Low Cost In-Situ Drop Analysis System for Ink Jet and Other Non-Contact Dispensing Technologies

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Abstract

A compact, low cost, fully integrated machine-vision based system has been developed for in-situ drop watching and measurement of drops-in-flight in ink jet and other non-contact dispensing technologies.

In R&D, measuring the in-flight characteristics of fluid droplets under different conditions can aid in optimizing dispensing system settings, fluid formulation and overall system performance. Manufacturers of dispensing tips and heads, driver electronics and actuators, fluids, and dispensing systems can benefit from analysis of drops-in-flight during development and system integration. During dispensing system operation, the in-situ drop analysis system can be used to verify dispensing performance and can be used for process control by providing accurate feedback for on-the-fly system adjustment.

The in-situ drop watching and analysis system has a flexible optical design to allow for several different geometries to fit into both stationary and scanning applications. The system uses an LED strobe that is synchronized to the firing or ejection signal, so it is independent of the specific print head, dispensing tip or dispensing system being used. The very short strobe pulse width allows single droplets to be imaged by the camera with minimal motion blur. The system offers digital control of strobe pulse width, delay times, and strobe intensity for optimal imaging for a variety of dispenser settings and materials. An open architecture software package allows for powerful and accurate image analysis, including drop trajectory, velocity, radius and volume. Volume of individual droplets, ligaments, and drop streams can be reported. Movies and images can also be captured and archived.

This paper will give an overview of the details of this system as well as show some of the system capabilities through several examples of drop analysis. It will also discuss the wider range of options available for R&D environments such as face plate wetting visualization, automated motion for sequential analysis of multiple dispensing tips or jets, and an integrated capacity for frequency sweep actuation and output analysis.

Introduction

Measuring the in-flight characteristics of ink drops under different conditions can aid in optimizing system settings, ink formulation and printer performance. Manufacturers of ink jet print heads, head driver electronics, inks, and integrated printing and material deposition systems can benefit from analysis of drops-in-flight.

An integrated, machine-vision system, JetXpert, has been developed for the visualization and measurement of drops-in-flight.[1,2] The system combines a high-powered LED strobe and sophisticated strobe control electronics, one or more cameras, specialized optics and ImageXpert software to provide a flexible platform for analyzing the performance of any print head. A new, smaller system configuration is available that can be used to integrate directly into dispensing and jetting equipment for in-situ performance adjustment and verification.

System Description

Overview

In the JetXpert system, a high speed, high-powered strobe is used to capture stop motion images of drops in flight.

The strobe is slaved to the firing frequency of the print head so it can be used to measure drops-in-flight for any print head or dispensing system where a copy of the TTL drive signal is accessible. An external signal generator can be used to trigger the strobe in cases where a firing signal is not available.

The strobe control software includes a graphical user interface to access digital control of strobe pulse width (offering a very short minimum pulse width of 125ns, with standard operation at 500ns); imaging of single or double drops with delay times defined by the user; and the strobe intensity for optimal imaging for a variety of print heads, dispensing systems and materials. In addition, the strobe control software and system are designed for single event strobing (one strobe per image), which allows for single droplets to be imaged and analyzed.

The digital black and white camera in the R&D unit has 1032 x 776 pixels (other camera formats are available for the in-situ configuration). The optical design enables imaging and analysis of drops from 1 nanoliter (nl) to 1 picoliter (pl) in volume.

Powerful ImageXpert image analysis software is used for droplet analysis including drop trajectory, velocity, radius and volume. Other measurement methods can be applied and other features can be measured (such as time of flight to a specified standoff) depending on the requirements of the application.[3] Volume of drop series and ligaments can also be reported.

The optical system is calibrated using a precision slit, and the software returns calibrated results from droplet analysis in real-world units such as picoliters and meters/second.

Strobe Control GUI

The strobe is essential to the success of the system for image capture. The strobe control electronics are set up and controlled via a user interface. The strobe control graphical user interface allows for selection of pulse type, pulse width, delay times, LED intensity and camera shutter speed. The strobe settings also feed directly into image analysis by providing current values of specific variables such as delay times.

***Figure 1**: JetXpert strobe control user interface (GUI): Standard Tab showing a double pulse set-up*

In standard operation, the JetXpert operates in a double pulse (double drop) mode where the strobe is fired twice per image, which images the same droplet at two different times, two different instances. Delay1 is the time between the firing signal and the first strobe event, and delay 2 is the time between the end of the first strobe event and the beginning of the second strobe event. Pulse width determines the length of each strobe.

The two-drop (double drop) image that is captured using double pulses can be used to measure projected drop trajectory and drop velocity as will be discussed in the Measurement section.

Theory of Operation

JetXpert runs in a slave mode and is triggered by an external signal from a print head driver or signal generator. The strobe timing is determined based on settings in the GUI (pulse type, pulse width and delay settings). The following sketch shows the conceptual relationship between the incoming firing signal, the camera trigger signal and the strobe in a double strobe scenario.

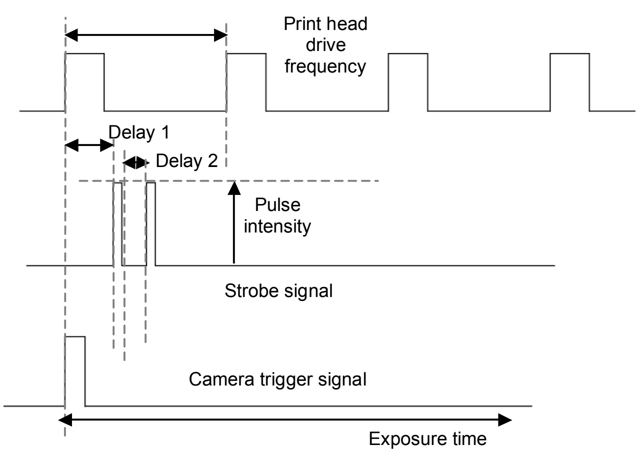


***Figure 2**: Conceptual sketch of a double drop (two strobes, two delays for two instances of the same drop in a single image) signal relationship between print head firing frequency, the camera, and the strobe, assuming a rising edge trigger.*

If a strobe delay (the delay time between the firing signal and the strobe actuation) is longer than the firing frequency, there will be some firing signals that arrive during the delay that will not be used to trigger the firing of the strobe or initializing the strobing sequence. Some firing pulses may arrive after strobing is complete, but during the ongoing exposure time. In both cases, these “intermediate” firing pulses will be ignored.

System Diagrams

The two configurations discussed in this paper are the R&D unit and the in-situ unit. The R&D unit is a full featured, flexible platform for drop in flight visualization and analysis.

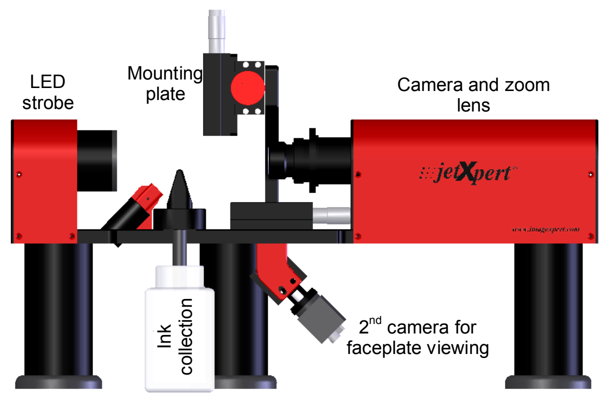


***Figure 3:** JetXpert R&D unit diagram showing a second camera and light source for faceplate wetting visualization and the specially designed ink collection system*

The R&D system configuration offers many options that will be discussed in a later section.

The underlying architecture is very similar between the R&D system and the in-situ variation: both rely on careful synchronization between the firing signal and the strobe (which requires sophisticated strobe control electronics), both rely on a triggered camera to synchronize image capture, and proprietary optics allow for the best possible image. At the core of both systems is ImageXpert software.

There are also significant differences between the two configurations: the in-situ system’s hardware is not as flexible once it has been selected for a specific application and installed. A zoom lens in the R&D system is replaced with a fixed focal length lens in the in-situ system. The use of smaller camera formats may decrease image size and field of view. Application requirements may dictate that a smaller set of pre-programmed algorithms is sufficient for image analysis and data handling.

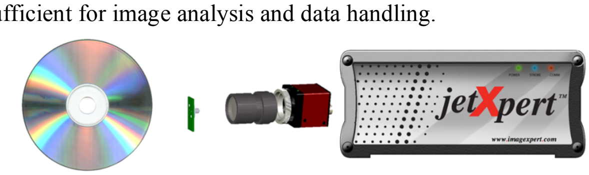


***Figure 4**: Basic JetXpert in-situ components: strobe control and image analysis software, strobe control electronics (box), strobe, camera and lens (specific hardware and software configurations will change based on application requirements)*

In order to maximize flexibility of the in-situ system, the camera and light source can be configured in a variety of geometries to achieve the necessary imaging. By adding prisms, the camera and light source can be arranged in a variety of ways as shown in the following figure.

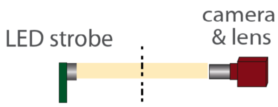


Figure 5a: Conceptual sketch of the standard linear configuration with drop stream (dashed line) between camera and light source set along one linear optical axis.

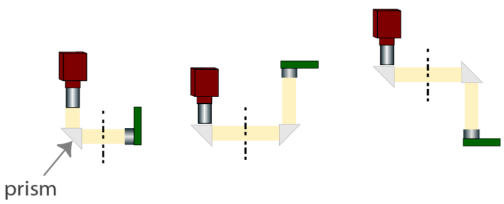


Figure 5b: Several conceptual examples of alternative geometries using the same camera and light source but with redirection using one or more prisms. (Changes in optics may be necessary to accommodate for different image path lengths).

In addition to the geometric variations possible by using prisms, the LED strobe can also be coupled with a fiber optic to reposition or reroute the light source in tightly packed hardware environments.

Measurements

Several different drop attributes are commonly of interest: velocity, volume and trajectory.

Measurement Definitions

Drop Velocity

In the standard configuration, a double-drop mode is used to capture a single image that includes two instances of the same droplet at different delay times from the actuating signal. In the image, the droplet is first captured with a strobe pulse that fires at "delay1", then again with a strobe pulse that fires at delay1+strobe pulse width+delay2. The distance the drop travels between the two instances can be used to calculate the velocity.

In other words, drop velocity is calculated by measuring the distance between the centroids of the instances of the imaged droplet, and dividing that distance by the delay time (delay2) between them plus the pulse width.

Velocity = distance between drop 1 and drop 2 centroids / (delay2+pulse width) (1)

The software reads the values for Delay2 and pulse width automatically in order to make the calculation. Velocity is reported in m/s.

The reason that for the standard JetXpert method velocity is not usually calculated using the position of the first drop relative to the nozzle plate is that although the first delay time is known, there is some additional unknown delay time between when a firing pulse is sent to a jet or nozzle and when the jet is actually fired or the nozzle actually ejects the droplet. This uncertainty makes the measurement of the velocity of drop 1 potentially inaccurate if only delay1 is used. If the internal delay time is known, the system can be set up to add the internal delay to delay 1 and velocity can be calculated using one drop and the distance it has traveled from the jet or nozzle.

Drop Trajectory

Drop trajectory is measured (by default) as the angle of the best-fit line through the two drop instances in the double drop image. The angle is usually reported relative to the image buffer, which assumes careful alignment between the ejection device and the camera. Drop trajectory is reported in degrees. Trajectory is a projection of trajectory in the 2-D image plane as defined by the camera sensor plane. Trajectory errors in the plane orthogonal to the image plane will not be measured.

Drop Volume

Drop-based drop volume is the system default and is based on the presumption of spherical drops when drops are in free flight. The average radius of the drop is measured and the volume is calculated based on the radius.

$$\text{Volume} = 4/3\pi\, r^3 \qquad (2)$$

Volume is reported in picoliters (pl).

Drop Volume, Velocity and Trajectory Example

In the following figure (6a,b), droplet volume, velocity and trajectory are measured and reported.

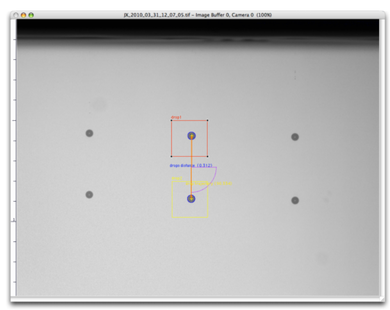
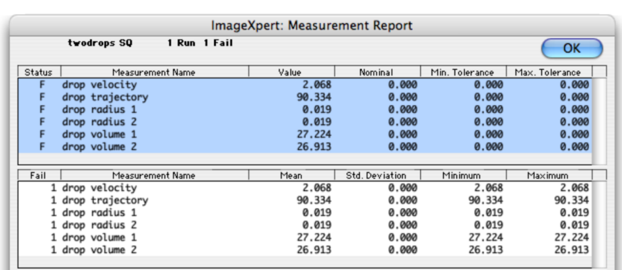


Figure 6a: Droplet volume measurement using double drop image (two instances of each drop imaged in the same frame offset by a time delay, daley2)



ImageXpert: Measurement Report

twodrops SQ 1 Run 1 Fail OK

Status	Measurement Name	Value	Nominal	Min. Tolerance	Max. Tolerance
F	drop velocity	2.068	0.000	0.000	0.000
F	drop trajectory	90.334	0.000	0.000	0.000
F	drop radius 1	0.019	0.000	0.000	0.000
F	drop radius 2	0.019	0.000	0.000	0.000
F	drop volume 1	27.224	0.000	0.000	0.000
F	drop volume 2	26.913	0.000	0.000	0.000

Fail	Measurement Name	Mean	Std. Deviation	Minimum	Maximum
1	drop velocity	2.068	0.000	2.068	2.068
1	drop trajectory	90.334	0.000	90.334	90.334
1	drop radius 1	0.019	0.000	0.019	0.019
1	drop radius 2	0.019	0.000	0.019	0.019
1	drop volume 1	27.224	0.000	27.224	27.224
1	drop volume 2	26.913	0.000	26.913	26.913

Figure 6b: Close-up view of the on-screen measurement report, showing both individual runs and accumulated statistical data

If drops are known or suspected to be more elliptical than spherical, the software can be modified to calculate the area based on the presumption of prolate elliptical drops:

$$\text{Volume} = 4/3\pi*(\text{major axis})*((\text{minor axis})^2) \qquad (3)$$

If the volume of another object such as a ligament or series of droplets is of interest, the software can be changed to apply Ligament-based volume analysis.

Ligament Volume

Ligament-based drop volume is calculated based on the edge points of the ligament or drop stream, as defined and bounded by a region of interest (ROI). The presumption is of rotational symmetry around the vertical axis; the volume of the ligament or droplet stream is measured based on the rotated 2-D projection.

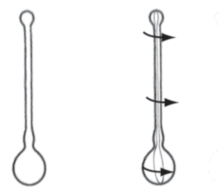


Figure 7: *Ligament-based volume measurement method*

The following figure shows an example of a ligament and ligament-based volume calculation.

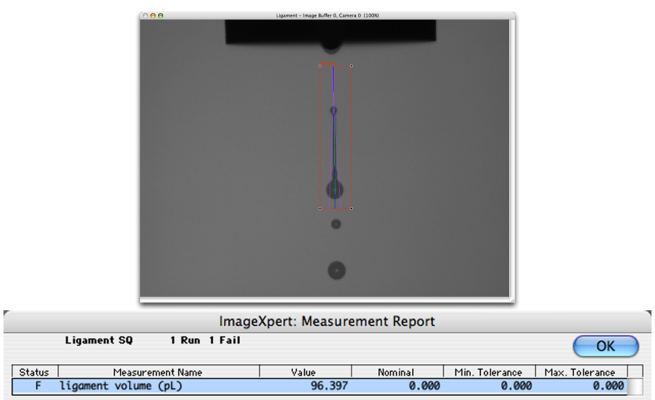


Figure 8*: Ligament-based volume example*

Ligament-based volume is most often used in dispensing applications where drops are not fully formed in flight before contacting the substrate.

R&D Unit Details

While the in-situ system was designed to be very small with a flexible geometry, it is limited in that it includes a single camera and a fixed focal length lens. Not only does the standard hardware of the R&D unit provide more flexibility (inherent in the design is flexibility for a wide range of drop sizes using the zoom lens.) it also offers wide range of options.

Additional capabilities are possible through optional add-ons such as:

- A second camera and light source for off-axis faceplate wetting visualization
- One axis of automated motion for sequential analysis of multiple dispensing tips or jets
- An integrated capacity for frequency sweep actuation and output analysis
- A universal ink supply system

Faceplate Visualization

A second camera and light source can be set below the print head and offset at an angle allow for visualization of the faceplate in real time as the print head is being fired. Visualization of the nozzle plate or dispensing tip during operation can provide insight into ink build-up and mobility, which can have a significant impact on firing quality and reliability.

A live video feed from the camera can be viewed on-screen and images, image series, and movies can be captured and saved from this second camera.

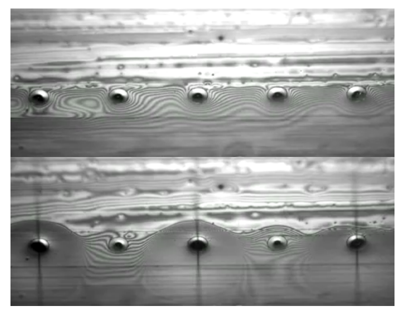


Figure 9: *Image of faceplate before firing (top) and faceplate during firing of odd nozzles (bottom).*

Automation

Automation is enabled using one automated axis of motion. Motion control is available through the underlying ImageXpert software, to enable automated “scripts” that step across the print head for example, capturing images of drops-in-flight from each nozzle, performing analysis on those images, and saving relevant data.

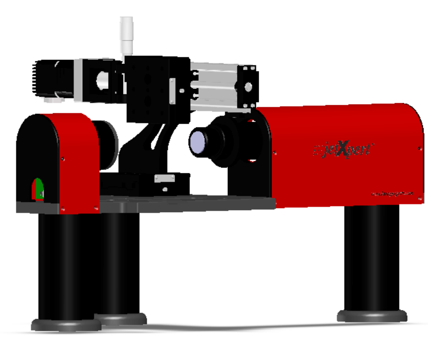


Figure 10*: JetXpert system sketch showing automated lateral motion stage to automatically move print head in front of camera for sequential analysis of all jets on a print head during print head characterization or tuning*

The one axis of automated motion (the other two axes are manually adjustable) has a range of motion of approximately 5" in the standard configuration.

Print head characterization is possible by using automated motion for automatic sequential inspection of each jet across a print head. Combining ImageXpert's motion control, automation capabilities, and drop analysis algorithms can significantly increase measurement efficiency over use of a manual stage for print head positioning.

Some print heads have tunable voltages per section or nozzle, so having objective and quantitative feedback about actual performance of each jet can allow for on-bench tuning and optimization.

Frequency sweep

Print heads and fluids often perform differently at different firing frequencies. In order to decrease variability and to optimize performance, it is often desirable to assess printing system performance over a range of frequencies.

To address this need, ImageXpert also offers a frequency sweep capability as an add-on to existing JetXpert systems or as an option when purchasing new systems for use in R&D.

The JetXpert software sends commands to a programmable signal generator defining the desired firing frequency, and the signal generator then triggers the print head drive electronics. The JetXpert system (camera and strobe) can be triggered directly by the signal generator or via a copy of the firing signal of the print head for synchronization.

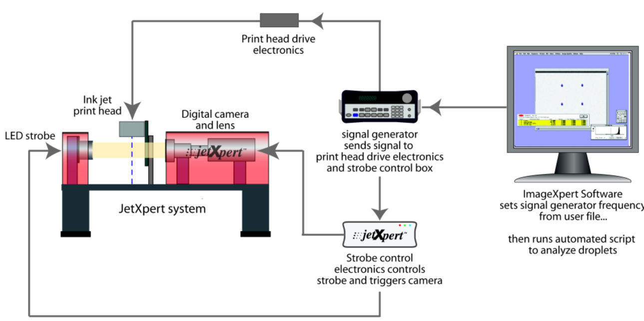


***Figure 11**: Frequency sweep system diagram*

The JetXpert frequency sweep option uses a frequency settings file that includes a list of frequencies that will be called in order with a single instance of image capture and analysis at each step. A Frequency Editor user interface lets the user load a pre-defined file or edit or create a new one. The following figure shows an example of the frequency editor window.

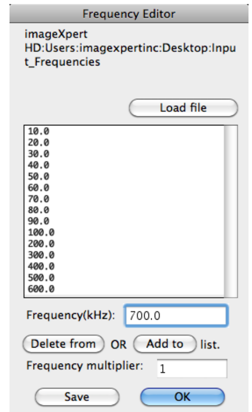


***Figure 12**: Frequency Editor interface example*

By integrating the control of a signal generator into the JetXpert software, the system can automatically step through a range of actuating frequencies as specified by the user in a settings file, and the system can be used to assess the impact of firing frequency on fluid behavior (velocity, volume, repeatability) and print head performance with minimal operator intervention.

The following graph shows an example of an actual study for a print head a fluid combination showing the impact of firing frequency on droplet volume.

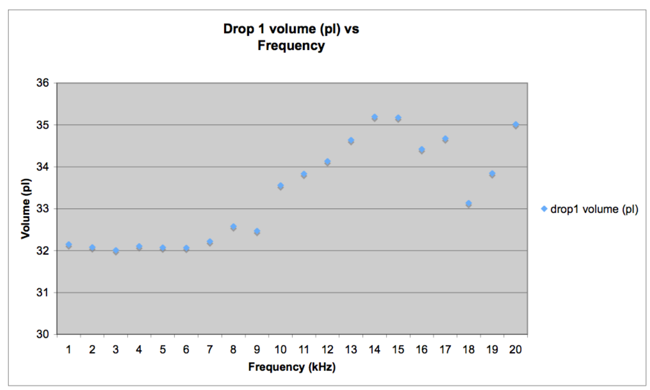


***Figure 13**: Example of relationship between drop volume and firing frequency*

JetXpert uses a proprietary method to determine the most appropriate analytical method for calculating droplet velocity. Selection is based on the firing frequency and a priori knowledge of the impact of frequency on droplet spacing in the images captured using the JetXpert system.

Universal ink supply system

In R&D, many companies explore many different print heads to validate their jettable fluids or to select the most appropriate print head for their application.

Many makeshift ink delivery systems have been used, including syringes and other low tech or manual feed methods.

To help minimize startup times in R&D, and to decrease complexity and changeover time when moving from one print head to another, ImageXpert has developed a universal single color ink delivery module that works with aqueous, solvent-based and UV curable inks. The ink supply system was designed such that the meniscus level remains constant while printing.

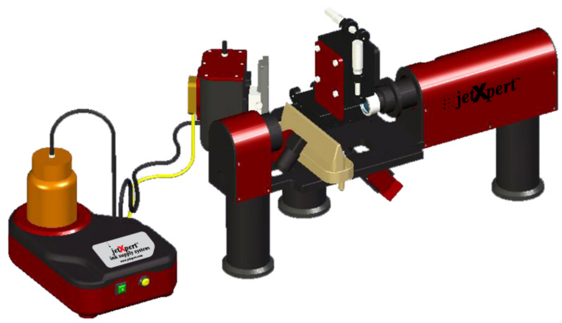


Figure 14: *Universal ink supply system diagram*

The ink supply system includes two primary components: a box that houses the power and purge/prime buttons, pumps, and a holder for the ink supply tank, and a sub tank positioned on a vertical stage that supplies ink to the print head.

This fully integrated ink delivery system is available as a stand-alone unit, or as an add-on to new or previously purchased JetXpert systems.

Conclusion

JetXpert R&D drop watching and analysis systems offer a wide range of capabilities for exploring the relationships between fluids and print heads, and between actuating signals and print head performance. However, once optimal settings are defined and printing and dispensing systems are developed, the standard R&D JetXpert system is too large to be integrated easily into dispensing and printing systems for in-situ performance verification. To address the need for on-board process control and feedback, a smaller unit has been developed with an optical system that was designed to offer multiple geometries to fit into a wider range of equipment. Objective data from the on-board JetXpert system can be used to verify or tune dispensing or printing system performance in the field.

References

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[3] Y.Kipman, et al., Three Methods of Measuring Velocity of Drops in Flight Using JetXpert, NIP25: International Conference on Digital Printing Technologies and Digital Fabrication, p. 71-74 (2009)

Author Biography

Mr. Kipman is the president and founder of ImageXpert Inc., the industry leader in automated machine vision systems for image, part and process inspection. Since 1989, ImageXpert has offered a diversified product line to a wide range of markets including digital printing and fabrication, non-contact dispensing, and microfluidics. Mr. Kipman holds a M.S. in mechanical engineering, with a major in electro-optics from the University of Connecticut and a B.S. from the Technion Institute of Technology.