically, leading to increased process efficiency, minimised pollution levels, and reduced downtime. There is a real requirement for a low cost, efficient, accurate, and low-maintenance solution to this problem. Ideally the solution will be non-intrusive to the flow and be installed easily into existing pipe-work. A number of methods have been proposed for sizing, including those based on electrostatics [1], laser diffraction and laser imaging [4]. Proposed methods for velocity measurement include cross-correlation and Doppler systems [2]. There are methods for simultaneous measurement of size and velocity [3, 5]; however, few systems have achieved commercial success to date.

Digital imaging is becoming increasingly attractive because of the availability of low-cost high-performance imaging devices and computing hardware. An advantage of using the imaging approach is that non-intrusive real-time measurement of many individual particles can be measured concurrently and continuously.
This paper presents a new solution for the measurement of size and velocity of particulates within a gas/solid pneumatic conveying pipeline using low-cost opto-electronic components and imaging hardware. There are a plethora of well documented problems associated with digital imaging including: depth-of-field focus, sub-micron particle scattering & dispersion, fogging, image blur as well as many others [3, 6]. The system developed overcomes these problems to a high degree. This paper describes the fundamental principle of the methods, key aspects of the sensor design and test results obtained using a laboratory test rig.

2. Fundamental Principle

The basis of the developed technique is in the use of high-power light emitting diode (LED) sources of multiple wavelengths, these are utilised with a colour CCD digital video camera equipped with a Beyer mosaic colour filter. The Beyer filter produces pixels that are alternately sensitive to red and green light on one line and sensitive to blue and green light on the following line, repeated over the whole active sensor area. The Beyer mosaic produces an image that has twice the amount of green pixels to either red or blue pixels to imitate the sensitivity of the human eye. This pattern has not proved to be a problem in the preliminary work as the embedded digital signal processor (DSP) used in most digital colour cameras produces a good result by interpolation, resulting in minimal actual error. The green channel is used for the primary reference due to its higher physical resolution.

The LED sources and the camera assembly are positioned on opposing sides of the pneumatic pipeline perpendicular to the particle flow, as shown in Figure 1. The LEDs are driven independently with very short pulses using a drive system that minimises charge effects, resulting in very fast turn on and turn off times. LED drive pulses are synchronised to the camera frame period, the width and position of these pulses within the frame differ for each LED colour as dictated by the overall system dynamics. The result is the creation of a time shifted image for each of the colour channels within the frame.

It is important to effectively combine the light output of the high power red, green and blue LEDs to produce a uniform semi-parallel collimated light that is well mixed, combination is achieved in multiple stages by diffusion and re-collimation. As it takes a finite time for camera exposure, each particle within the image will include blur that is proportional to its own velocity, becoming the dominant feature for small particles with high flow-rates. A velocity of 40 m/s is common, resulting in an image blur of 40 µm for each micro-second of exposure time. By correlating the images from the different RGB channels this blur can be calculated for each individual particle in both the X and Y axes. These correction factors are then applied to the original image to produce an accurate blur-corrected image.

Errors will be created due to the small delay differences of the different LED drive paths and operational speed variations for different wavelength LED sources, these errors are eliminated by pulsing all of the LEDs simultaneously and any differences recorded and subsequently used as a correction factor. The camera’s DSP interpolation algorithm will add a small error but this should be no more than a single pixel.

The lens arrangement is critical to the whole system. A low-cost high-resolution finite conjugate imaging lens was modified for this purpose producing the required magnification, depth-of-field and working length. The chromatic and image distortion of this modified lens were negligible enabling all processing power to be used for the imaging algorithms and not wasted on image distortion correction.

The image frames are pre-processed using a Fast Fourier Transform (FFT) based algorithm to remove any out-of-focus particles from the image. The use of a narrow depth-of-field enables the detection of un-focussed particles to be easily achieved thereby freeing higher level algorithms to process this reduced information at a high data-rate. The correlation of multiple time-shifted images within the same frame allows the measurement of particle size, velocity, acceleration, and orientation for each particle. This allows precise statistical information to be produced for each individual particle, thereby giving a much higher degree of accuracy for the particle and flow statistics, which has up to now been impossible to achieve.
3. System Design and Implementation

An aluminium spool piece has been constructed as shown in Figure 1; this is inserted into a 40mm bore gas/solids flow test rig. Small circular windows in the spool piece provide an environmental seal and protect the camera and LED source from the pipeline media. Any contaminants on the window are so far from the focal point they act only as a density filter, the lower image brightness is compensated for by the control loop by increasing the LED power as necessary; this is one advantage over laser diffraction imaging systems where glass contamination can be a problem. There of course, will be a limit to the amount of contamination that can be tolerated particularly during long term industrial installation.

![Diagram of the imaging system]

**Figure 1. Overview of the imaging system**

As measurement of particle characteristics is undertaken in both the X and Y axes, the requirement for precision mounting of the instrument is eliminated. The magnitude and direction of the vectors are used for the calculations.

System calibration is very straightforward and is realised off-line by the use of a low-cost precision 500µm lined reticule. Figure 2 shows this as an overlay on the top right image, a higher magnification instrument will require a corresponding higher resolution reticle. The calibration is automatically accomplished in software, producing scaling factors which are correspondingly applied to the final results. It is possible to use this method to correct for optical aberrations as well, but this has been avoided by the use of a high quality lens system. The instrumentation system will dynamically adjust its operating conditions, producing the best results possible for the current flow pattern.

4. Results and Discussion

The images in Figure 2 have all been taken from the same test run using the prototype imaging system installed on the gas/solid test rig. The particles tested are granular salt with a solids concentration of around 0.2%. It can be seen in Figure 2 that the particles behave in totally different fashions, highlighting the problems associated with the measurement of particles in a pneumatic suspension.
Figure 2. Raw and processed images from the prototype system
The right-most images in Figure 2 are processed versions of the left after removal of the out-of-focus particles. Each processed image contains three representations for each particle and these are used for subsequent processing, if less than three exist they are removed by the software. The current system does not exploit the Z axis for calculations, so small errors will exist. A stereoscopic version may present a solution to this problem [3]. This said, the measurement system does calculate in one more dimension than most other systems, thus giving highly accurate results.

The images in Figure 2 were taken using 100µs delays between the LED pulses and the width of these pulses are fixed at 1µs. From this information it is now possible to extrapolate statistical information for each particle. The topmost image is used as an example. Figure 3 shows this image expanded with the geometric centres marked. The particle is moving from left to right. It can be seen that this particle is moving primarily in the X direction with small movement in the Y direction. The movement of the particle is not the same between pulses; it is therefore undergoing acceleration. It can also be observed that the particle is spinning clockwise.

![Figure 3. Geometric centres of processed image](image)

![Figure 4. Angular movement of image](image)

The average velocity of the particle is determined from:

\[ v = \frac{xl}{t} \]  

where \( x \) is the number of pixels between centres, \( l \) is the pixel size and \( t \) is the time between pulses.

It is known from the calibration procedure that \( l = 5.882 \mu m \), the measured distance \( (x) \) between the first and second geometric centres is 78 pixels and the distance between the second and third centres is 87 pixels, the time delay between the centres \( (t) \) is 100 µs. This gives velocities of 4.59ms\(^{-1}\) and 5.11 ms\(^{-1}\) respectively, the acceleration is therefore 0.52ms\(^{-2}\). These figures are for the X axis. The corresponding figures for the Y axis are 0.44ms\(^{-1}\), 0.82ms\(^{-1}\) and 0.38ms\(^{-2}\) respectively. The vector quantity for the actual velocity between the first two pulses is then 4.64ms\(^{-1}\) at an angle of 5.5° to the horizontal and the velocity between the last two pulses is 5.18ms\(^{-1}\) at an angle of 9.1° to the horizontal. The accuracy of the measurements is in the order of a couple of percent.

Figure 4 shows the angular displacement of the particle between the LED pulses. The angle between the first two pulses \( (\theta_a) \) is measured at 39° and between the last two \( (\theta_b) \) is measured at 62°, assuming that the particle has not rotated more than 360° between pulses. The time between two pulses is 100 µs, therefore, the particle is revolving clockwise at an average of 65,000rpm during the first two pulses and an average of 103,000rpm between the last two. It is possible to take more than one set of images within each frame, a shorter duration second set of LED pulses will confirm if the
particle has rotated by more than 360°. It should be noted that the particle may be rotating in more than one dimension.

The green channel is used as the reference channel for all calculations as this has greater resolution due to the Bayer matrix filter than either the red or blue channels. The red and blue channel LEDs may be pulsed simultaneously to produce identical resolution to the green, but the acceleration component will be lost. The statistical information for the particles shown in Figure 2 are summarised in Table 1.

### Table 1. Statistics for individual particles

| Particle Number in Figure 2 | 1     | 2a    | 2b    | 3     | 4     | 5     |
|-----------------------------|-------|-------|-------|-------|-------|-------|
| Particle Size (µm)          | 423.5 | 344.1 | 191.2 | 349.9 | 538.2 | 111.8 |
| Aspect Ratio (l:w)          | 1.18:1| 1.02:1| 1.03:1| 1.02:1| 1.15:1| 1.38:1|
| Particle Area (mm²)         | 0.152 | 0.088 | 0.029 | 0.093 | 0.235 | 0.009 |
| Mean Velocity (m/s)         | 4.896 | 3.110 | 5.115 | 4.036 | 2.767 | 6.235 |
| Mean Orientation (deg)      | 7.317 | 13.12 | 3.950 | 3.346 | 1.804 | 0.540 |
| Linear Acceleration (m/s²)  | 0.574 | 0.057 | -0.147| 0.053 | 0.237 | 0.000 |
| Angular Velocity (rad/s)    | 80370 | 3979  | 3184  | 19900 | 7960  | 39800 |
| Angular Acceleration (rad/s²)| 36610 | 124   | 231   | 9754  | 1220  | 27452 |

5. Conclusions
The current research work has established that the use of low-cost opto-electronic components and imaging hardware provides a viable solution for on-line sizing and velocity measurement of particles in gas/solid pneumatic pipelines. By using this method it is possible to extrapolate a vast amount of information on individual and mass particle behaviours that has not been possible with other measurement systems.

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