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aci CONCRETE CONVENTION

Development of a Real-Time Geometric Quality Monitoring System for 3D Printed Concrete Filaments Using a Rotating Nozzle and 2D Laser Detection

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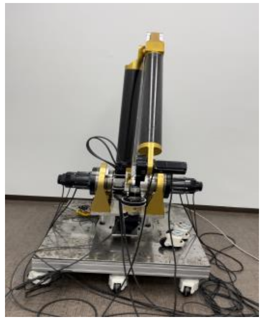
YONSEI UNIVERSITY
CONSTRUCTION ROBOT & AUTOMATION LAB

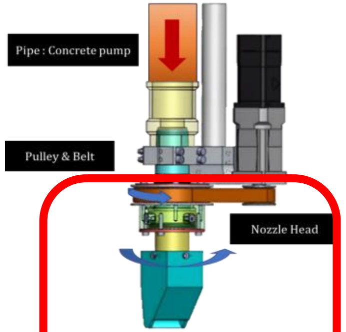
01

Development of a Real-Time Geometric Quality Monitoring System for 3D Printed Concrete Filaments Using a Rotating Nozzle and 2D Laser Detection

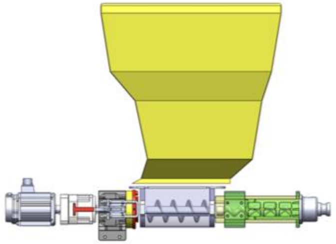
3D Concrete Printing System



Robotic arm
3D concrete printer
of Yonsei University



Rotatable Nozzle
of Yonsei University



Concrete Extruder
of Yonsei University

Control System

Main controller

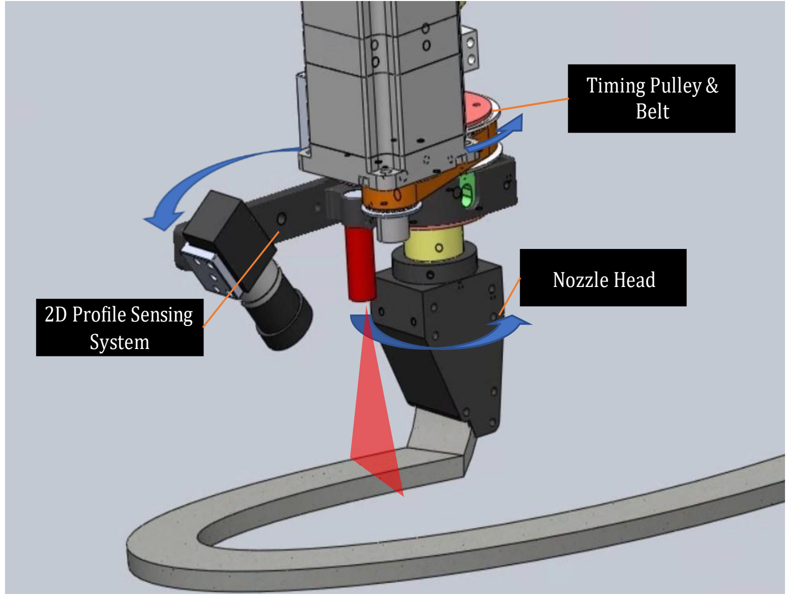
Mini pc

2D Layer Detection System

Camera

2D Line Laser

Contents



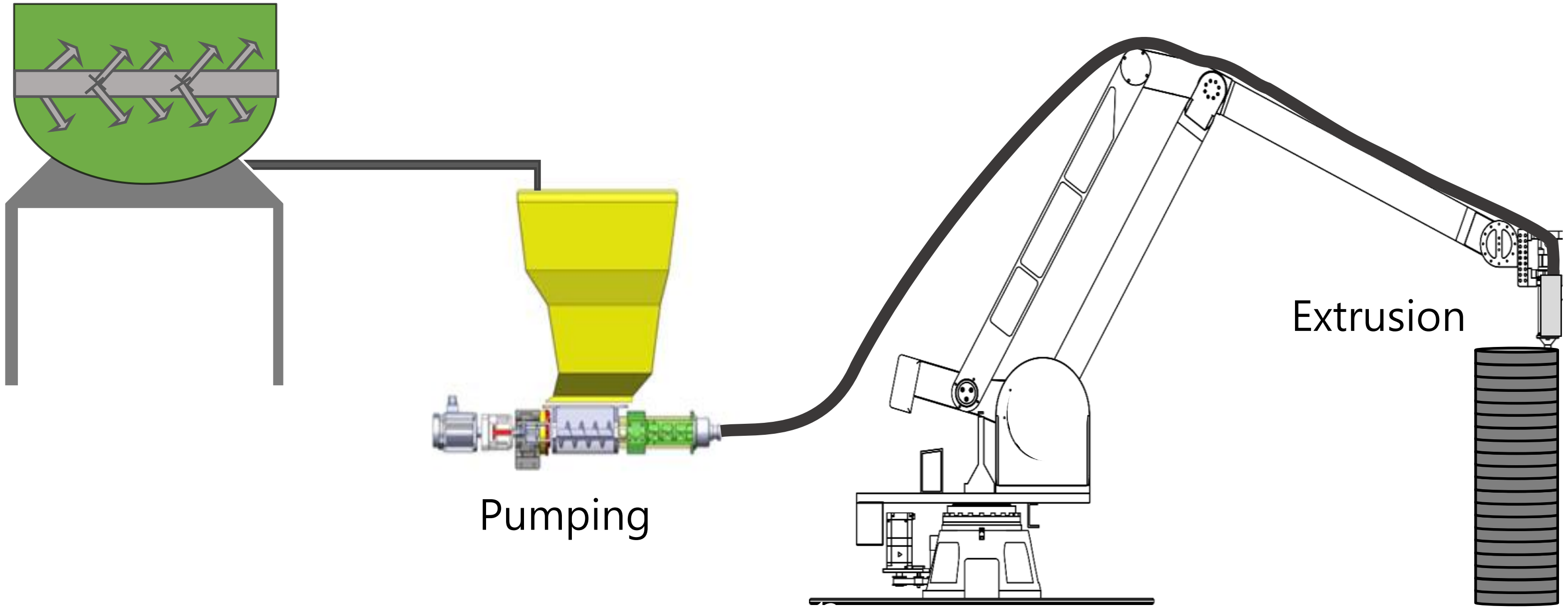
01

Extrusion-based 3D Concrete Printing and importance of processing monitoring

Plastic FDM

solidification within 1 second after exiting the nozzle.

VS

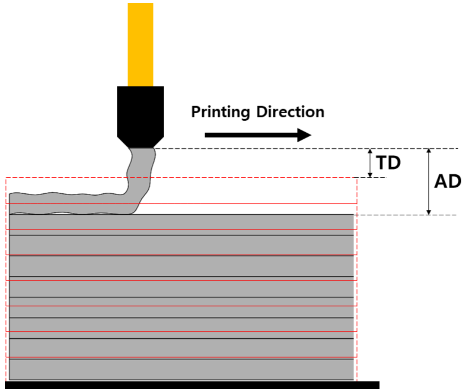


An extrusion based Robotic Arm 3D Concrete Printer used in this study

Special Characteristics of 3D Concrete Printing

- **Limited Performance** of Material
- **Uncertainty of Materials**
- **Limited Controllability**

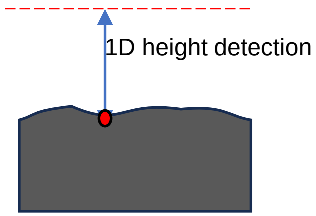
: So <u>3DCP Process Monitoring</u> and <u>Active Process Control</u> are essential!

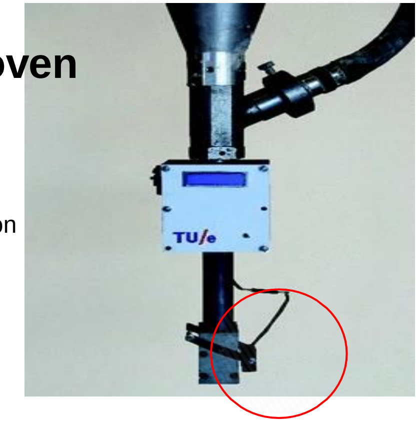


CHAPTER 1. Introduction

Relevant Research

(1) TU Eindhoven [1]





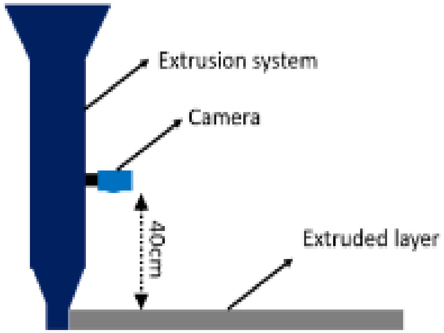
Concrete **layer height** detection system using **1D laser** distance sensor & feedback control for the printing gap

→ **1D** → It can miss the measurement point from the single point measurement

∴ In this study, the concrete **2D profile** was measured using laser triangulation method.

[1] R. J. M. Wolfs, F. P. Bos, E. C. F. van Strien, and T. A. M. Salet, "A real-time height measurement and feedback system for 3D concrete printing," High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 fib Symposium. pp. 2474–2483, 2017.

(2) Univ. of Southern California [2]



Real-time extrusion quality monitoring system using **single camera.**

→ Detected **only width** of the extruded concrete layer assuming the height of the layer

∴ In this study, the developed system can assess **width, height and area** of the concrete layer in real-time.

[2] A. Kazemian, X. Yuan, O. Davtalab, and B. Khoshnevis, "Computer vision for real-time extrusion quality monitoring and control in robotic construction," Autom Constr, vol. 101, no. August 2018, pp. 92–98, 2019

CHAPTER 1. Introduction

Relevant Research

[3] H. Lindemann1, R. Gerbers, S. Ibrahim, F. Dietrich,E. Herrmann,K.Dröder, A. Raatz, and H. Kloft "Development of a shotcrete 3D-printing (SC3DP) technology for additive manufacturing of reinforced freeform concrete structures," RILEM Bookseries, vol. 19, pp. 287–298, 2019

[4] X. Yang, O. Lakhal, A. Belarouci, and R. Merzouki, Adaptive Deposit Compensation of Construction Materials in a 3D Printing Process, 2022 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), 2022

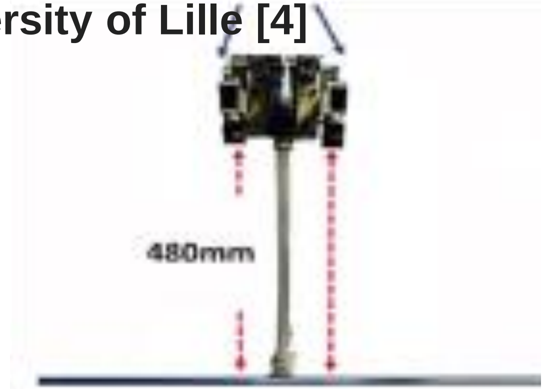
(3) TU Braunschweig [3]

Layer profile detection system using **laser triangulation method** in **shotcrete** 3DCP to adjust the **width and height** of concrete filament in linear wall

→ limited to linear printing path
→ **No extrusion rate control**, Cross sectional area calculation (?),

∴ In this study, the sensor can calculate the **area** as well as the layer's height, and width in real-time.
The developed sensor is attached to the rotatable nozzle which allows layer profile detection in both linear and **rotary printing path.**

(4) University of Lille [4]

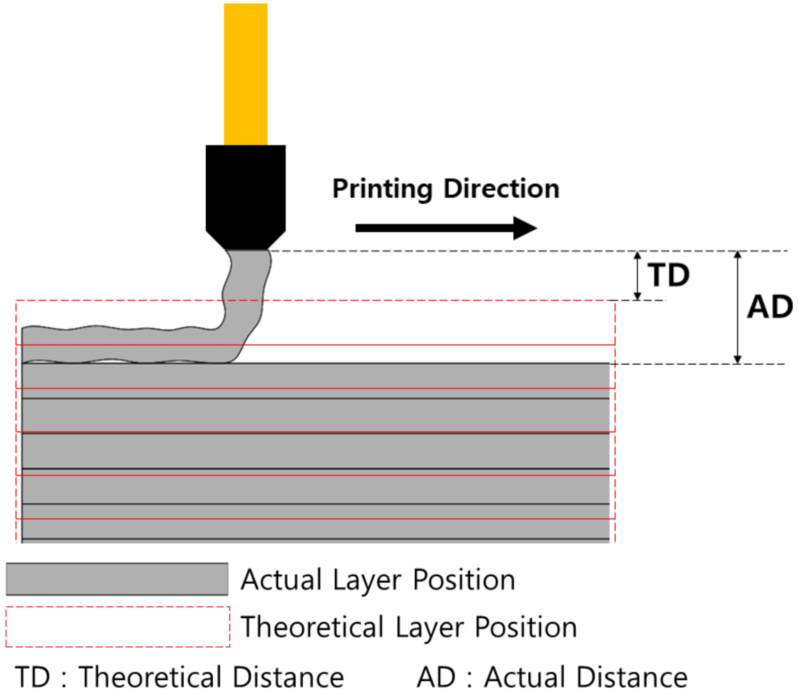


Quality monitoring system for layer geometry inspection using **stereo camera**

→ Limited to detecting layer width
→ Requires high process time

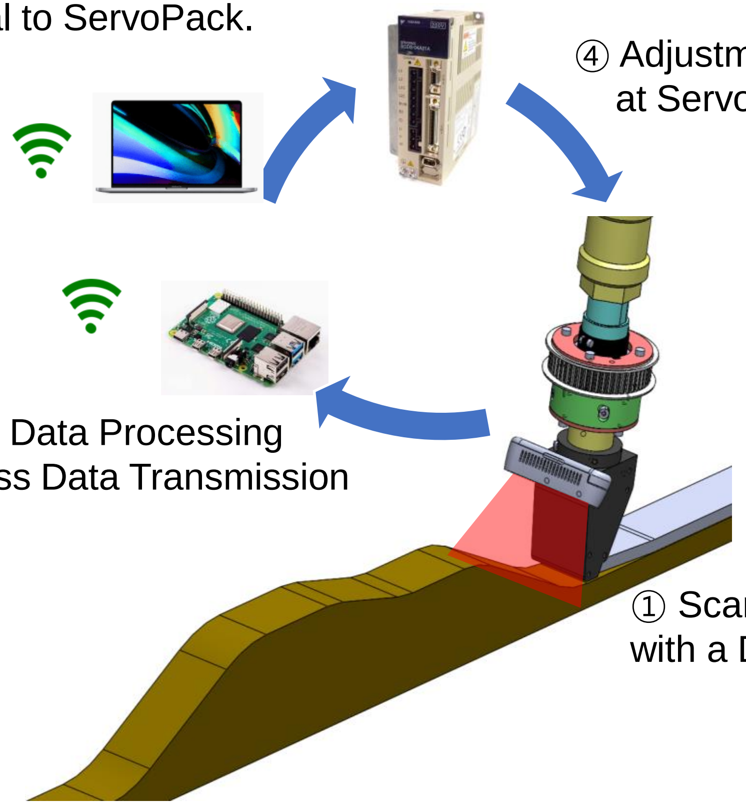
∴ In this study, **at the specific cross section**, the 2D profile and area of extruded concrete layer can be accurately measured in real-time using layer triangulation method

(Relevant Research @ Yonsei Univ.)
Real-time Nozzle Gap Feedback Control based on Depth Sensor



③ Height Feedback Control from an external computer.
Transmitting control signal to ServoPack.

④ Adjustment of Z-axis height at ServoPack

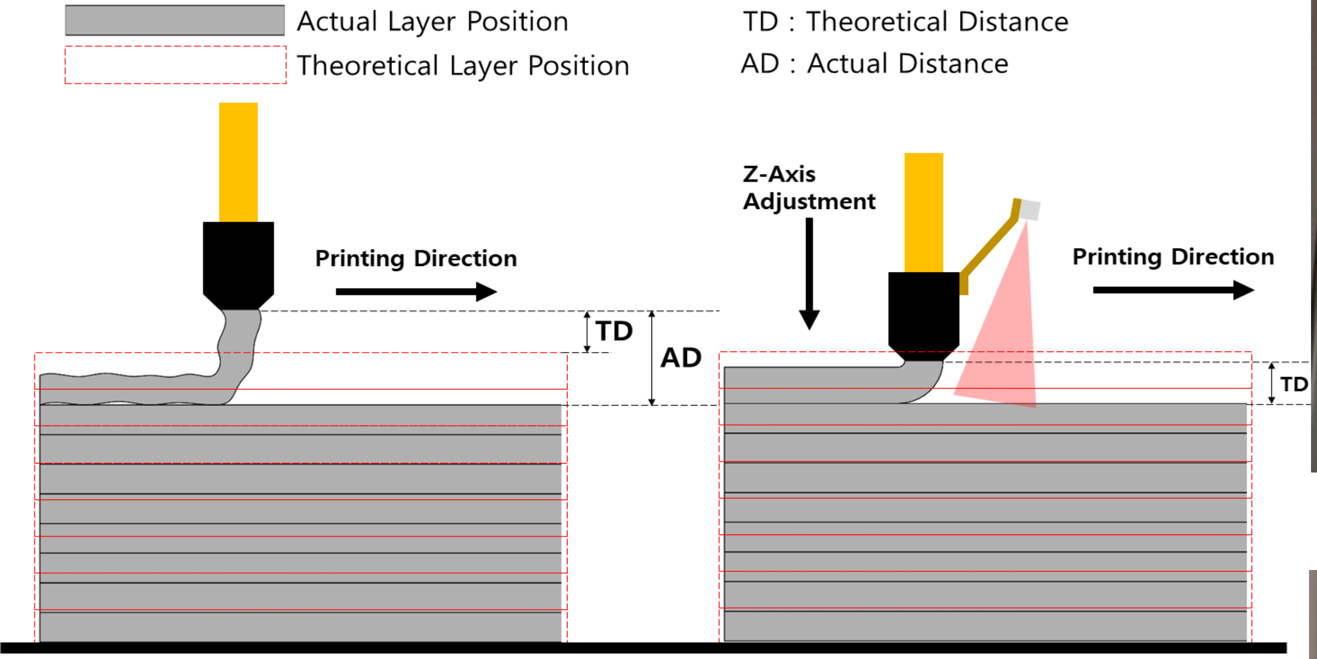


② Depth Data Processing & Wireless Data Transmission

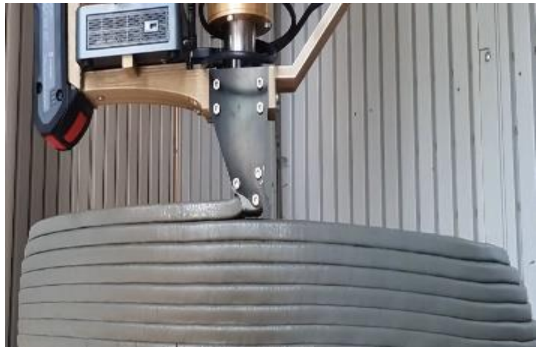
① Scanning Preceding Path with a Depth Camera

01

(Relevant Research @ Yonsei Univ.) Real-time Nozzle Gap Feedback Control based on Depth Sensor

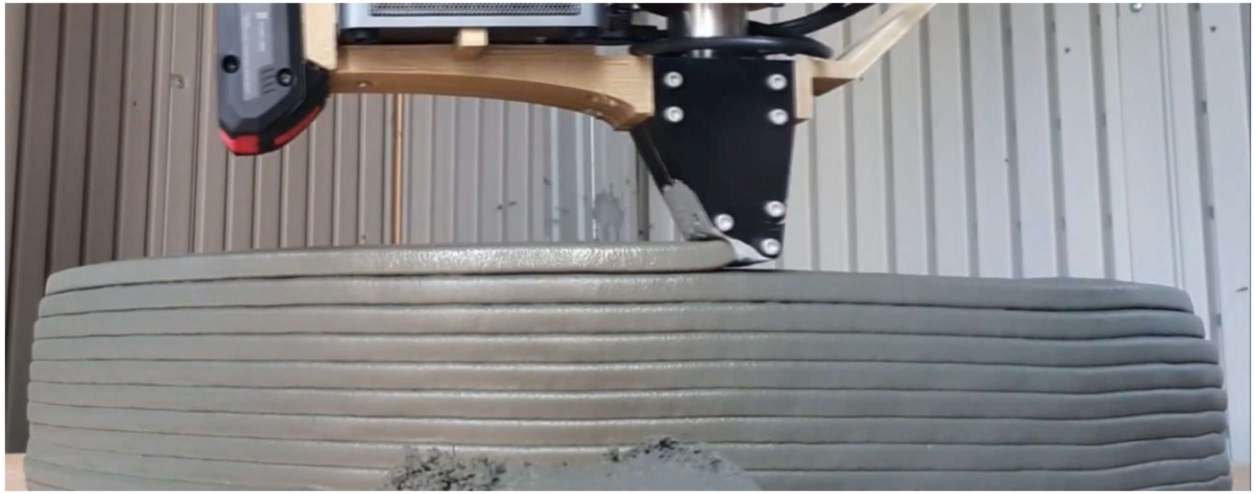


▪ Without feedback control



▪ With feedback control

• Conventional Position based Control



• Feedback of height information

J.W. Lee and J. H. Kim, " Real-Time Monitoring and Quality Control of 3D Concrete Printing Process using Depth Sensor",KSCE 2020 Convention.

In-Situ Quality Monitoring System for Extruded Filament of 3DCP

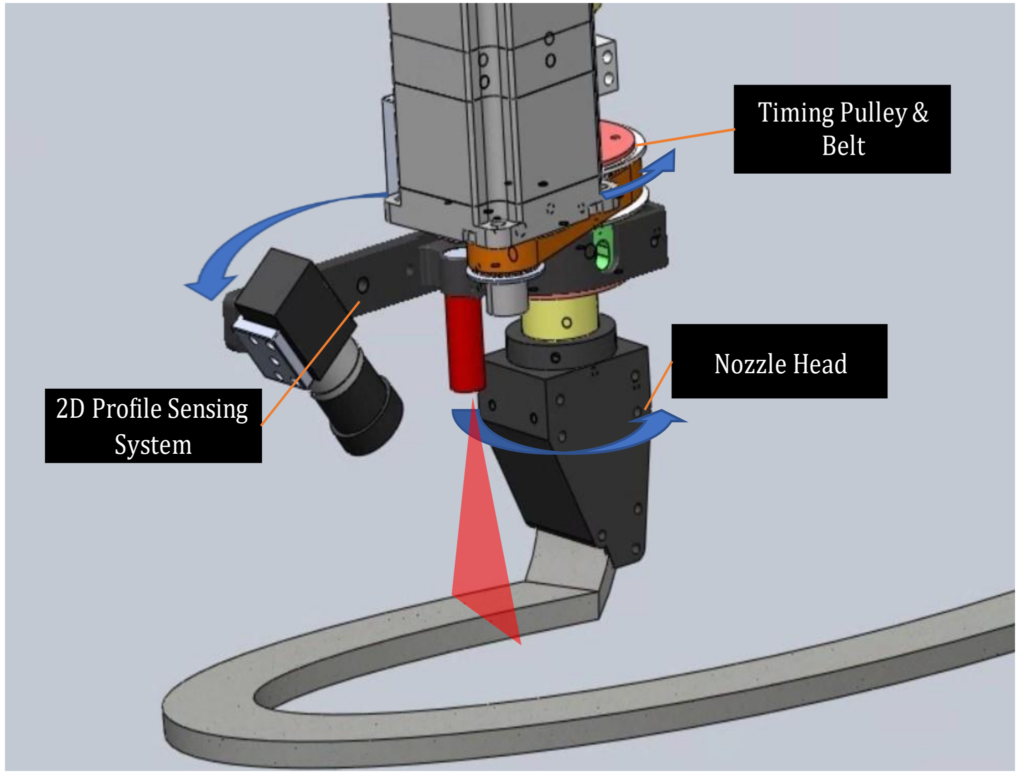
- Low Cost vs $8,000 USD
- Customized for compact volume & light weight
- Curved Path Monitoring

Acquisition of Video

Image Processing

Realtime Calculation of Cross section area, width, height

The Advantages of Developed 2D Laser Profile Sensing System



- **Cost-effective** and **Precise**
- Capable of measuring not only **width** but **height and cross-sectional area** of extruded concrete layer
- **Real-time** processing algorithm
- Nondistructive **In-line quality monitoring** can save time, material waste and cost
- Due to **Infinitely Rotatable Nozzle**, it is applicable to profile detection system in both linear and **rotational printing path**
- This study proposes the **real-time area detection processing algorithm**

02

Modeling of 2D Profile Sensing System and its Calibration

- Basics on Perspective Transformation
- Design of 2D Profile Sensing System

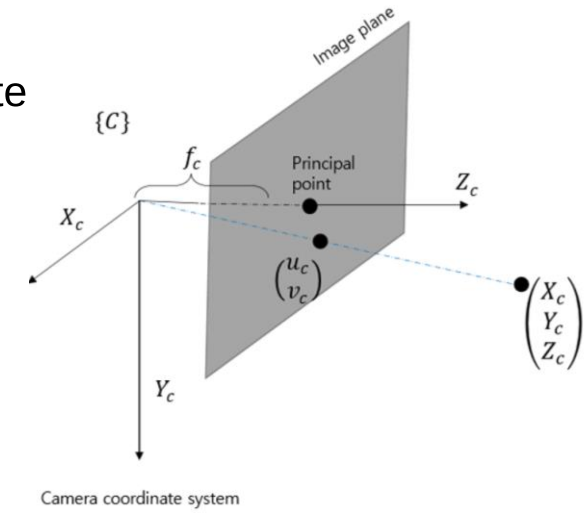
- Representation of (x,y) using (u,v) and *calibration parameter*
- Calibration result of a 2D Profile Sensing System

Perspective Transformation

The relationship between 2D images and 3D space.

1. Relationship between image plane and camera coordinate

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}f_x & 0 & c_x & 0\\0 & f_y & c_y & 0\\0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}X_C\\Y_C\\Z_C\\1\end{bmatrix} \qquad (1)$$



2. Relationship between {C} and {W}

$$\begin{bmatrix}X_c\\Y_c\\Z_c\end{bmatrix}=\begin{bmatrix}r_{11} & r_{12} & r_{13}\\r_{21} & r_{22} & r_{23}\\r_{31} & r_{32} & r_{33}\\0 & 0 & 0\end{bmatrix}\begin{bmatrix}t_1\\t_2\\t_3\\1\end{bmatrix}\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix} \quad (Z_w=0) \qquad (2)$$

Rotation matrix   Translation matrix

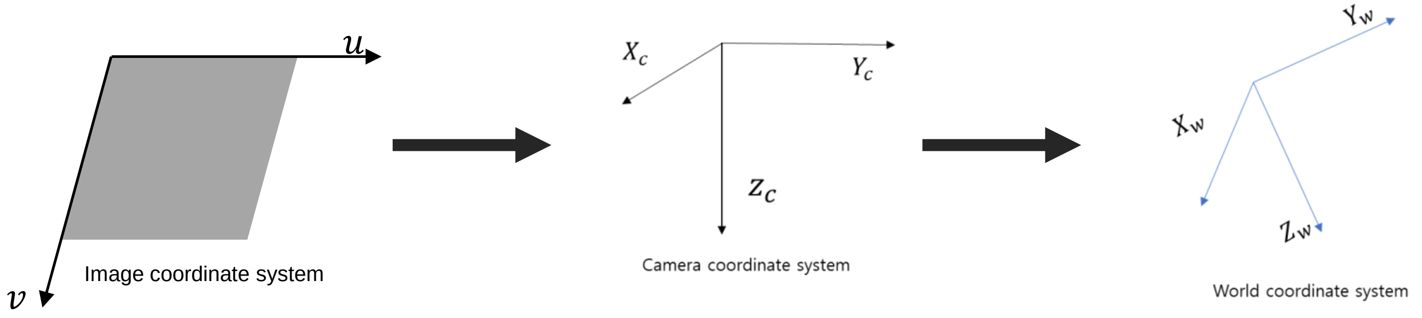
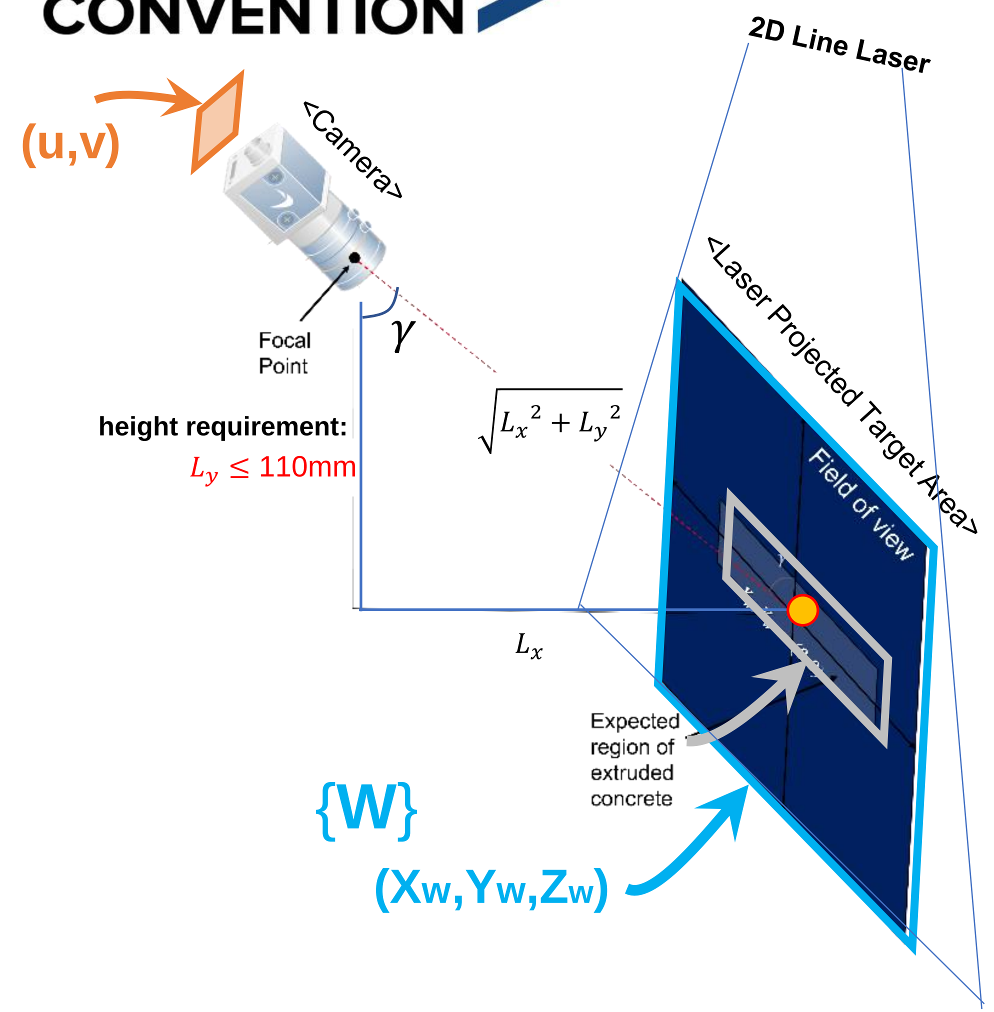


Image coords → Camera coords → World coords

Design of 2D Profile Sensing System



Relationship between (u,v) and {W} on the 2D laser plane was calculated using triangulation method.

$$s\begin{bmatrix}u\\v\\1\end{bmatrix} = \begin{bmatrix}f_x & 0 & c_x & 0\\0 & f_y & c_y & 0\\0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}r_{11} & r_{12} & r_{13} & t_1\\r_{21} & r_{22} & r_{23} & t_2\\r_{31} & r_{32} & r_{33} & t_3\\0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix} \quad (3)$$

Camera Intrinsic — Camera Extrinsic

$(Z_w = 0)$

Constraint: Height requirement $\boldsymbol{L_y} \leq$ **110mm**

- Unknown variables : $\boldsymbol{\gamma}$, $\boldsymbol{f}$
  $here, L_x$ is not independent parameter
- Known variables : c_x, c_y, L_y

[Design Problem]
→ By the suitable **choice of γ and f**,
we can satisfy the given requirement of FOV(Field of View)

Perspective Transformation

$$s\begin{bmatrix}u\\v\\1\end{bmatrix} = \begin{bmatrix}f_x & 0 & c_x & 0\\0 & f_y & c_y & 0\\0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}r_{11} & r_{12} & r_{13} & t_1\\r_{21} & r_{22} & r_{23} & t_2\\r_{31} & r_{32} & r_{33} & t_3\\0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}X_W\\Y_W\\Z_W\\1\end{bmatrix}. \quad (3)$$

Camera Intrinsic — Camera Extrinsic

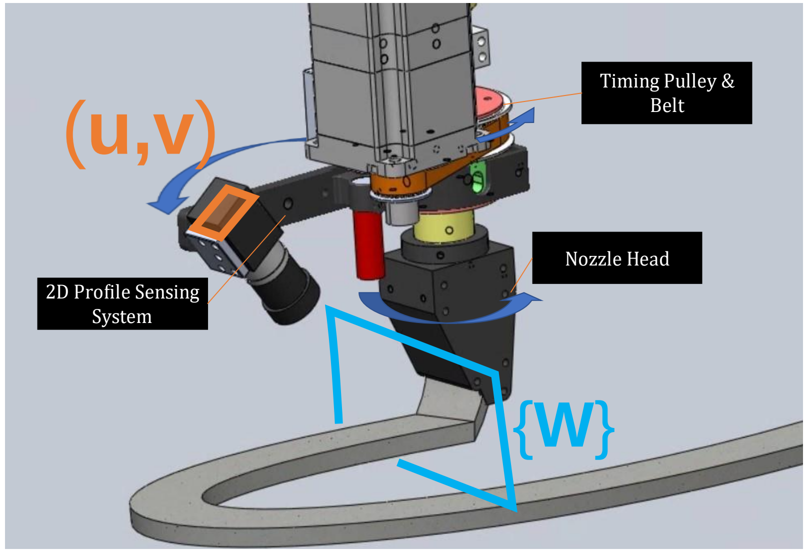
$$s\begin{bmatrix}u\\v\\1\end{bmatrix} = \begin{bmatrix}h_{11} & h_{12} & h_{13}\\h_{21} & h_{22} & h_{23}\\h_{31} & h_{32} & h_{33}\end{bmatrix}\begin{bmatrix}X_W\\Y_W\\1\end{bmatrix} \quad (4)$$

h parameter

$$su_i = (h_{11}X_i + h_{12}Y_i + h_{13}) \quad (5)$$

$$sv_i = (h_{21}X_i + h_{22}Y_i + h_{23}) \quad (6)$$

$$s = h_{31}X_i + h_{32}Y_i + \boldsymbol{h_{33}} \quad (7)$$



it can be expressed as a simpler relationship:

$$s\begin{bmatrix}u\\v\\1\end{bmatrix} = \begin{bmatrix}h_{11} & h_{12} & h_{13}\\h_{21} & h_{22} & h_{23}\\h_{31} & h_{32} & 1\end{bmatrix}\begin{bmatrix}X_W\\Y_W\\1\end{bmatrix}. \quad (8)$$

$$u_i = \frac{h_{11}X_i + h_{12}Y_i + h_{13}}{h_{31}X_i + h_{32}Y_i + 1} \qquad v_i = \frac{h_{21}X_i + h_{22}Y_i + h_{23}}{h_{31}X_i + h_{32}Y_i + 1}$$

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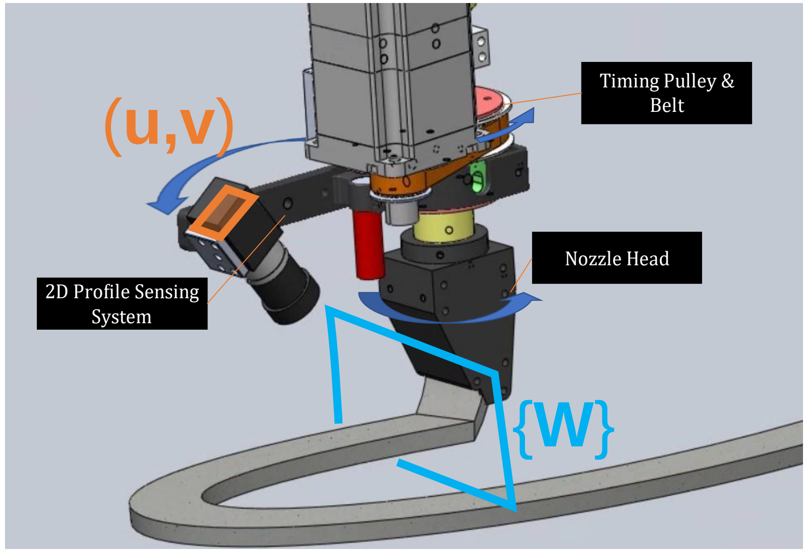
Representation of (x,y) with (u,v) and *h*



Calibration : The process to obtain unknown camera parameters (*h* matrix)

These unknown calibration parameters can be determined from *n*-pairs of datasets on the point (u_i, v_i) and the point (X_i, Y_i)

- Rearranging *h* after expanding (8) gives the following (10):

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -u_1x_1 & -u_1y_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -v_1x_1 & -v_1y_1 \\ & & & & \vdots & & & \\ x_4 & y_4 & 1 & 0 & 0 & 0 & -u_4x_4 & -u_4y_4 \\ 0 & 0 & 0 & x_4 & y_4 & 1 & -v_4x_4 & -v_4y_4 \\ & & & & \vdots & & & \\ x_i & y_i & 1 & 0 & 0 & 0 & -u_ix_i & -u_iy_i \\ 0 & 0 & 0 & x_i & y_i & 1 & -v_ix_i & -v_iy_i \\ x_n & y_n & 1 & 0 & 0 & 0 & -u_nx_n & -u_ny_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -v_nx_n & -v_ny_n \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \end{bmatrix}}_{h} = \underbrace{\begin{bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ \vdots \\ u_4 \\ v_4 \\ \vdots \\ u_i \\ v_i \\ u_n \\ v_n \end{bmatrix}}_{B} \quad (9)$$

$h = (A^T \cdot A)^{-1} A^T b$ **: calibration parameters**

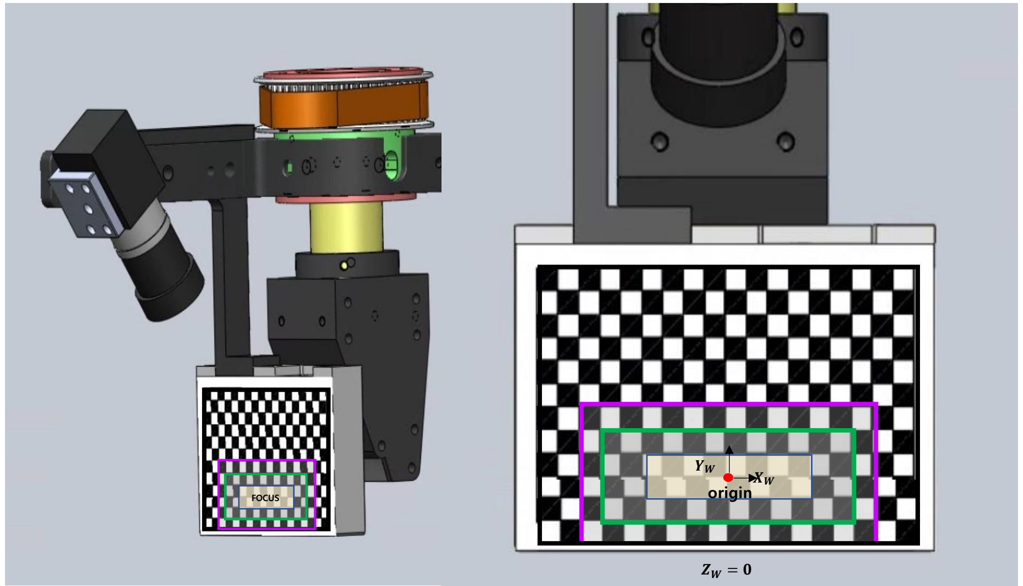
{W} (u,v)

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} uh_{31} - h_{11} & uh_{32} - h_{12} \\ vh_{31} - h_{21} & vh_{32} - h_{22} \end{bmatrix}^{-1} \begin{pmatrix} h_{13} - u \\ h_{23} - v \end{pmatrix} \quad (10)$$

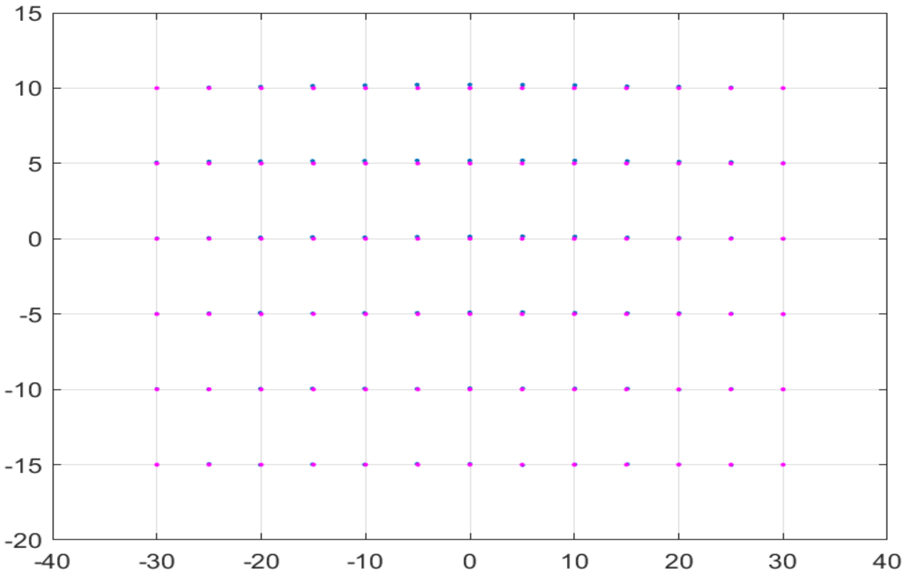
∴The equation (10) shows that the actual dimension of concrete layer can be acquired by using its image

Calibration of 2D Profile Sensing System

1. The checker board image is acquired by the camera of our sensor.
2. *h* parameter is obtained using 78 pair of pixel points of checkerboard image
3. Using the *h* parameter, the pixel coordinate (image coordinate) is transformed into world coordinate



FOV (field of view) : 70mm×30mm (W x H)



Calibration result

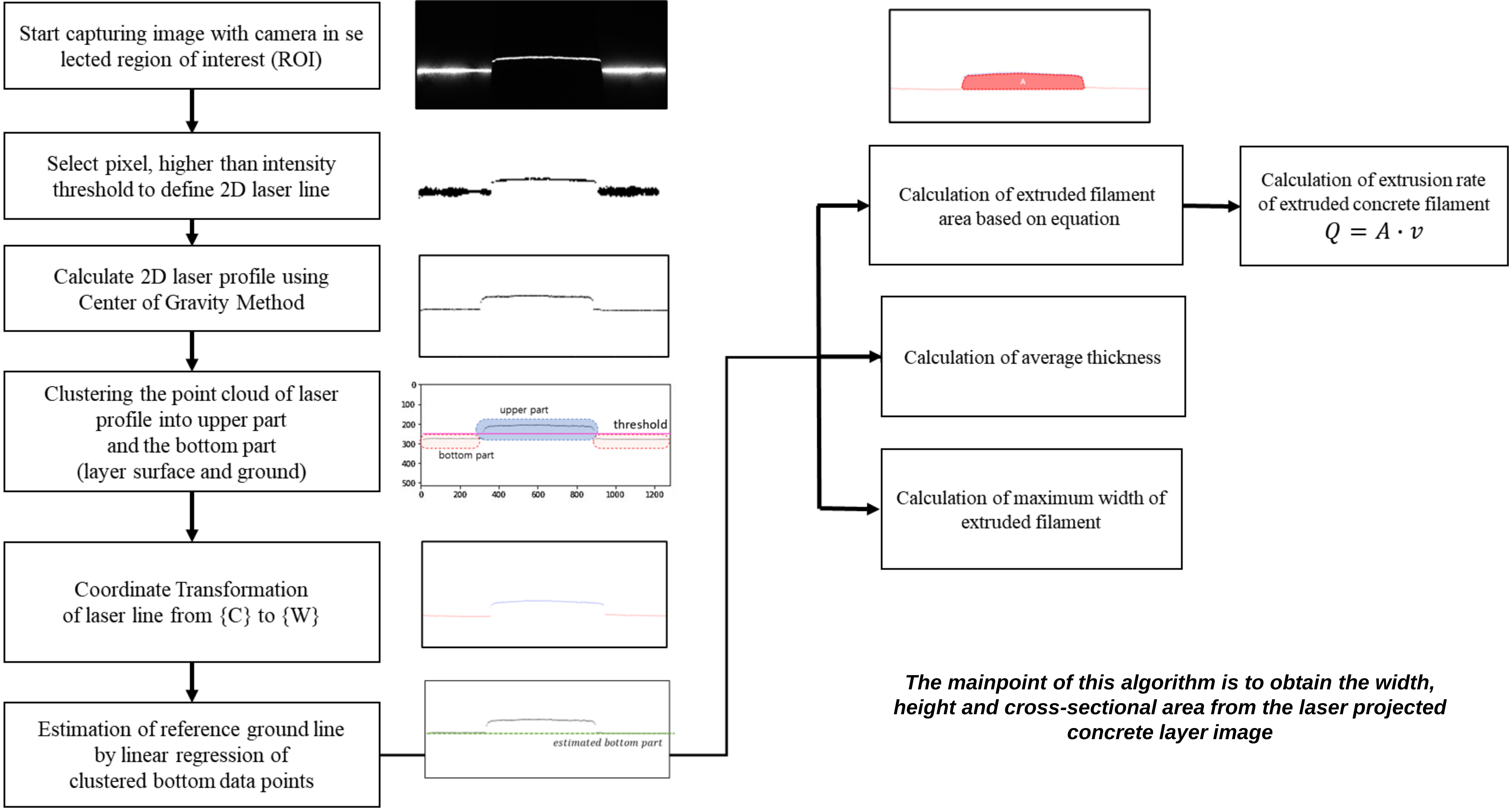
Accuracy : 0.087mm with std of 0.044mm

The calibration box was designed regarding the FOV (field of view) of camera and the position where the concrete layer is extruded in the FOV (purple : field of view, solid yellow : position where the concrete will be extruded)

03

Processing Algorithm to Compute the 2D Profile of Extruded Concrete Filament

03



The mainpoint of this algorithm is to obtain the width, height and cross-sectional area from the laser projected concrete layer image

Flow chart of real-time process monitoring system to acquire 2D profile of extruded concrete layer

(1) Image Segmentation: Thresholding

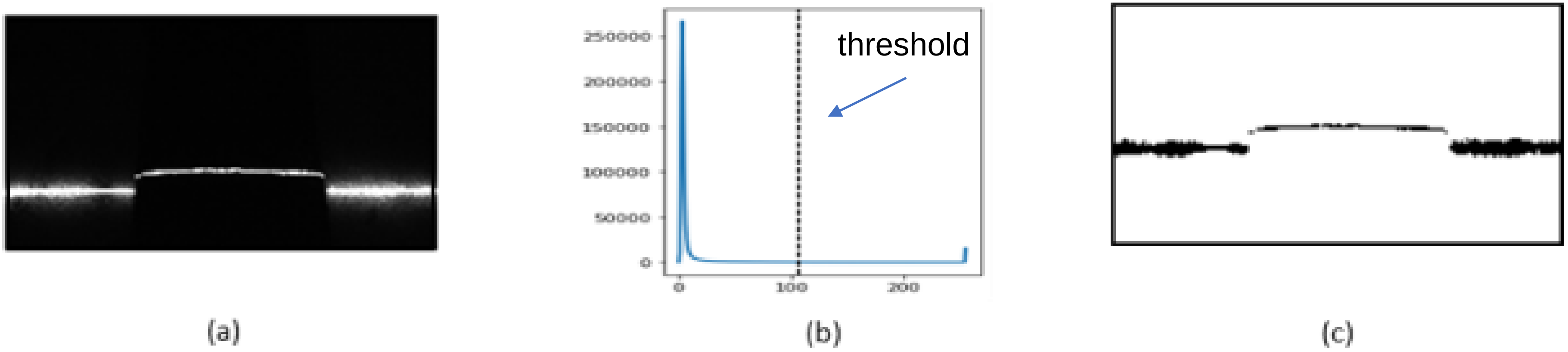
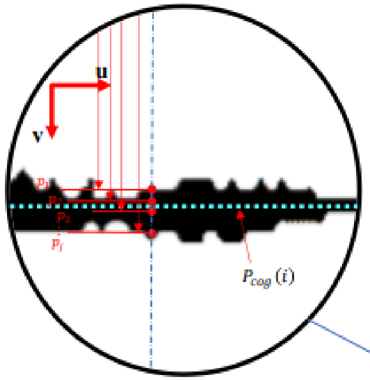


Figure 4-2 Otsu's threshold algorithm for image segmentation, defining laser line

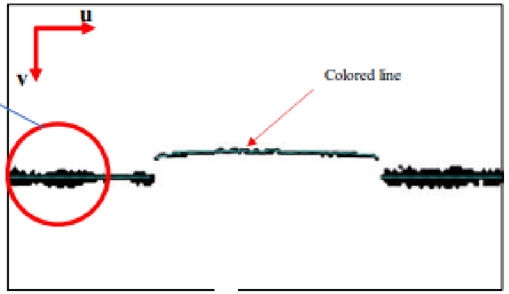
(a) Using the camera of developed sensor, the image is acquired within **ROI**(region of interest), and it is converted into **greyscale**.
(b) **Find an optimal threshold** based on intensity distribution of pixel values in the image by using Otsu's threshold.
(c) The image is **binarized** using thresholding algorithm and the laser line is segmented (Laser line point cloud).

CHAPTER 3. Processing Algorithm

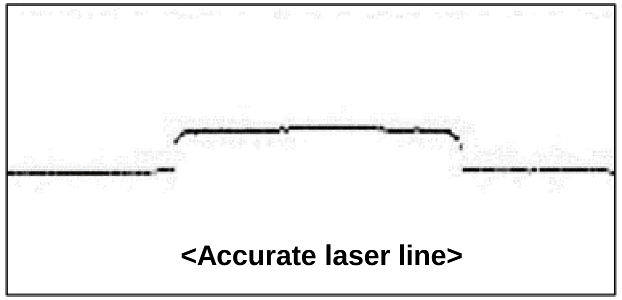
(2) Extraction of Laser Profile using Center of Gravity Method



<Laser line point cloud>



Segmented pixel point cloud



Accurate Laser line after applying CoG

- CoG method:

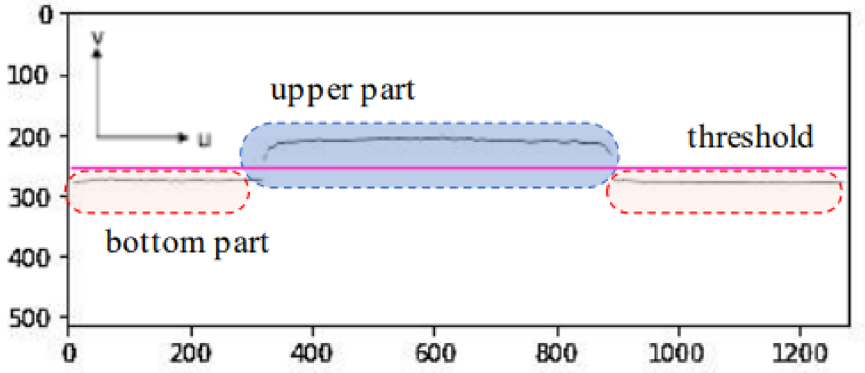
$$\text{Laser Position} \quad P_{cog}(i) = \frac{\sum_{j=1}^{N} I_i(p_j) \cdot p_j}{\sum_{j=1}^{N} I_i(p_j)}$$

$$\text{But if } I_i(p_j) < \text{Threshold } I_i(p_j) = 0$$

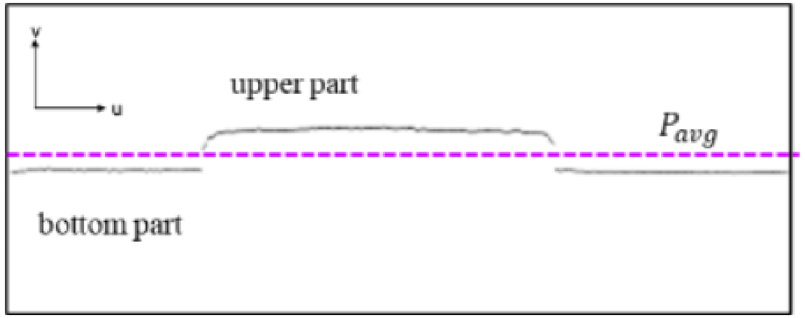
Here, pi : position of the line laser pixel
$I(pi)$: intensity value of a laser position pi

CHAPTER 3. Processing Algorithm

(3) Separation of Laser Profile using Clustering Method



(a) Separation (k-nearest clustering method)



(b) Separation (average position value method)

The separation of the laser profile is necessary for the next step to define the surface and ground. (upper part : layer surface, bottom part : ground)

1. The defined laser line is separated into the upper part and bottom part using the **k-nearest clustering method** (KNN)

2. However for a **faster processing speed**, we used the average position value method instead.

* **Average position value of laser line**:

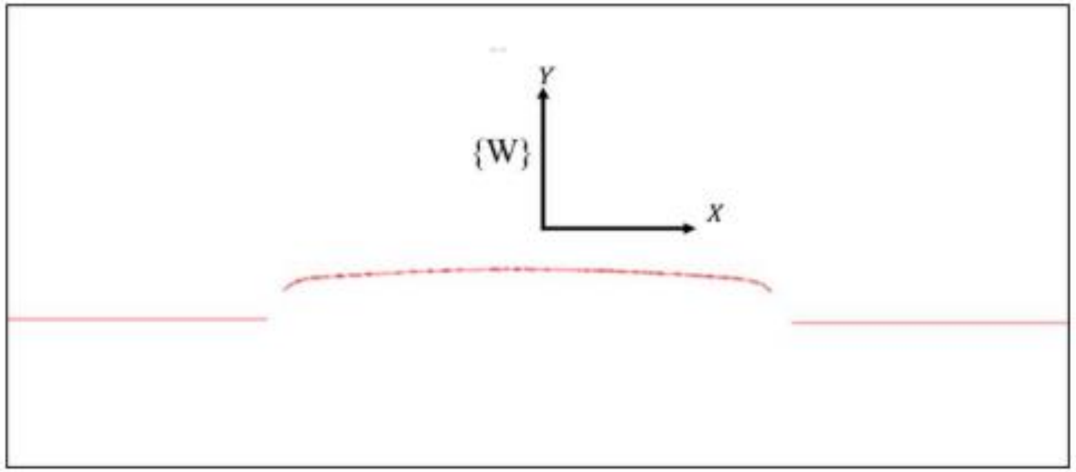
$$P_{avg} = \frac{\sum_{i=0}^{K-1} P_{cog}(K)}{K}$$

(4) Coordinate Transformation from {C} to {W}

The defined laser position in camera coordinate(ui , vi) → points in world coordinates (Xi , Yi)

{W} (u,v)

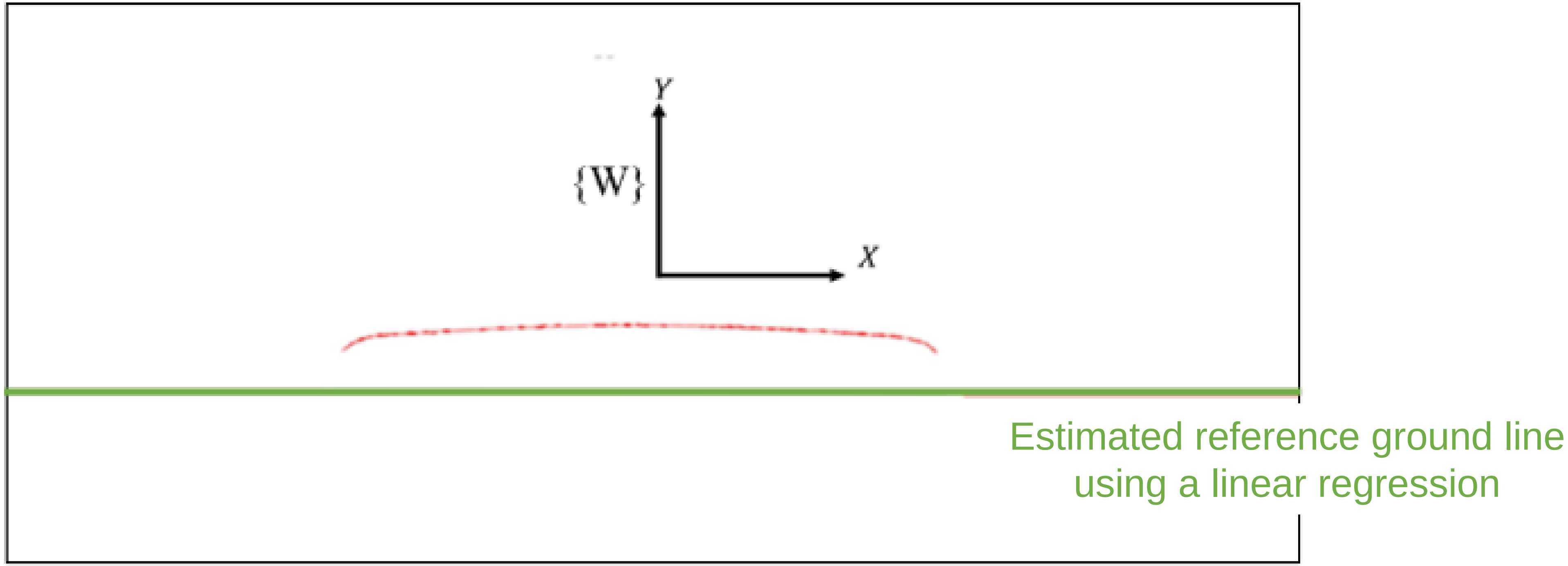
$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} uh_{31} - h_{11} & uh_{32} - h_{12} \\ vh_{31} - h_{21} & vh_{32} - h_{22} \end{bmatrix}^{-1} \begin{pmatrix} h_{13} - u \\ h_{23} - v \end{pmatrix} \quad (10)$$



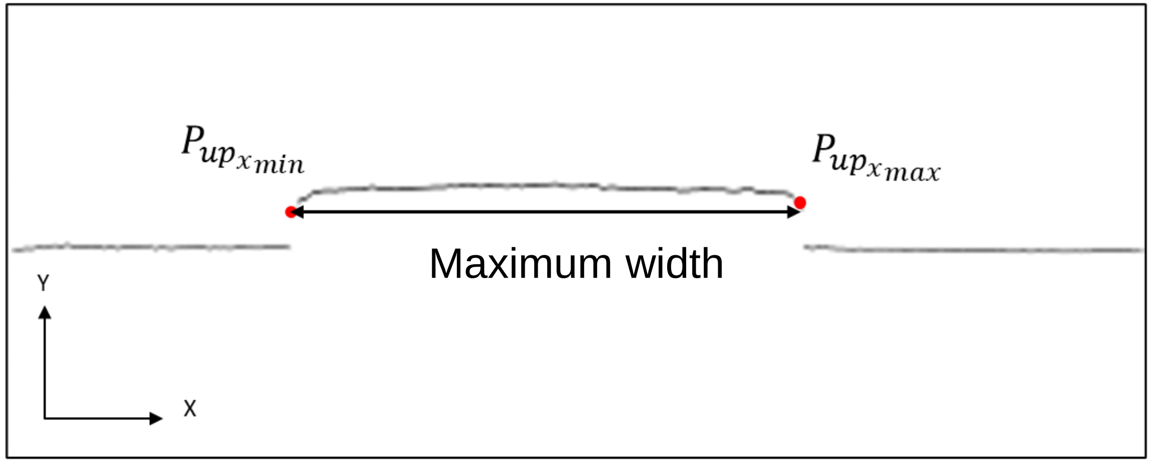
2D laser profile in world coordinates

(5) Estimation of Reference Ground Line by Linear Regression

For the calculation of the width and cross-sectional area measurement, a best fitting line was estimated by using 1D linear regression.

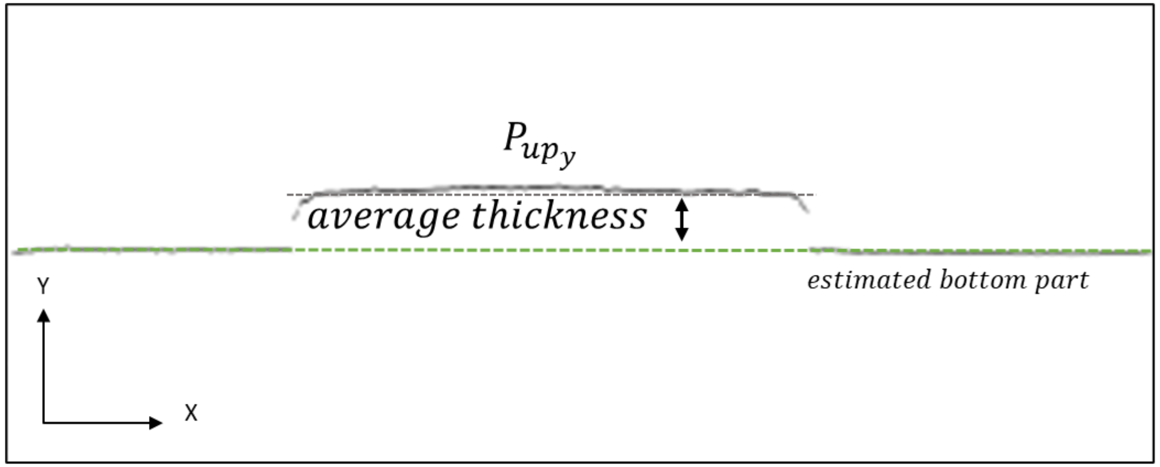


(6) Calculation of 2D Profile (width, thickness)



Width of upper profile $= P_{up_{x_{max}}} - P_{up_{x_{min}}}$

(Subtraction of the pixel of each end of the upper part)

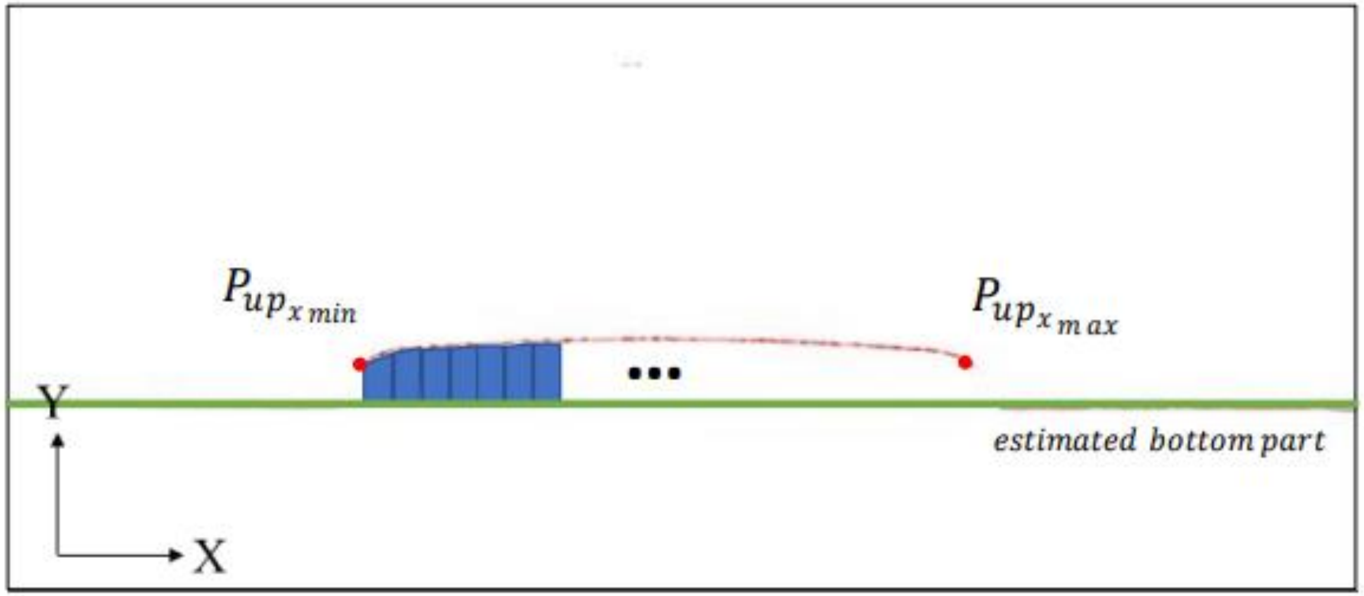


$$\text{Average thickness} = \sum_{i=0}^{m-1} \frac{P_{up_{y_i}} - P_{bot_{y_i}}}{m}$$

P_{up_y} : y coordinate of upper part laser line

P_{bot_y}: y coordinate of bottom part laser line redefined by 1 D linear regression

(6) Calculation of 2D Profile (cross-sectional area)



- Cross-sectional area (trapezoid rule)

$$A = \sum_{i=0}^{m-2} (x_{i+1} - x_i) \frac{h(x_i) + h(x_{i+1})}{2}$$

- Extrusion rate

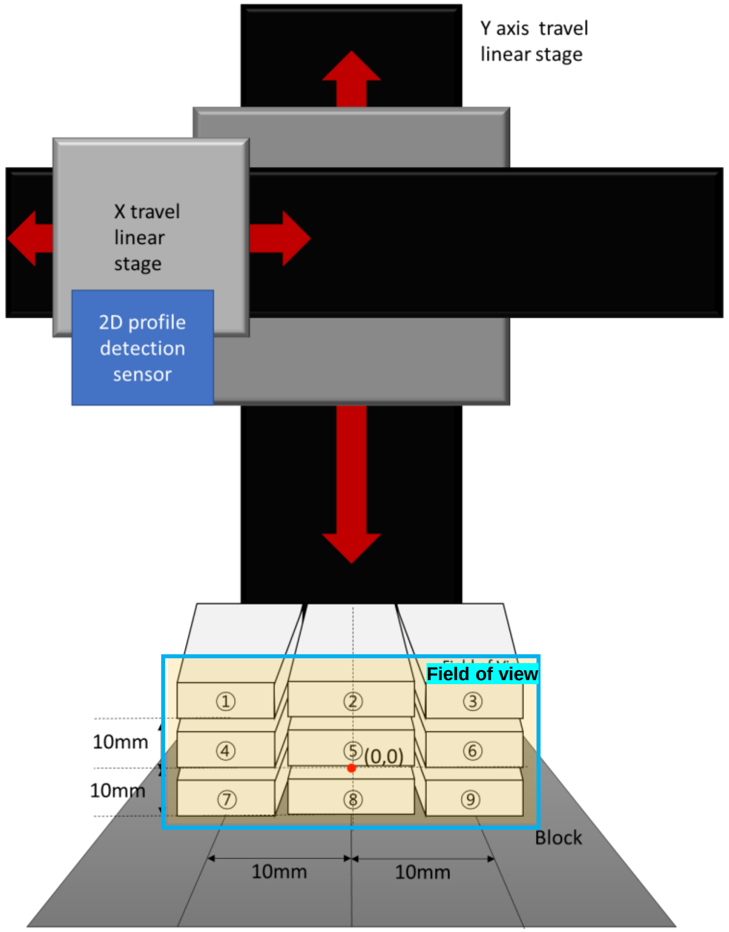
$$Q_{measured} = A \cdot v$$

04

Performance Test of Developed Sensing System

- **Performance Test under Static Condition**
- **Performance Test under Active Condition**
- **Performance Test during 3D Concrete Printing**

Performance Test under Static Condition



- **Static** condition: By incrementally shifting the scan position 10mm using the two-axis linear stage, the object's 2D profile was acquired.(position : ①~⑨)

TABLE 1. 2D profile measurement under static conditions. Block dimensions: 40 mm, 10 mm (width, height).

	Average	Standard deviation	Mean absolute error
Area [mm^2]	402.50	2.30	2.18
Thickness [mm]	10.07	0.05	0.07
Width [mm]	39.99	0.08	0.05

- In actual 3DCP experiments, the **vibration** of the robotic arm will cause the concrete filament to be detected at different positions within the camera's field of view (FOV).

Experimental Set Up for Static Test

CONCRETE CONVENTION

Performance Test Under Active Condition

Experiment video for Active Test

TABLE 2. Comparison of measured errors for active condition and static condition

	average error of measurement (Active): A	average error of measurement (Static): S	A/S
Area [mm2]	1.64	0.54	3.04
Average thickness [mm]	1.73	0.18	9.61
Width[mm]	1.13	0.48	2.35

Error under motion > error under **static** condition

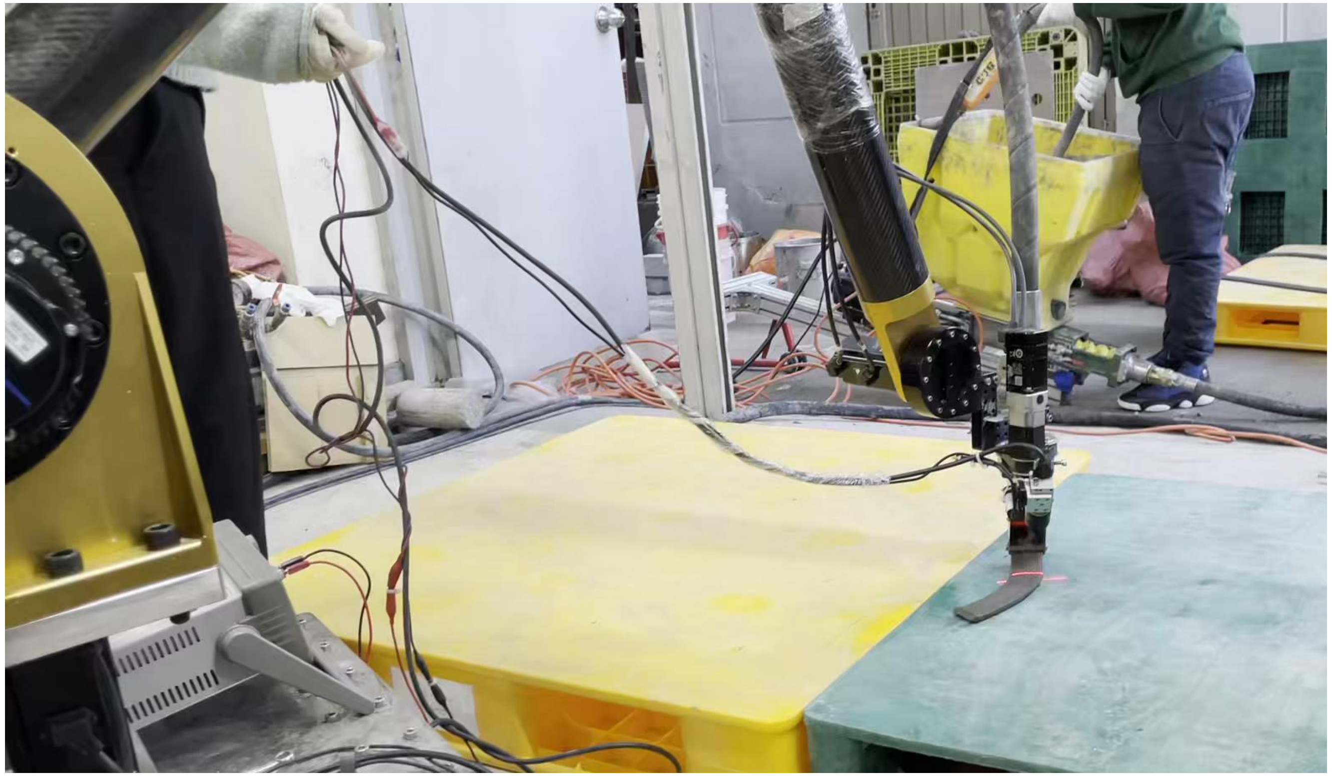
(the movement of the robotic arm moving along the uneven ground might have caused an error.)

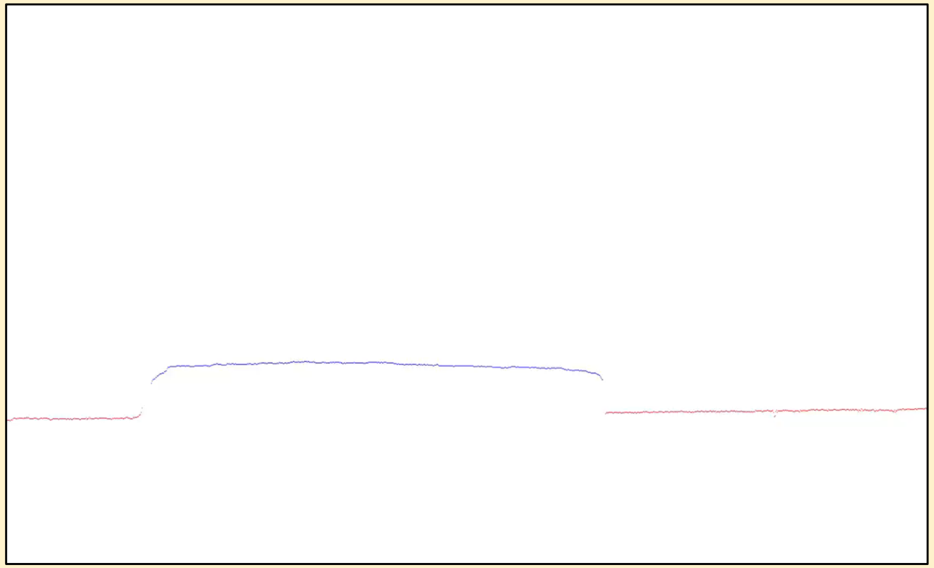
Robotic arm concrete printer was used for the test.

2D profile sensing system was attached to the end effector of robotic arm and it detects the 2D profile of plywood bars with printing speed of 1200mm/min

CHAPTER 4. Performance Test of 2D Laser Profile Sensing System

Performance Test during 3D Concrete Printing





Visualization of 2D profile of concrete layer during 3D concrete printing

(Blue : layer surface , Red : ground)

Performance test video with visualization of 2D Profile of concrete layer

As the robotic arm concrete printer extrudes the layer, the sensor detects its 2D profile

Performance Test during 3D Concrete Printing

Printing Result

Figure 5-13 Shape of extruded concrete filament after printing

Printing path (including linear and curved path)

- Total length : 2656.64mm
- Velocity : 20mm/sec
- Total duration : 132.832sec (2min 21sec)

05

Conclusion

- Contribution
- Future Avenue
- References

CHAPTER 5. Conclusion

Contribution

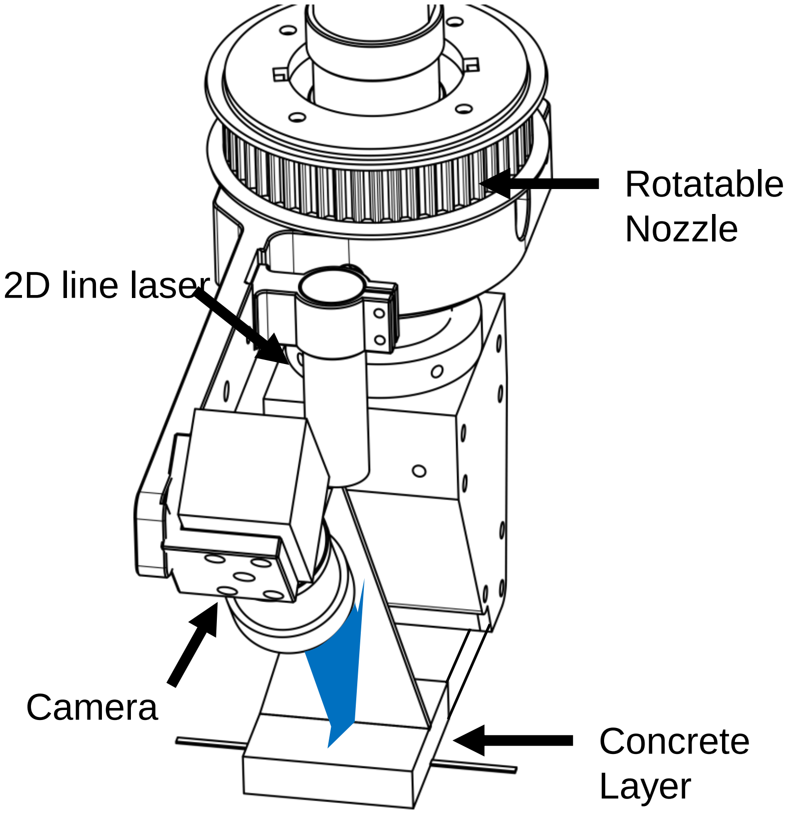
1. Developed for a **low-cost, customized** 2D profile detection sensor considering the camera's FOV, and installation area of concrete printer.

2. This study first suggests **real-time processing algorithm** to automatically measure the cross-sectional area of extruded concrete layer

3. This study suggests the sensing system that can measure the 2D profile and cross-sectional area **along both rotational and linear printing paths.**

4. This study provides **accurate** sensing system for 2D profile detection of extruded concrete during static, motion and concrete printing experiments

→ Measurement error : **0.54** mm^2, **0.18 mm, 0.48 mm** (area, thickness, width)



Future Avenue

Quality Monitoring (Concrete Layer Shape Detection)

The developed sensing system has high accuracy in detecting 2D profile and cross-sectional area of extruded concrete layer

Quality Monitoring and Control (Concrete Layer Shape Extrusion)

It can be used to regulate the command flow rate ($Q = A \cdot v$) by applying closed-loop feedback of extrusion rate based on the 2D profile sensing system.

Monitoring of Concrete Quality + Inline Material assessment by Concrete Layer Shape Detection

This study can be expanded as a material assessment method by using the relationship between the w/c ratio and the slumped shape. Therefore, it can monitor the concrete quality in both geometrical and material aspects

Thank you!

Q & A

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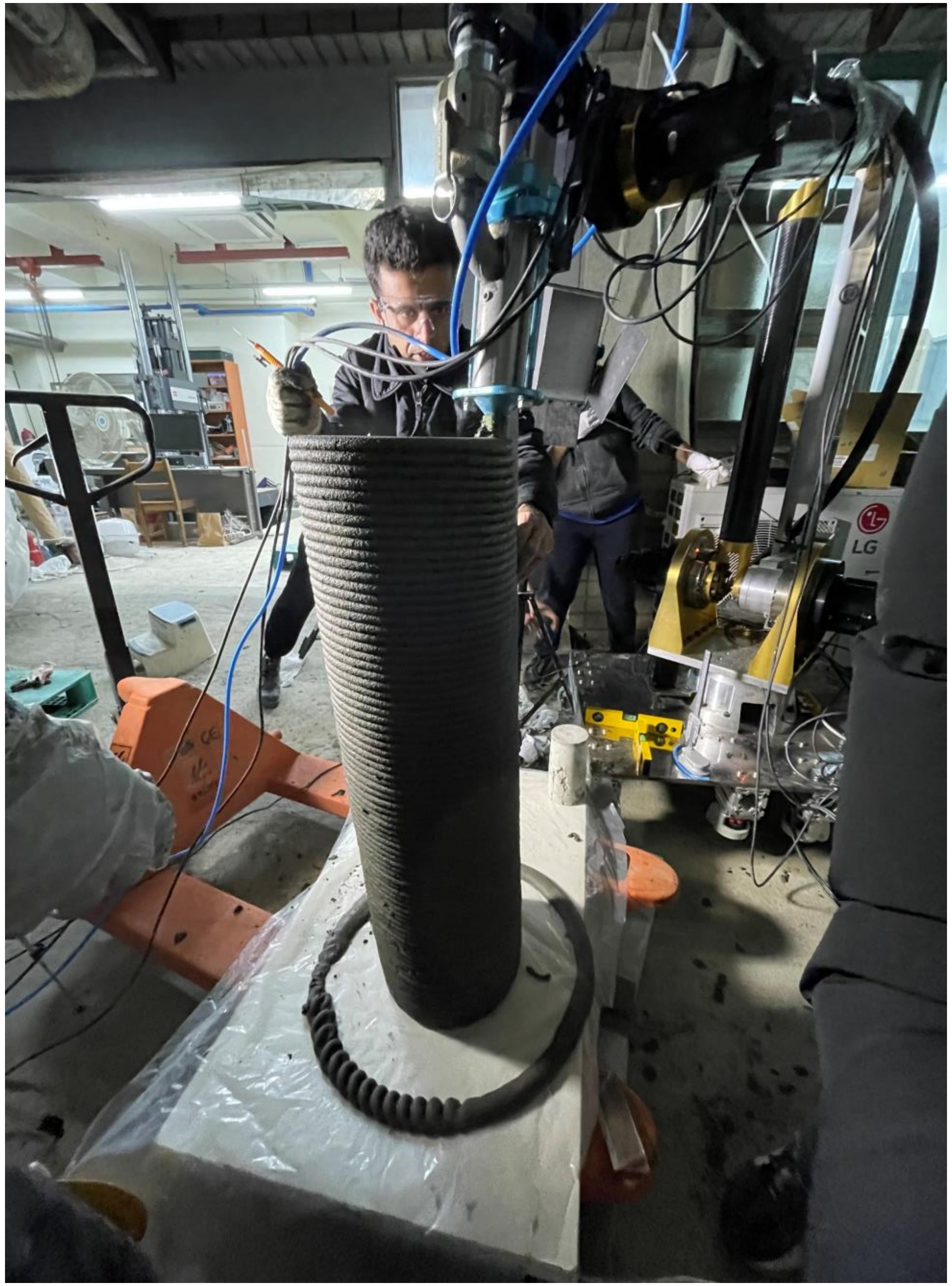
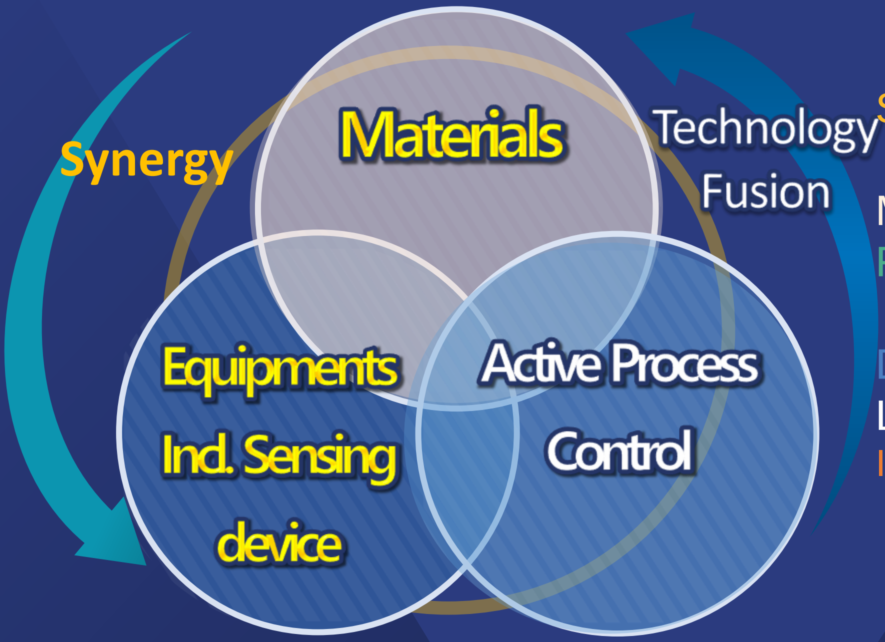
YONSEI UNIVERSITY
CONSTRUCTION ROBOT
& AUTOMATION LAB



Digital construction

Digital design process + Digital fabrication process

- Mechanization
- Automation
- Management



Simulation

Mechanization
Feedback

Digital Data
Learning
Intelligent Construction Management

For successful commercialization and ultimate utilization of 3DCP in the construction industry, a multidimensional approach and synergistic integration in these three areas is essential.

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Effective geometric quality assurance for 3D Concrete Printing (3DCP) requires automated, real-time, cost-effective and non-destructive methods. In this regard, this study presents the working operation of a newly developed automated test for monitoring the width, thickness, and cross-sectional area of extruded filaments. The hardware of the quality monitoring system consists of a rotating nozzle and a laser triangulation-type 2D laser detection system, which consists of a 2D line laser and a CMOS camera. It is specifically designed for real-time use while considering the requirements for the camera's field of view (FOV), minimum object distance (MOD), physical dimensions and weight requirement suitable for the rotating nozzle. Unlike previous research, the rotatable nozzle attached to the 3D printer allows monitoring the extrusion for all directions along the printing path. The proposed processing algorithm to compute the profile information of extruded filament involves image segmentation, extraction, and clustering for laser profile, coordinate transformation, estimation of reference ground line, and calculation of the geometry of the filament. The basic performance test under static conditions shows a sufficient accuracy of 0.087mm in FOV, and the experimental results demonstrate the feasibility of the developed system for in-situ quality monitoring during the 3DCP process.