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Key Design Considerations for Measurement of Drops-In-Flight using Machine Vision

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Abstract

Inkjet technology is in the process of revolutionizing traditional printing and dispensing industries. An ever-increasing number of startups and established companies have been working hard to create their own proprietary inkjet knowledge and advanced materials. Machine vision tools have become integral to this R&D process, especially for imaging and measuring drops in flight.

Drop in flight imaging is usually accomplished using a strobe light synchronized with the firing frequency, together with a camera and workstation (Figure 1). Analysis is accomplished using machine vision techniques, including automatic thresholding, edge finding, and connectivity.

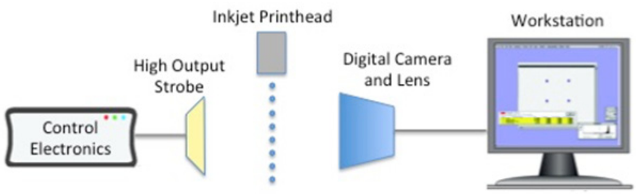


Figure 1 - Basic Drop Analysis System Layout

The implementation of this type of system, however, is far from trivial. In order for measurements to be accurate and repeatable, it's very important that proper system design and analysis methods are used.

In this paper, we will discuss imaging techniques and other important considerations for drop-in-flight volume and velocity measurements. Broadly speaking, categories include print controller requirements, optical design, image analysis algorithms, and calibration, as well as other factors and pitfalls.

The impact of these design choices will be explained using theory, experimental data and practical examples.

Single Event Imaging

Firstly, it's important that a dropwatching system have **single event** capabilities. In other words, it must be capable of imaging a single drop, rather than averaging or summing images of several drops. This is necessary for high quality drop visualization, and it's even more important for drop measurement.

Some drop-to-drop variation is unavoidable, whether using piezo or any another drop dispensing technology. Drop to drop variations mean that multi-drop images appear blurred, and transient effects, like satellites, are usually indistinct. An example of the difference between single event imaging and multi event imaging is shown in Figure 2.

The challenge in developing a system capable of single event imaging is producing a strobe capable of outputting sufficient light in a single pulse, of short enough duration to produce crisp images.

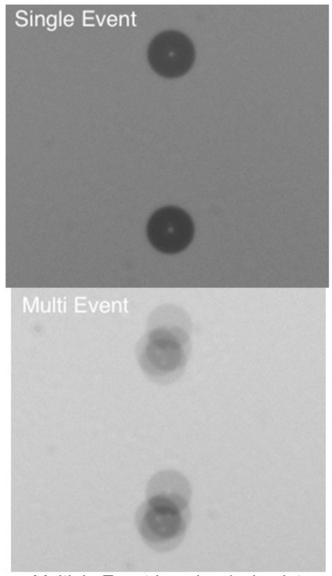


Figure 2 – Single vs. Multiple Event Imaging (using jetxpert)

Figure 3 – Drop Formation, Single Event Imaging (JetXpert)

Short Strobe Pulse

The strobe light source must be capable of short pulse widths, in the range of one microsecond or less. This is because inkjet ejected drops travel at high speed, usually at least several meters per second. When a fast moving drop is imaged using a long strobe pulse, the result is blur. The relationship between drop speed, pulse width, and blur, is shown in Figure 4. Like multi-event imaging, drop blur is harmful to both drop image clarity and measurement accuracy

When the strobe pulse width is reduced, less total light is emitted. Thus, if an imaging system has insufficiently powerful lighting, it may be impossible to get both high clarity, and high contrast. Similarly, a main reason dropwatcher designers sometimes resort to multi-event imaging is that the light source is insufficient. Also, certain lighting sources simply are not capable of sub-micron pulsing. It is recommended that dropwatching systems include powerful lighting sources capable of short pulse widths, at least as low as 1um, but preferably significantly lower. Powerful lighting sources are also a critical component towards making single event imaging possible.

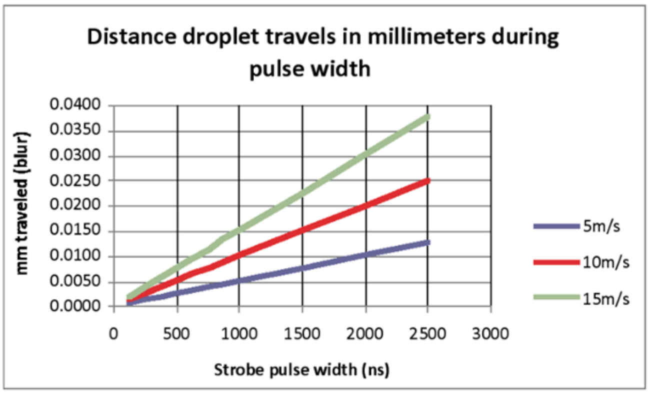
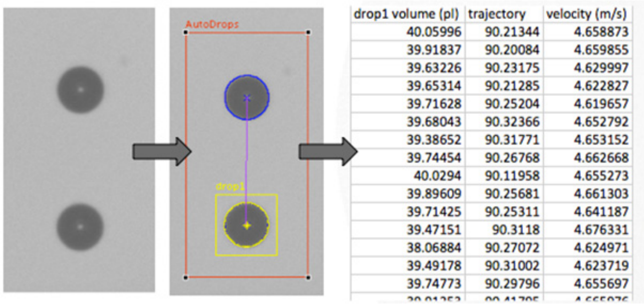


Figure 4 – Pulse Width vs Image Blur

Double Strobe

If a dropwatching system is intended to measure drop velocity or trajectory it's important that they system be capable of capturing **double strobe** images. Double strobe images are captured by flashing the strobe twice, with a short, known interval between flashes. Because the camera shutter is left open during this process, the two flashes result in two images of each drop in the field of view, each at a different point in time.

This double strobe image is analyzed by finding the centroid of each image of the drop, and measuring the distance between the centroids (Fig. 5).



drop1 volume (pl)	trajectory	velocity (m/s)
40.05996	90.21344	4.658873
39.91837	90.20084	4.659855
39.63226	90.23175	4.629997
39.65314	90.21285	4.622827
39.71628	90.25204	4.619657
39.68043	90.32366	4.652792
39.38652	90.31771	4.653152
39.74454	90.26768	4.662668
40.0294	90.11958	4.655273
39.89609	90.25681	4.661303
39.71425	90.25311	4.641187
39.47151	90.3118	4.676331
38.06884	90.27072	4.624971
39.49178	90.31002	4.623719
39.74773	90.29796	4.655697

Figure 5 – Double Strobe Analysis (JetXpert)

Because the time between the flashes is known, the drop velocity may be simply calculated according to:

$$V = \frac{\sqrt{(D_{2x}-D_{1x})^2+(D_{2y}-D_{1y})^2}}{T_2-T_1} \quad (1)$$

where V is velocity, T_2 - T_1 is the interval between flashes, D_{1_x} is the x position of the center of the first drop image, D_{2_x} is the x position of the center of the second drop image, etc. Similarly, trajectory may be calculated by (for example):

$$T = \arctan\left(\frac{D_{2x}-D_{1x}}{D_{2y}-D_{1y}}\right) \quad (2)$$

In some more rudimentary systems, users estimate velocity by imaging different drops at different delays, and inferring drop velocity. However, this method is not accurate, for the same reason that multiple event imaging does not create accurate images: drop-to-drop variations. Even small drop-to-drop variations can cause significant inaccuracies in drop velocity measurements based on single strobe images.

The effect of variations in drop velocity on the accuracy of single-strobe velocity measurements is easily calculated. If the first drop is being measured at time T_1, and the next drop is measured at time T_2, drop-to-drop velocity variations of magnitude ΔV will cause errors in drop velocity measurements of magnitude

$$V_\varepsilon = \frac{T_1 \Delta V}{T_2 - T_1}$$

(3)

An example illustrating this effect is shown in Figure 6.

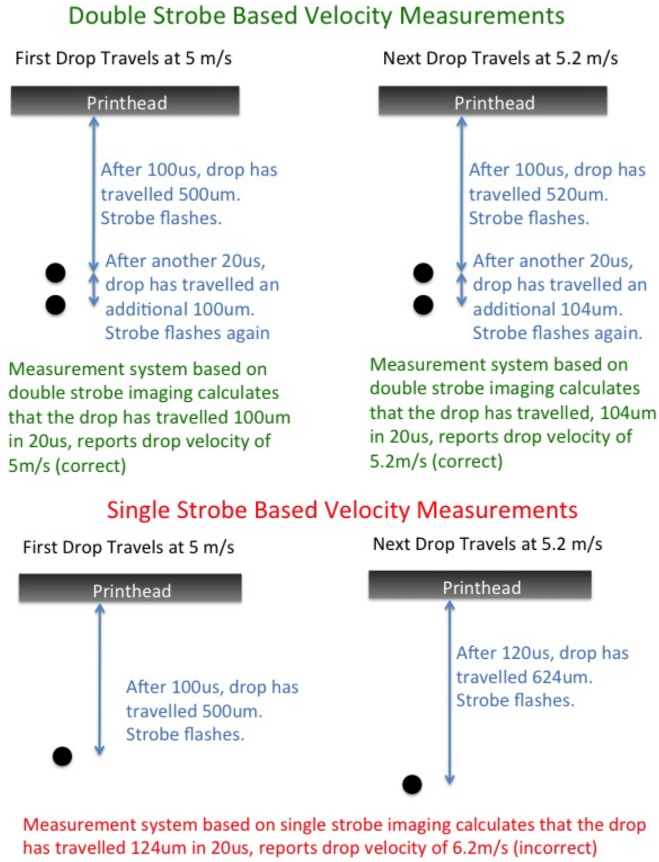


Figure 6 – Double Strobe Analysis Reports Correct Velocity; Single Strobe Method Amplifies Errors

In Figure 7, experimental results are shown, comparing actual velocity measurements made using a double strobe method, with velocity measurements made using single strobe. The drops being measured using each method are produced by the same printing system (same ink, waveform, etc). It is easy to see that in this case (which is not atypical), the single strobe analysis vastly over-reports drop velocity variations.

Problematic error sources for single strobe measurements are not limited to drop-to-drop velocity variations. There are also variations in the time between the firing pulse and drop ejection from the nozzle. When using single strobe measurement methods, these variations are also a significant source of error. Furthermore, even very small trajectory variations completely invalidate trajectory measurement results from single strobe methods. Indeed, of all drop watching system attributes, double-strobe capabilities may be the most important.

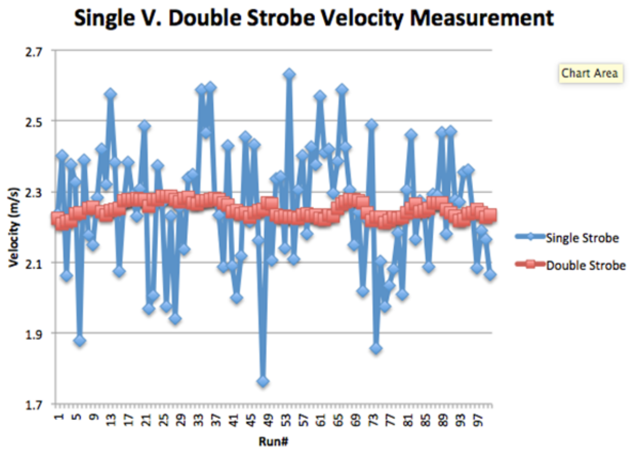


Figure 7 – Experimental Comparison Between Single and Double Strobe Velocity Measurements

Telocentric Optics

Telecentric optics are a general requirement for machine vision applications, and drop-in-flight analysis is no exception. There are several reasons for this.

Low Distortion

Significant distortion is unacceptable for machine vision applications, for obvious reasons. Accurate measurement of feature dimensions or distances requires that the distances between features on the image be proportional to the corresponding distance in real space. One of the advantages of telecentric optics is that they usually have far lower levels of optical distortion than non-telecentric alternatives. The illustration below shows a distortion pattern taken with a telecentric lens, on the left, and with optics showing common forms of distortion, in the center and on the right.

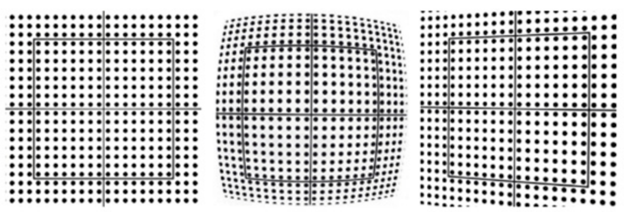


Figure 8 – Illustration of radial and trapezoidal distortion (credit: Opto-Engineering)

Elimination of Parallax Error

Parallax error causes objects of identical size that are positioned closer or farther away from the primary lens, to appear to have different dimensions. For machine vision applications where the object to be measured may appear at various distances from the primary lens, it's critical to eliminate parallax error by using telecentric optics.

For a drop analysis system, this particular error may not be as great of a concern if the drop is consistently positioned relative to the light source and camera optics. However, it can still be a meaningful source of error in non-telecentric systems, and is another reason to select telecentric options for drop analysis applications.

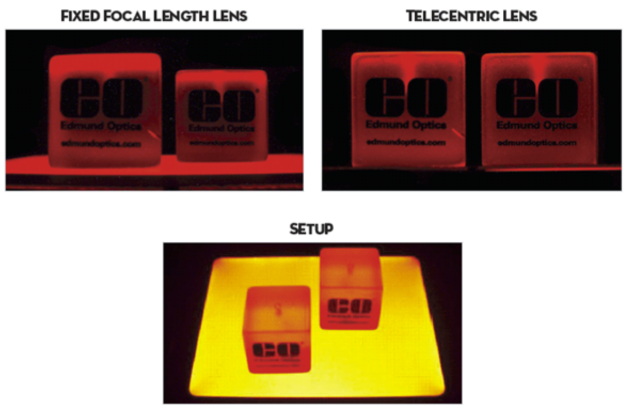


Figure 9 – Illustration of Parallax Error, Solved By Use of Telecentric Lens (credit: Edmund Optics)

Stable Edge Dimensions under Focus Changes

Even when the goal of a machine vision application is to use a fully focused image of the object to be measured, it is inevitable that there will be some level of defocus. With telecentric optics, blurring due to defocus occurs evenly, centered around the edge itself. This means that measurement algorithms can still measure dimensions and distances accurately, despite a small level of defocus.

If defocus causes the edge to shift significantly, as may be the case when using non-telecentric optics, significant error may be introduced.

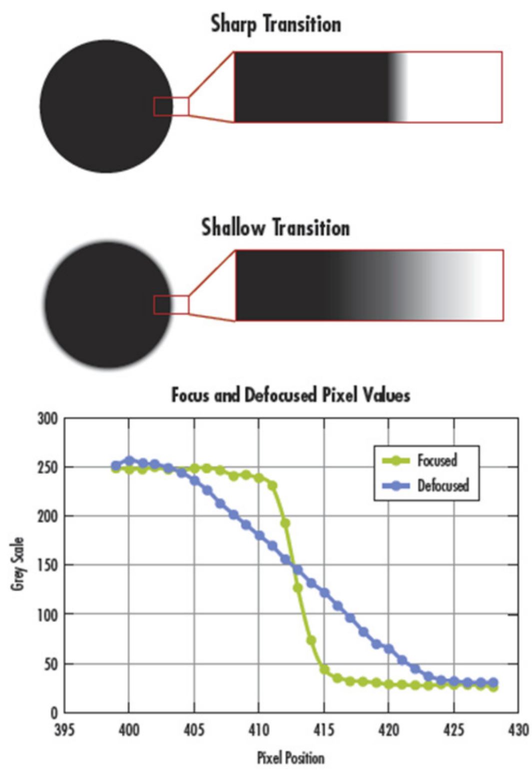


Figure 10 – Illustration of the Effect of Defocus on Edge Position (credit: Edmund Optics)

Analysis Algorithms

Even if a system is capable of capturing high quality images, appropriate machine vision tools are still needed to derive measurement data from those images. One of the most important factors to consider is background light variations.

When imaging most printing systems, light levels decrease closer to the head. If algorithms cannot measure a consistent drop edge when a background gradient is present or light levels are varying, both volume and velocity measurement accuracy will suffer.

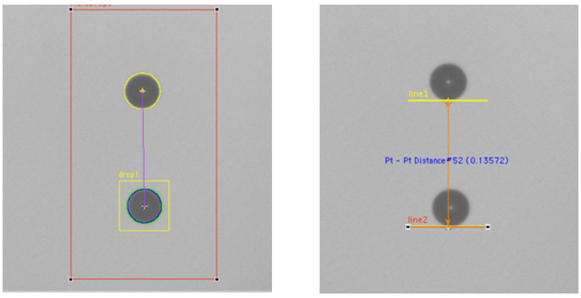


Figure 11 – Full Edge Analysis vs Single Point

It's also important that the entire drop perimeter be measured, in order to calculate the drop radius and center, not merely a leading or trailing edge. Measurements based on leading and trailing edges only are not only far less accurate, but they can be particularly misleading in cases where drop shape is changing over time. By contrast, centroid based velocity measurements and full edge based volume measurements can easily achieve significant sub-pixel accuracy, if properly implemented (figure 11).

Measurement algorithms may be capable of handing a variety of situations, including satellites, ligaments, and drop-out.

Figure 12 – JetXpert (Includes Automated Testing Options)

Automation

It is worth taking time to consider what types of measurements will be performed by developers, and whether they can be automated. Great dropwatching systems have automation tools available that can save hundreds of hours of engineering time, by automating test procedures that would otherwise need to be performed manually. This may include measuring drop performance over a range of frequencies, testing sustainability, testing latency/decap effects, collecting large sets of drop data for a single nozzle, or measuring each nozzle on the head. Generally, adding relevant automation capabilities to a dropwatching system is worthwhile. That said, inkjet crosses a wide variety of industries and applications. Some drop watching add-on capabilities, which others may find invaluable, may not be necessary for your application. It's worth putting thought into what tests your engineers will be doing, and what tools can best help them accomplish those tasks accurately and efficiently.

Added Capabilites

Modern drop watching systems are often combined with various print controllers, ink supply systems, drop weigh stations, print quality analysis tools, and print stations, in order to create vastly more capable R&D platforms. These systems go beyond mere dropwatching, and can save a considerable amount of engineering time, by preventing engineers from having to manually move ink, ink supply units, printheads, and controllers between various different test systems, in order to accomplish different tests. The JetXpert Print Station is an example of such a system (figure 13).

While these additional tools are not necessary for measurement of drops in flight, thinking ahead to integrate all necessary tools into one development platform is an important design consideration for any drop analysis system, and the effective use of such a tool can vastly speed the inkjet development process.

Figure 13 – JetXpert Print Station

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Author Biography

Paul Best received his BS in Mathematics and Computer Science from Wheaton College (2005), and his MS in physics from California State University, Los Angeles (2010). From 2006-2010 he worked as a Team Lead and Optical Engineer II at the national Jet Propulsion Lab in Pasadena, CA. Since then, he has worked as a Manager of Applications Engineering at ImageXpert, Inc, and serves as an IEC expert.