LuBan: Low-Cost and In-Situ Droplet Micro-Sensing for Inkjet 3D Printing Quality

Aosen Wang, Tianjiao Wang, Chi Zhou, Wenyao Xu

MiJeong Kim



1. INTRODUCTION

- Inkjet 3D printing is one of the most popular printing techniques in rapid prototyping and additive manufacturing to produce the object from a digital model.
- The key unsolved problem of inkjet 3D printing technology in real-world applications
  - High Precision Requirement
  - High Throughput Requirement
  - the lack of robust methods and inspection techniques to qualify and certify the part reproducibility and process repeatability.



1. INTRODUCTION

- LuBan 설계
  - The first droplet micro-sensing system designed to check the quality of the inkjet 3D printing process.
  - To accurately and reliably sense the behavior of droplets, we employ low-cost infrared diode to implement high precision (sub-millimeter level) sensing with the help of the computational light beam field.



2. BACKGROUNDS

- <2.1 Inkjet 3D Printers>
- Inkjet 3D printing is an additive manufacturing process that works in a similar way as the inkjet 2D printing used on a daily basis.

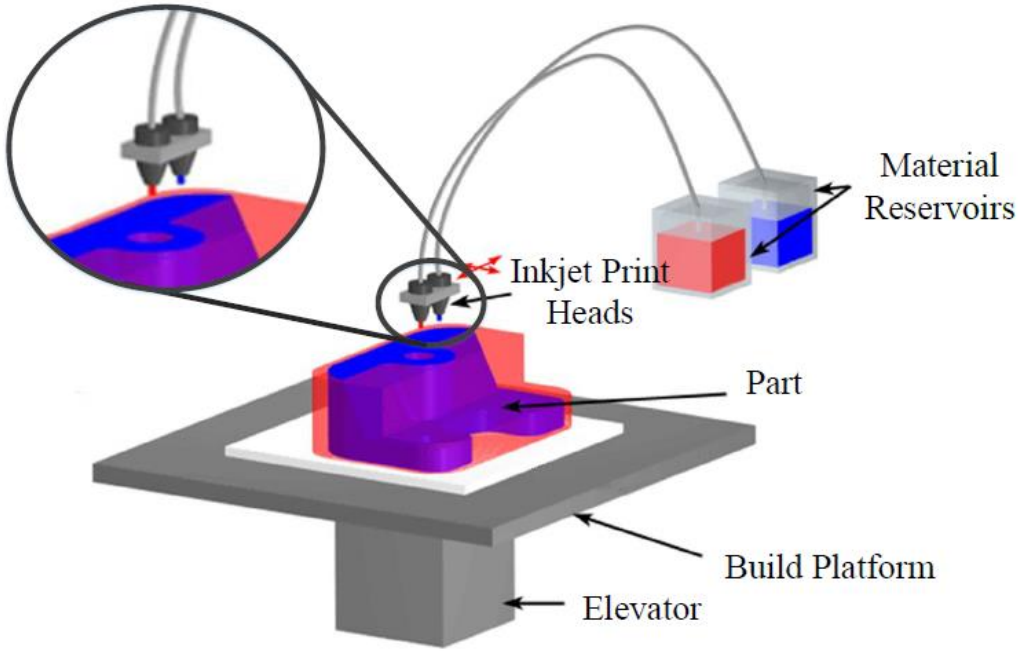
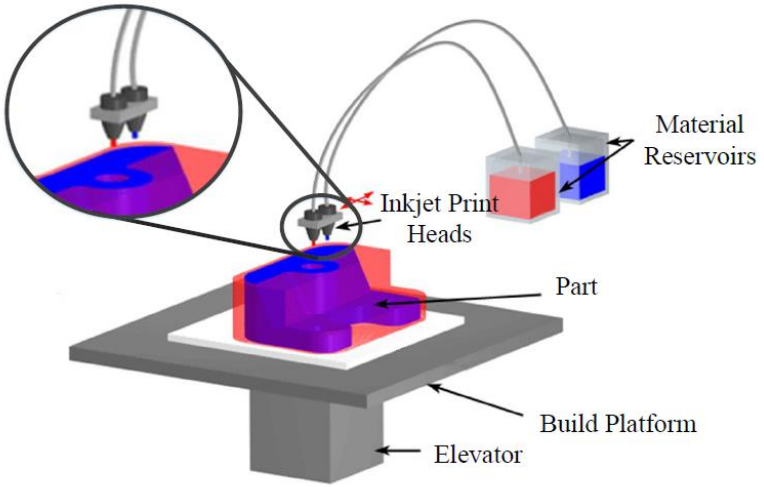


Figure 1: The inkjet 3D printer structure.

2. BACKGROUNDS



- <2.1 Inkjet 3D Printers>
- 프린팅 과정
  1. A nozzle or a print head is used to generate micro-size droplets of the printed material.
  2. The droplet is jetted to the solidified part.
  3. While the print head moves over the printing area based on the digital model, the jetted material is added and bound with the previous layer.
  4. The platform elevates downward by one layer-thickness after the current layer is formed.
  5. By repeating this process, the part is constructed in a layer-by-layer fashion.



2. BACKGROUNDS

- <2.2 Significance of Quality Assurance>
- Quality assurance is to examine key parameters in the manufacturing process to certify 3D printed products.
- Specifically, process precision(i.e., the droplet location) is the key quality metric which can facilitate the broader applications of inkjet 3D printers.
- Three representative implications of precision
  1. Printing quality 인쇄 품질 개선
  2. Environment adaptivity 불리한 환경 조건 방지(예: 진동)
  3. Resource economization 자원 절약 (결함 발생시 전체 부품 폐기하고 다시 제작해야 함)



3. LIGHT BEAM FIELD: CONCEPT AND CHALLENGES

- <3.1 Concept >
- light beam field ?

1. An innovative approach to accurately sense the droplet to enable quality assurance in inkjet 3D printing.
2. A characterized energy field distribution which results from a light source dispersing energy through the electromagnetic wave.



3. LIGHT BEAM FIELD: CONCEPT AND CHALLENGES

- <3.1 Concept >
- The generation and principle of light beam field

1. The infrared light is generated when an electric field is applied to a P-N junction in the diode.
2. The electrons are pushed from the N-region and recombine with the holes in the P-region.
3. To lessen the energy level, extra energy is emitted in the form of heat and light.

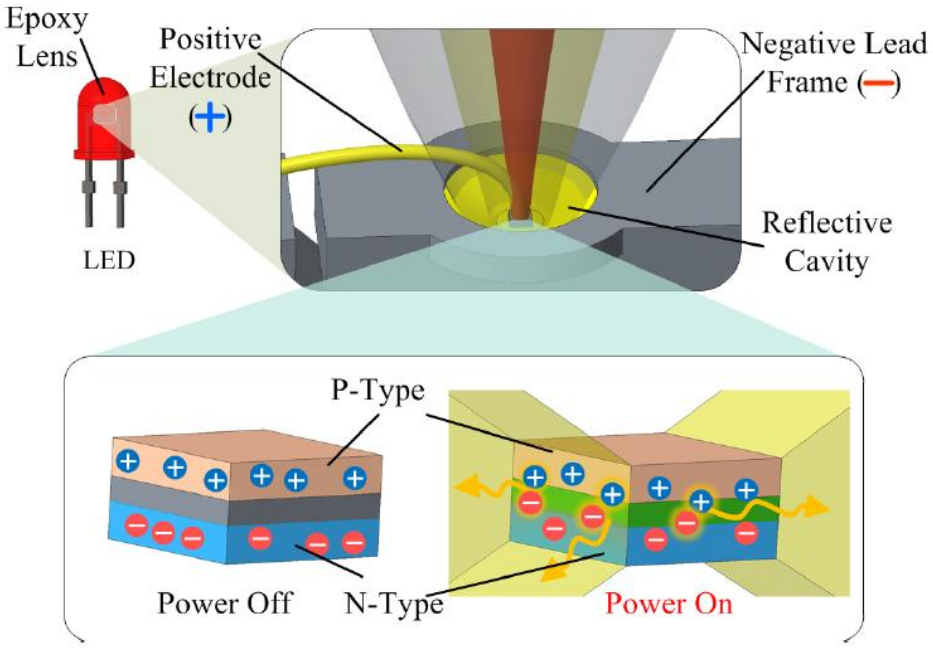
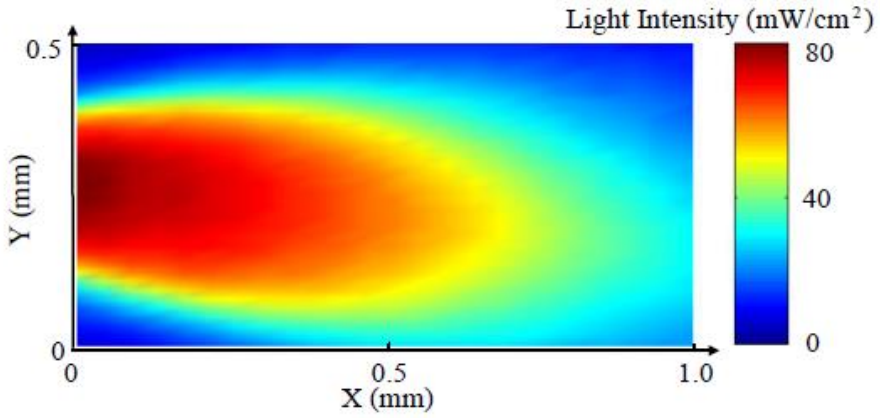


Figure 2: The concept of light beam field generation, which conveys three characteristics, field repeatability, energy continuity and energy anisotropy.

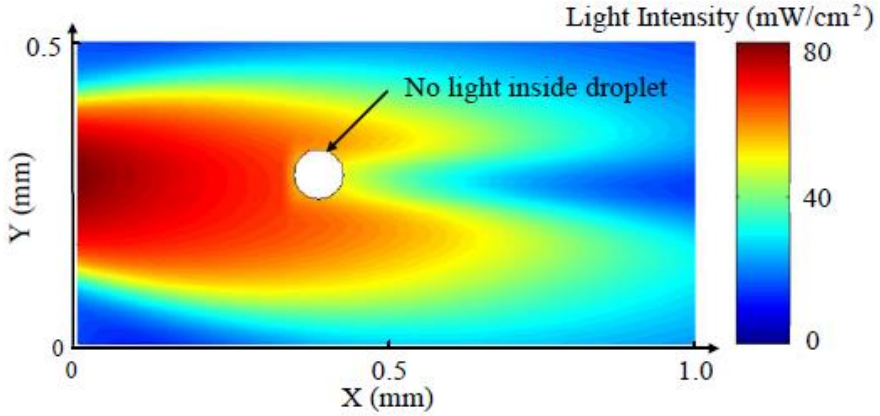
3. LIGHT BEAM FIELD: CONCEPT AND CHALLENGES

- <3.2 Field Interference Effect>

1. Field interference effect(간섭 효과) utilizes the electromagnetic disturbance(전자기 교란) to sense the tiny intruder object.
2. (a) The light beam field is built by a typical infrared emitter(적외선 이미터).
3. The field intensity is distributed stably and continuously.
4. (b) If the droplet enters into the field, can observe obvious field intensity changes.
5. The droplet induces an irregular and complex intensity pattern.
6. By quantitatively sensing this interference effect, it is promising to estimate the location of a tiny object in the field.



(a) Light beam field without a droplet



(b) light beam field with a droplet

Figure 3: An example of light beam field with and without interference from the droplet.

4. LUBAN: IN-SITU DROPLET MICROSENSING SYSTEM

- <4.1 System Overview>
- LuBan system
  1. The droplet precision is the critical factor in printing quality and reliability of inkjet 3D printer.
  2. Aims to precisely and efficiently sense the location of droplets
  3. Comprises two key components
     1. computational light beam field sensing
     2. integration-domain droplet location algorithm

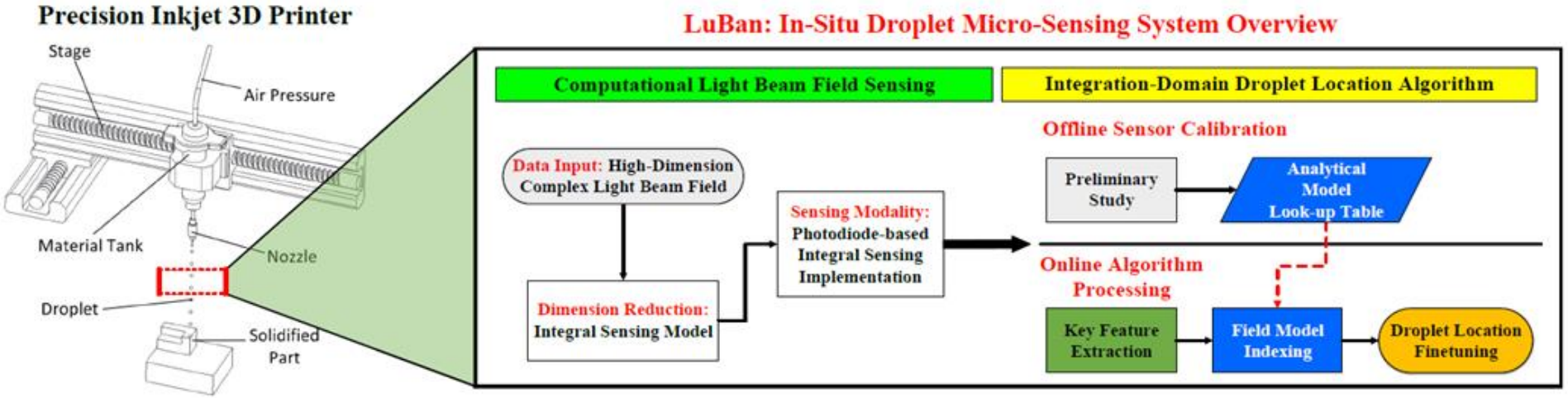


Figure 4: The system overview of in-situ droplet micro-sensing for inkjet 3D printing quality assurance.

4. LUBAN: IN-SITU DROPLET MICROSENSING SYSTEM

- <4.2 Module Details>
- 1) Integral Sensing Model
  - When the droplet goes through the light beam field, it will interact with the field, resulting in a highdimensional complex light energy pattern.
  - However, it is intractable to acquire the exact pattern of this interference in the analog domain.
  - Apply integral sensing to reduce the signal dimension from analog domain to digital domain to make light beam field "computational"
- 2) Key Feature Extraction
  - The data format obtained from integral sensing model is a time series signal.
  - We propose to extract the key feature of the time series to build the mapping relationship with the analytical model in a look-up table.
- 3) Field Model Indexing
  - Once we get the key feature, we can fetch its corresponding model for the preparation of location information estimation.
- 4) Droplet Location Fine-Tuning
  - we designed a geometry-based optimization method to accurately locate the droplet position in the printing space.



5. COMPUTATIONAL LIGHT BEAM FIELD SENSING

- <5.1 Integral Sensing Model>
- The photodiode detector integrates the complex field intensity distribution in 3-D space.
- Its view area is formed by the two boundaries, as shown by the gray planes in Figure 5.
- The reading D from the detector is the integral form of the complex pattern of the field F , and the integration process follows the equation:

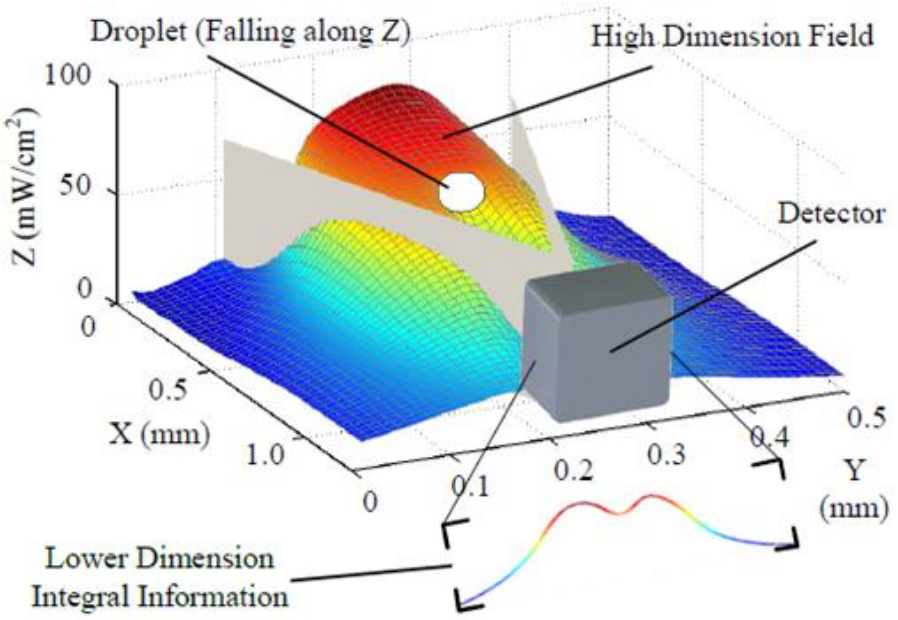


Figure 5: An example of complex field interference pattern sensing by an integral model.

$$D_{i,p} = \int_a^b \int_{i-\delta t}^{i} F_{i,p}(t,\phi)\, d_t\, d_\phi,$$



5. COMPUTATIONAL LIGHT BEAM FIELD SENSING

- <5.2 Sensing Modality: Integral Sensing Hardware Implementation>
- 5.2.1 Property of Emitter-Detector
  - In order to make full use of the energy anisotropy of light beam field to achieve a high precision location detection
    1. Emitter-Detector In-Pair 여러 개를 사용, 여러 위치에서 에너지 감지
    2. Emitter-Detector Coplanar X-Y평면에 평행한 동일한 평면에 위치
- 5.2.2 Sensor Layout
  - a three-pair solution with emitter-detector pairs arranged 120 degrees to each other.

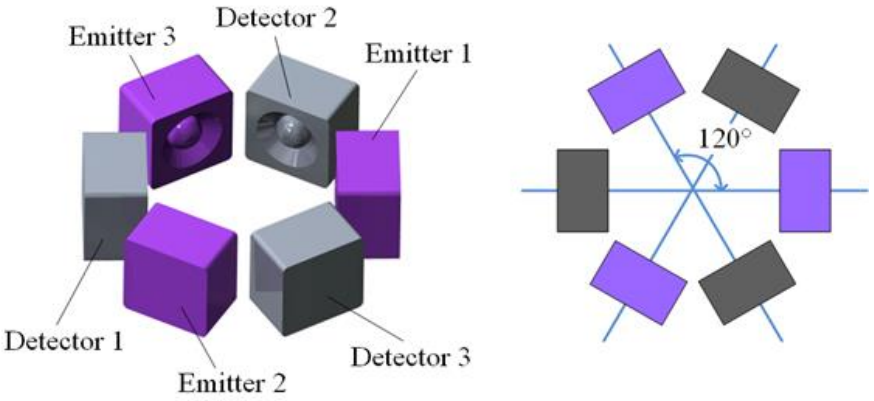


Figure 6: The sensor layout model in LuBan system.

6. INTEGRATION-DOMAIN DROPLET LOCATION ALGORITHM

- <6.1 Offline Sensor Calibration>
- The core part of software implementation in LuBan system
- Sensor calibration: required to build the reference in light beam field for the analytical model of the online sensing process.
  1. Calibration Process
  2. Analytical Model Fitting

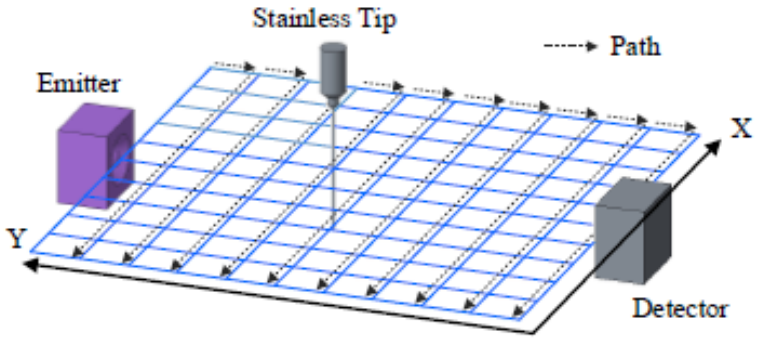


Figure 8: Sensor calibration of light beam field using stainless tip simulation.

In the calibration process, the characteristic data comes from a simulation of the droplet falling process by a thin stainless tip, as shown in Figure 8.

6. INTEGRATION-DOMAIN DROPLET LOCATION ALGORITHM

- <6.1 Offline Sensor Calibration>
- Analytical Model Fitting

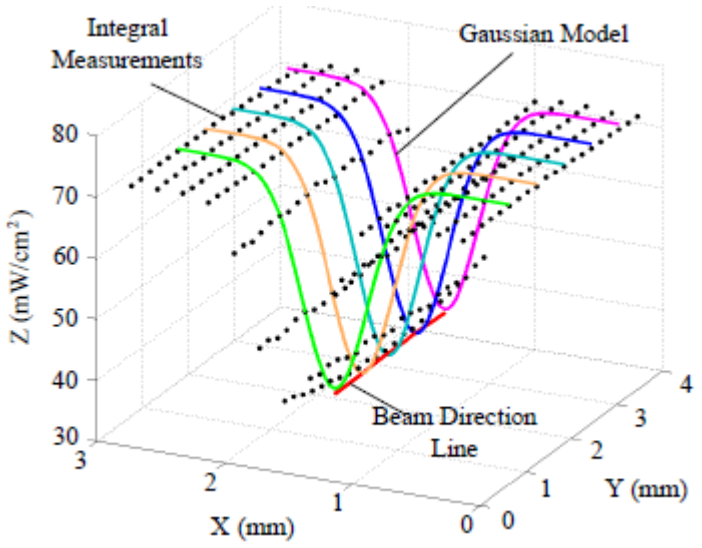


Figure 9: Analytic model fitting for integration domain measurements.

- After we obtain the characteristic data, we choose the analytical model to fit the data distribution for the convenience of data recording and indexing.
- we use a group of Gaussian functions fitting to model the interference effect on the light beam field in the integration domain
- The single Gaussian function is in the X-Z plane and the group of functions is along the Y axis.

6. INTEGRATION-DOMAIN DROPLET LOCATION ALGORITHM

- <6.2 Online Algorithm Processing>
- The entire processing for integration domain time series includes three main procedures, key feature extraction, field model indexing and droplet location fine-tuning.
  - 1) key feature extraction
    - Taking efficiency and accuracy into consideration, we adopt an automatic multiscale-based peak detection (AMPD) method to identify the peak value which is specifically designed for noisy applications.
  - 2) field model indexing
    - The next step of our algorithm processing is to fetch the surface model by the peak value from the time series on the photodiode detectors.
  - 3) droplet location fine-tuning
    - Estimate the droplet location information based on curves retrieved from field model look-up table built in sensor calibration.



7. EVALUATION PLAN

1. simulation study
   - Examining the effectiveness of LuBan
   - Use the location accuracy of the mimicking droplet

2. real-world experiments
   - Defect droplet detection rate and the whole system throughput
   - A good method to examine the overall system performance improvement resulting from our LuBan system



8. SIMULATED STUDY

- <8.1 Experimental Setup>
- To build the light beam field : 950-nm infrared LED and photodiode sensor
- Arduino MEGA 2560 to collect the data of sensors.
- Adopt a stainless tip : provide four different sizes of stainless tips with the diameters as 0.24, 0.42, 0.65 and 0.91mm.



8. SIMULATED STUDY

- <8.2 Overall Accuracy>
- Examine the accuracy of LuBan system to sense the position of the droplet.

1. High Precision : the overall accuracy of our luBan system is about 100 microns (which sufficiently matches the sub-millimeter manufacturing accuracy of inkjet 3D printers.)
2. Optimal Droplet Size : as the size of the droplet increases to 0.65mm, the error takes on a declining change. However, the error becomes larger as the size increases.
3. X-Y Similarity : the error in the horizontal axis (X) has a similar trend with the vertical axis (Y)

- choose droplet diameter of 0.65mm for the following simulated studies.

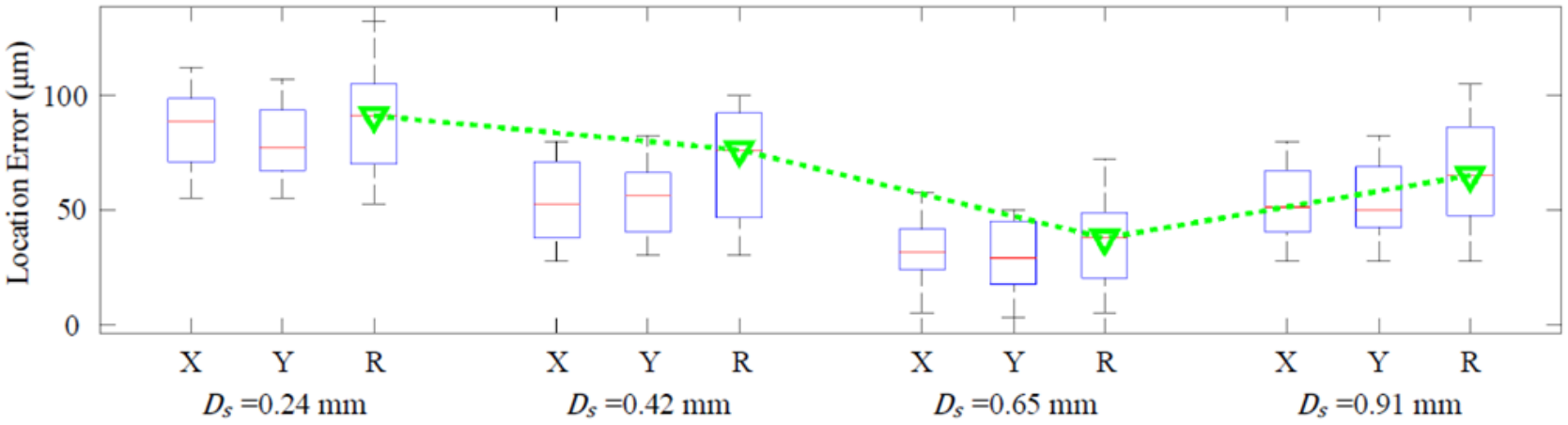


Figure 11: Overall accuracy results

8. SIMULATED STUDY

- <8.3 Spatial Accuracy Distribution>
- The spatial accuracy has smaller errors in the center area and around boundary area.
- The entire distribution is a symmetrical pattern : suitable for the droplet location detection (the droplet falls in the center area where higher accuracy is guaranteed.)

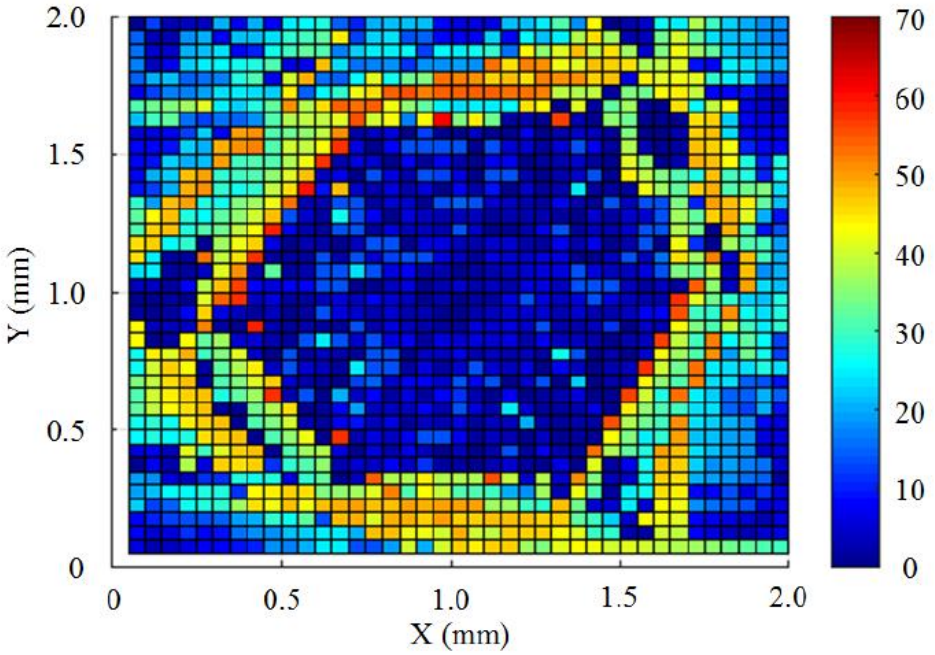


Figure 12: Spatial accuracy results of LuBan system.

8. SIMULATED STUDY

- <8.4 Misalignment Sensitivity>
- The Luban system needs multiple sensor pairs to construct the symmetrical sensor layout.
- Intentionally misalign the sensor pairs : at five levels, -10 (counter-clockwise), -5, 0, 5, and 10 degrees.
- Find : the small-angle misalignment does not cause much accuracy degradation. Although misaligned by 10 degrees, the accuracy is only decreased by about 4 microns.
- the sensor pair holds 120-degree angle : within 10 degrees will be easily corrected in such layout

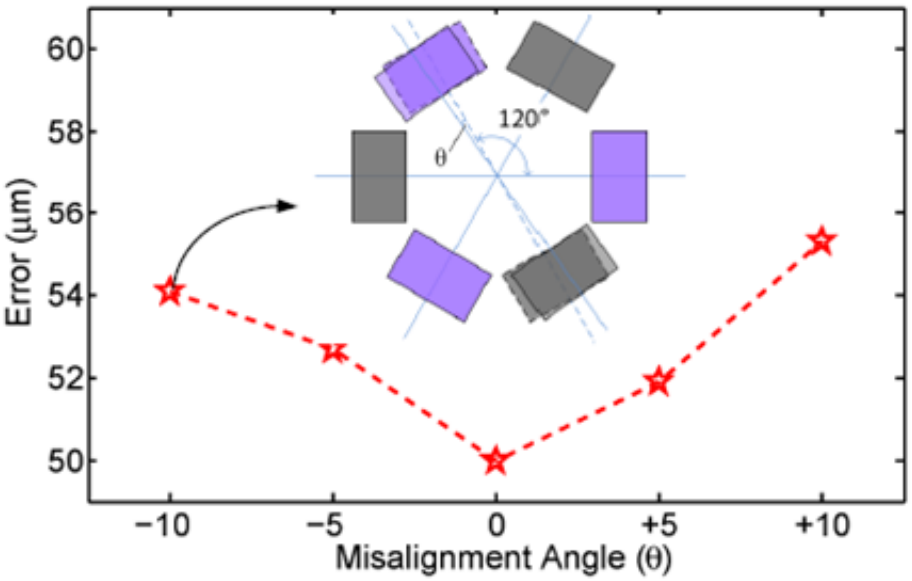


Figure 13: Accuracy under five misalignment cases.

9. REAL-WORLD STUDY

- <9.1 Experimental Setup>
- Examine four types of liquid materials(pure water, green ink, red ink, black ink)
- A camera with a microscope to examine the droplet position on the solidified part of the 3D printer

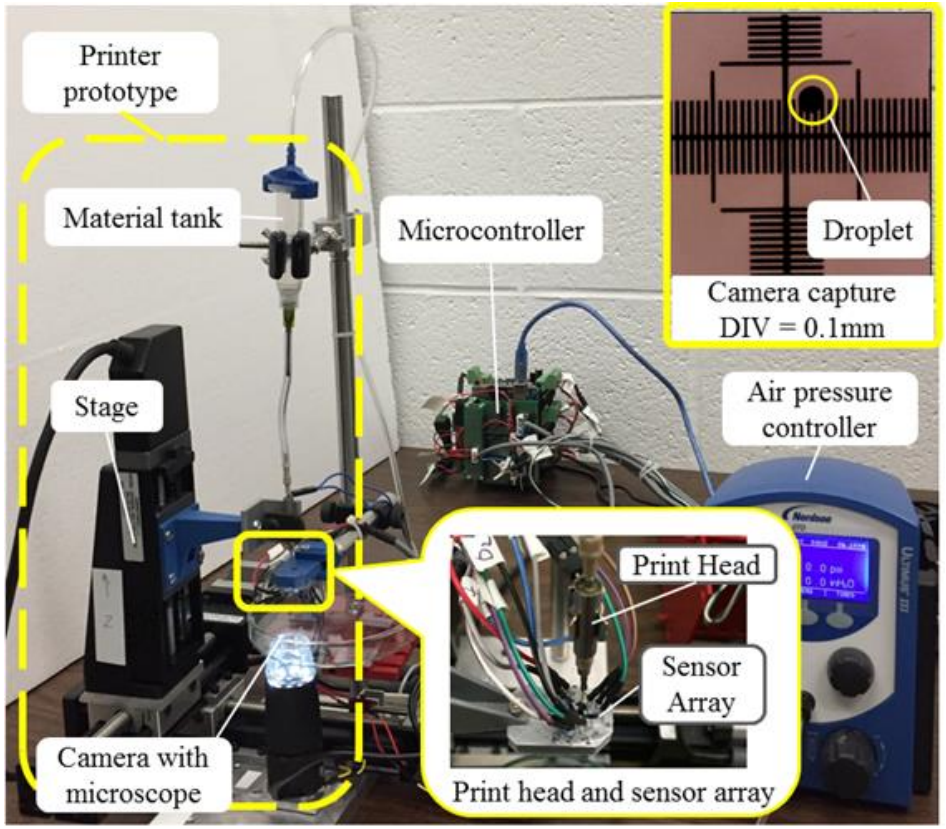


Figure 14: Prototype of our LuBan system, including 3D printer, sensor array, print head and control board.

9. REAL-WORLD STUDY

- <9.2 Test Accuracy>
- Identify droplet size by nozzle diameter, 0.13mm (0.005") and 0.25mm (0.01").
- Use three types of ink, red, green and black, percentage as 10%, 20% and 30% ink mixing with water
- 1. High Precision : recognition rate, more than 97%, large-size droplet can obtain better accuracy.
- 2. Material Impact : the black ink is better than green ink, and the green ink is better than red ink. Particles in the black ink can absorb the widest range of light in different wavelengths.
- 3. Concentration Impact : higher concentration, more particles in the water that can absorb more light energy.

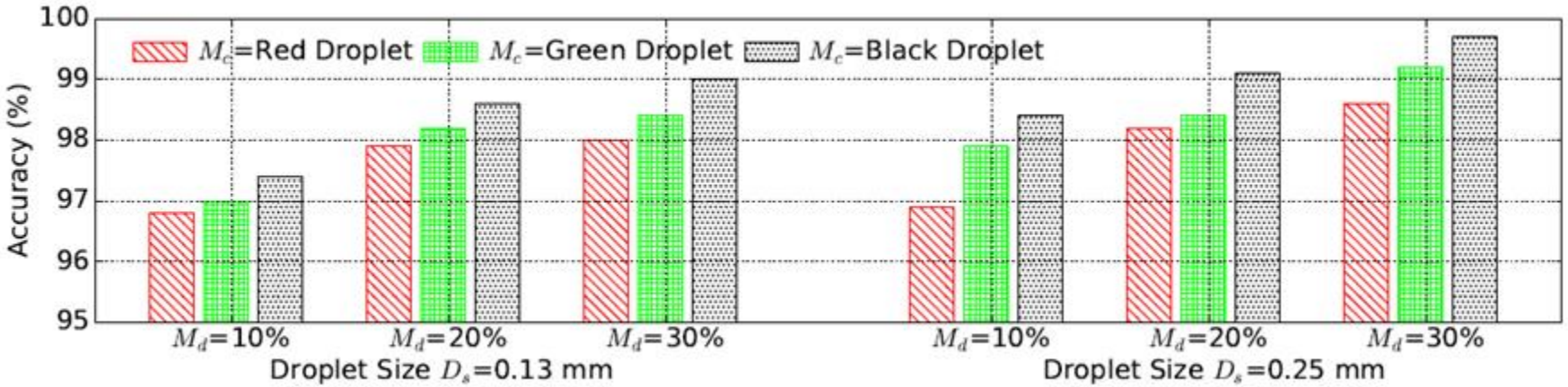


Figure 15: Accuracy of real world study. It compares the effect of droplet size (Ds), material color(Mc) and density (Md).

9. REAL-WORLD STUDY

- <9.3 Delay Overhead Analysis>
- Investigate the time efficiency of LuBan system.
- Choose the green ink with a density of 20% as the droplet source in this experiment.
- The total delay of our LuBan system is about 1.38 ms.
- This is rapid enough to implement an in-situ correction to remove the defective droplets in inkjet 3D printing with a 5ms time bound.

Sensor Response	AD Conversion	Location Algorithm	Total Delay
10.6 μs	66.7 μs	1302.5 μs	1379.8 μs

Table 1: Runtime of all components in LuBan micro-sensing system.



9. REAL-WORLD STUDY

- <9.4 Robustness to Ambient Light Noise>
- LuBan can successfully cope with the noise no more than 10 mW/cm2.
- Choose an environment with less light noise when using LuBan.

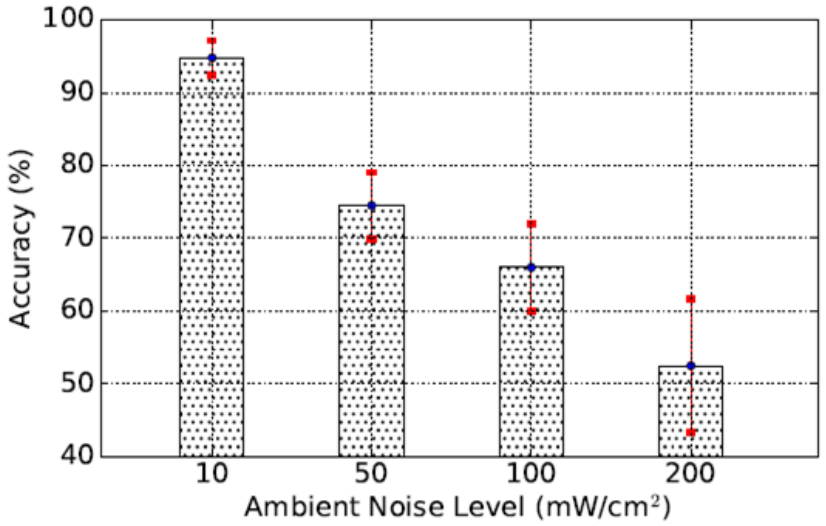


Figure 17: Accuracy of LuBan system under four environmental noise levels.



10. CONCLUSION

- A droplet micro-sensing system, 'LuBan', to examine the quality assurance of inkjet 3D printing.
- Extensive experiments : achieve sub-millimeter level precision (which can meet the quality assurance requirements)
- Real-world printing study : detect more than 99% defective droplets (to drastically improve the part quality of inkjet 3D printer)



critique

- 의미
  - 기존: focus on parameter tuning of droplet generation.
  - 3D printing quality assurance 초점을 맞춤
  - First droplet micro-sensing system 설계
  - Luban 설계시, computational light beam field를 활용할 수 있는 가능성을 증명함
- 시스템의 성능을 더욱 향상시킨다면 좋을 것 같음.

