

# Digital Technologies in Structural Safety: Opportunities and Gaps Between AI and Engineering Practice

Ihsan E. Bal

*Patras, 02.03.2026*



## Outline

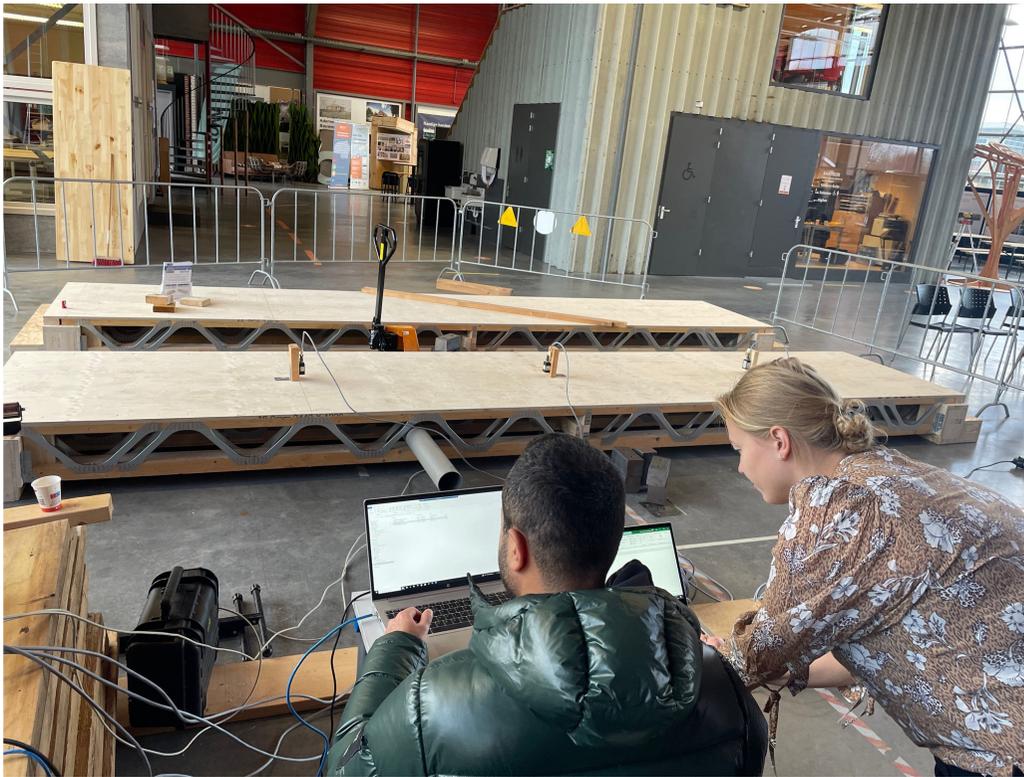
- Introduction
- AI-based crack detection – Use case of masonry surfaces
- Generation of 3D synthetic data
- 3D point cloud data – Use case of water defence dykes
- Future research

**Who am I / Who are we?**

# Hanze / BuildinG

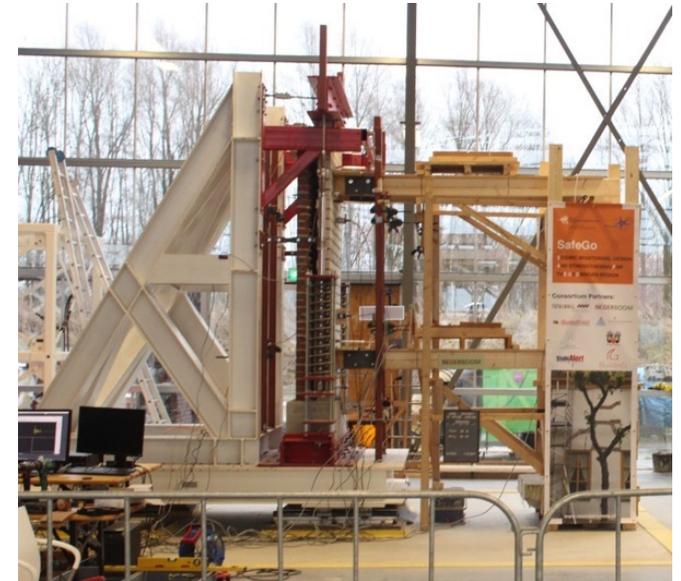
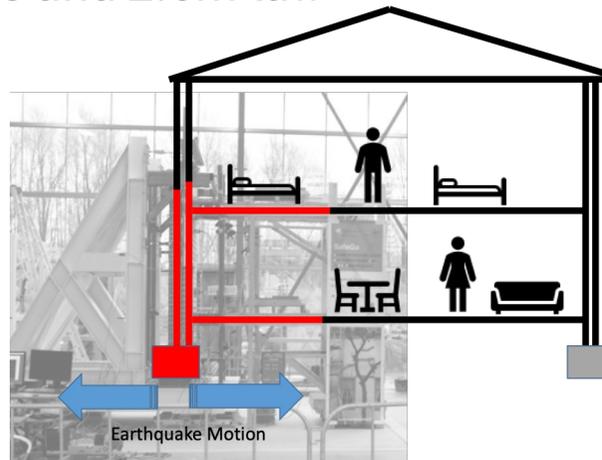


[www.building.nl](http://www.building.nl)



## An Example Project

- A typical 2-storey house is use for extracting a test specimen
- Specimen walls are 1.4m wide and 2.6m tall
- Two timber floors, sliding on the safety frame and loaded with mass, are attached to the walls in out-of-plane



- Arslan, O., Messali, F., Smyrou, E., Bal, I. E., & Rots, J. G. (2024). Characterisation of timber joists-masonry connections in double-leaf cavity walls – Part 2: Mechanical model. *Structures*, 68, 107165. <https://doi.org/10.1016/j.istruc.2024.107165>
- Arslan, O., Messali, F., Smyrou, E., Bal, I. E., & Rots, J. G. (2024). Characterisation of timber joists-masonry connections in double-leaf cavity walls – Part 1: Experimental results. *Structures*, 68, 107164. <https://doi.org/10.1016/j.istruc.2024.107164>
- Moshfeghi, A., Smyrou, E., Arslan, O., & Bal, I. E. (2024). Out-of-plane shake table tests on solid masonry walls with timber floors. *Structures*, 66, 106815. <https://doi.org/10.1016/j.istruc.2024.106815>



- Experiments on Groningen masonry

## **AI-based crack detection – Use case of masonry surfaces**



South façade

Cracks are dangerous. Yes, we know that.

But... There is a very big "BUT" !..

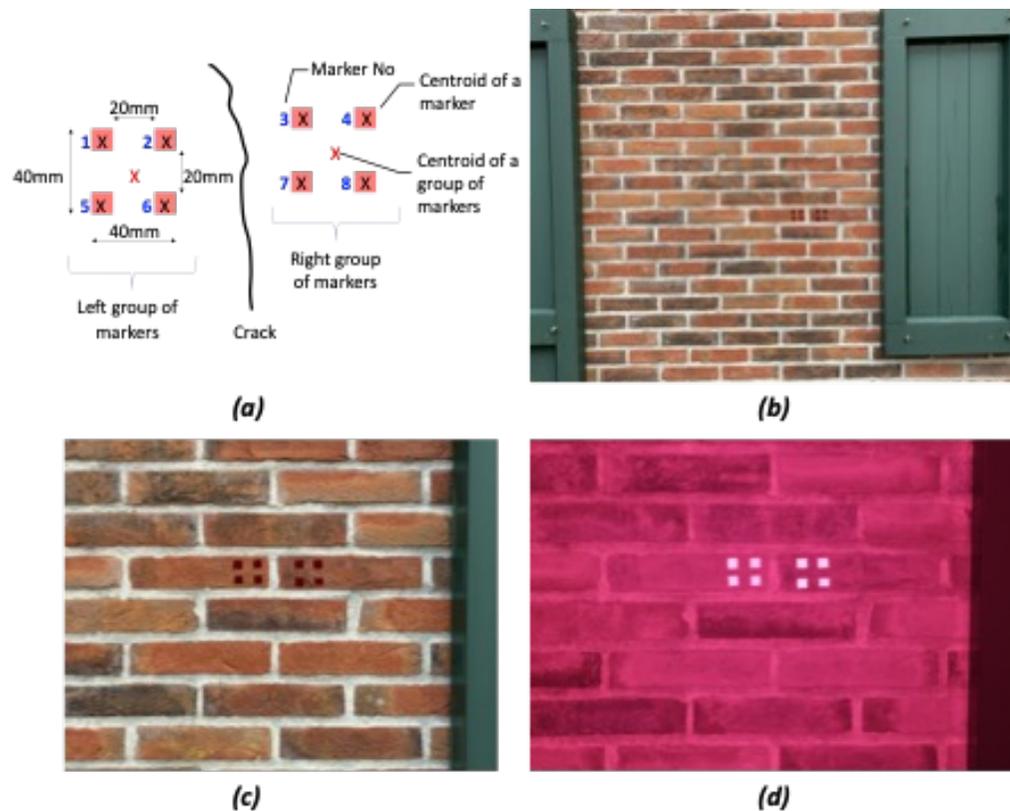
Not all cracks are dangerous, so who will decide what to do next, and how to do so?



## Monitoring cracks on masonry surfaces

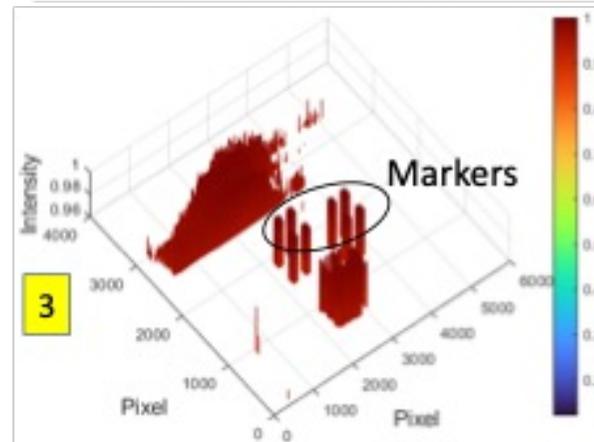
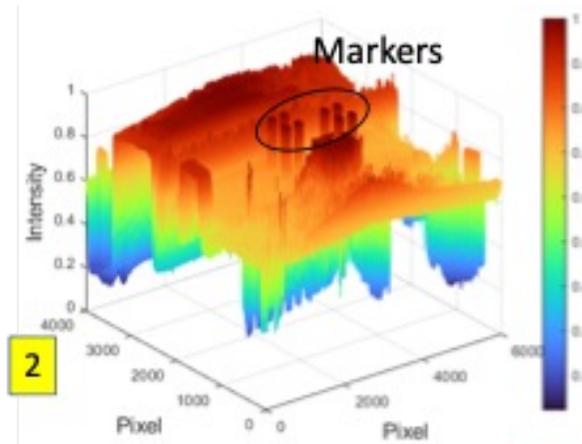
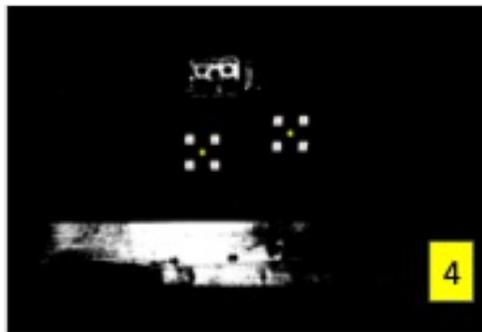
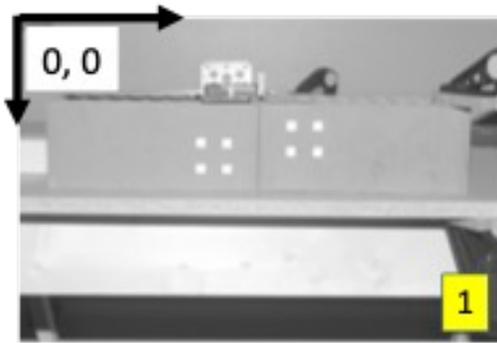
- As part of a project funded by the Dutch government, we started a project on how to monitor crack development on multiple objects more quickly and objectively
- Dimitrios Dais, University of Leeds / Hanze (2021) Monitoring, modelling and quantification of accumulation of damage on masonry structures due to recursive loads (V. Sarhosis, I.E. Bal & E. Smyrou)
- We focused on accumulation of damage on masonry, and objective monitoring of it.
  - *Sarhosis, V., Dais, D., Smyrou, E., Bal, I. E., & Drougkas, A. (2021) Quantification of damage evolution in masonry walls subjected to induced seismicity. Engineering Structures, 243, 112529. <https://doi.org/10.1016/j.engstruct.2021.112529>*
  - *Sarhosis, V., Dais, D., Smyrou, E., & Bal, I. E. (2019). Evaluation of modelling strategies for estimating cumulative damage on Groningen masonry buildings due to recursive induced earthquakes. Bulletin of Earthquake Engineering, 17(8), 4689–4710. <https://doi.org/10.1007/s10518-019-00628-5>*
  - *Dais, D., Bal, I. E., Smyrou, E., & Sarhosis, V. (2021). Automatic crack classification and segmentation on masonry surfaces using convolutional neural networks and transfer learning. Automation in Construction, 125, 103606. <https://doi.org/10.1016/j.autcon.2021.103606>*

## Use of invisible NIR markers



*Bal, I. E., Dais, D., Smyrou, E., & Sarhosis, V. (2021). Novel invisible markers for monitoring cracks on masonry structures. Construction and Building Materials, 299, 124013.*

## Use of invisible NIR markers



*Bal, I. E., Dais, D., Smyrou, E., & Sarhosis, V. (2021). Novel invisible markers for monitoring cracks on masonry structures. Construction and Building Materials, 299, 124013.*

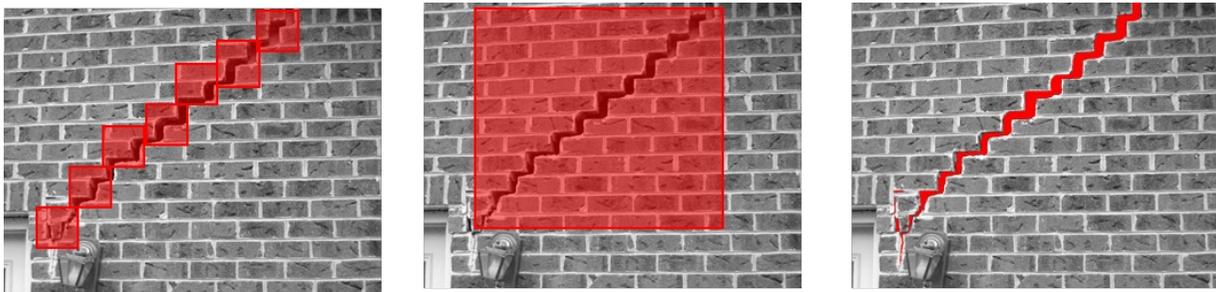
## Use of markers vs use of AI

- Markers are handy, but not easy to apply everywhere
- Maintenance of markers is an issue
- You need to know where the cracks will develop a priori
- Markers are good for crack width, but not for crack length
- They give discrete measurements at the location of application
- We need to capture the entire crack field

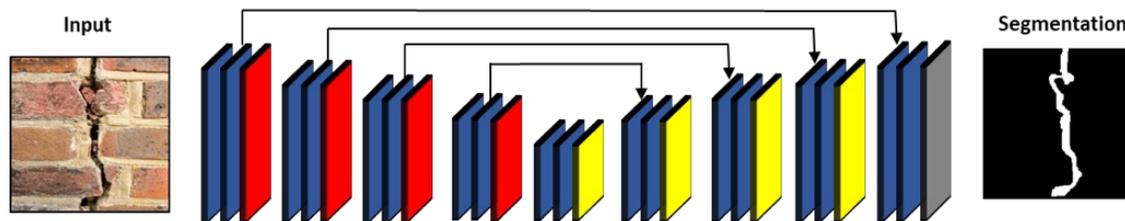
## Can AI Play a Major Role in Structural Defect Detection?

### Pixel-wise crack detection

- AI can detect cracks either by bounding boxes or by pixel-wise segmentation.
- Pixel-wise segmentation is preferred by engineers but is more challenging in data preparation and real-world deployment.
- In our work, we perform pixel-level segmentation, where each pixel is classified as crack or background.

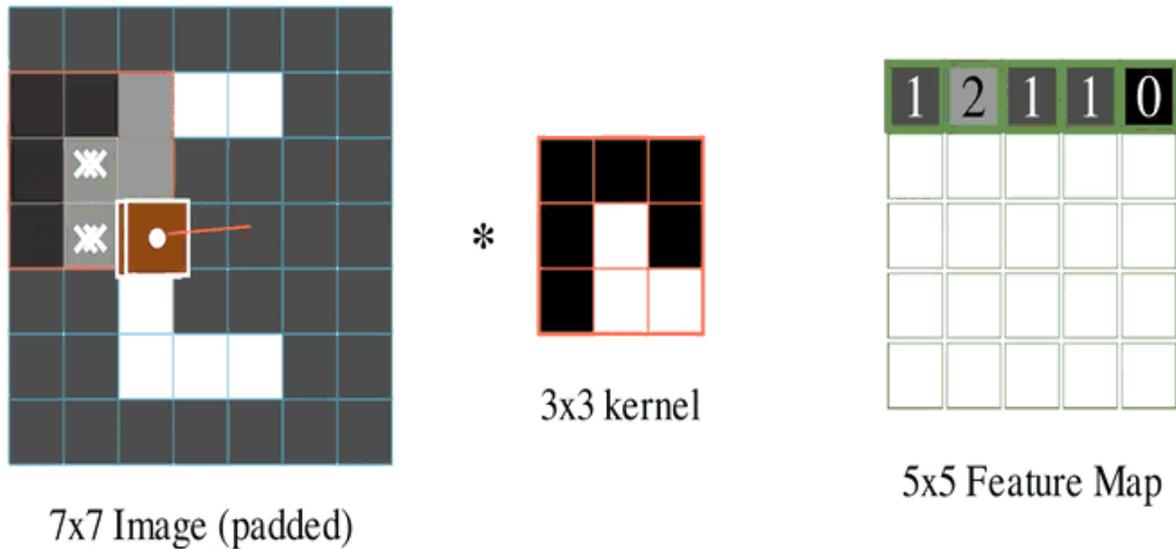


*Dais, D., Bal, I. E., Smyrou, E., & Sarhosis, V. (2021). Automatic crack classification and segmentation on masonry surfaces using convolutional neural networks and transfer learning. Automation in Construction, 125, 103606.*



## How CNNs work?

- CNNs were developed in the late 80s
- They were initially designed to recognize hand writing
- They are perfect for pixel-wise comparisons
- GPU-based calculations made it possible to create enough number of layers to detect more complex images than only letters and numbers

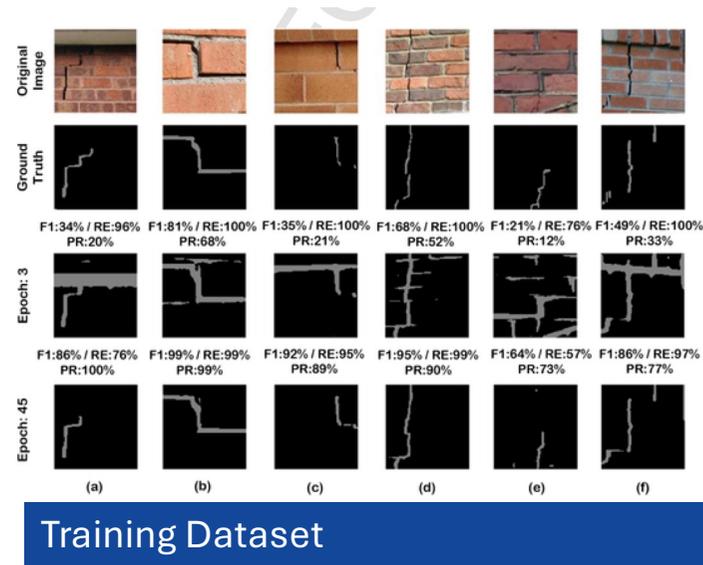


Source: [medium.com](https://medium.com)

# Can AI Play a Major Role in Structural Defect Detection?

Application to real-life problems

- Data needs to be prepared before training the model
- Unfortunately, the current models would give very poor results if trained with actual structural photos.
- This is reason why we pre-process the photos and make them "ideal" for training.



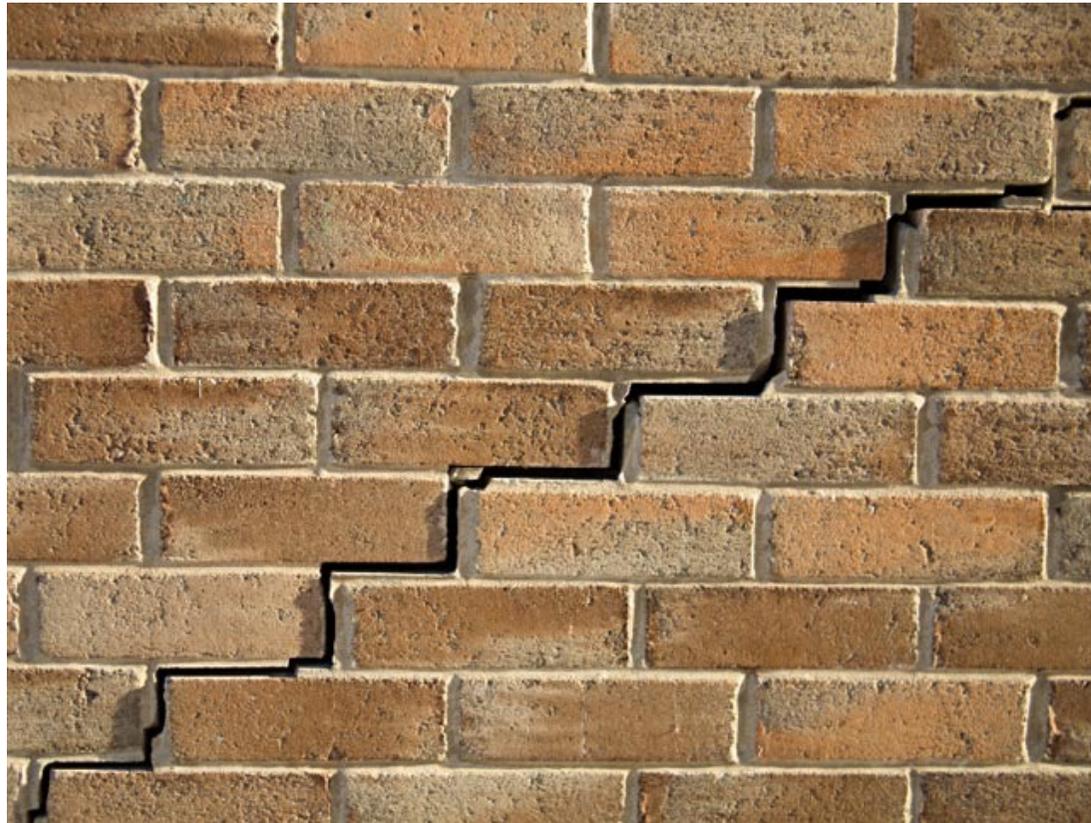
Koninklijke  
oosterhofholman

ARUP

# AI-based Crack Detection

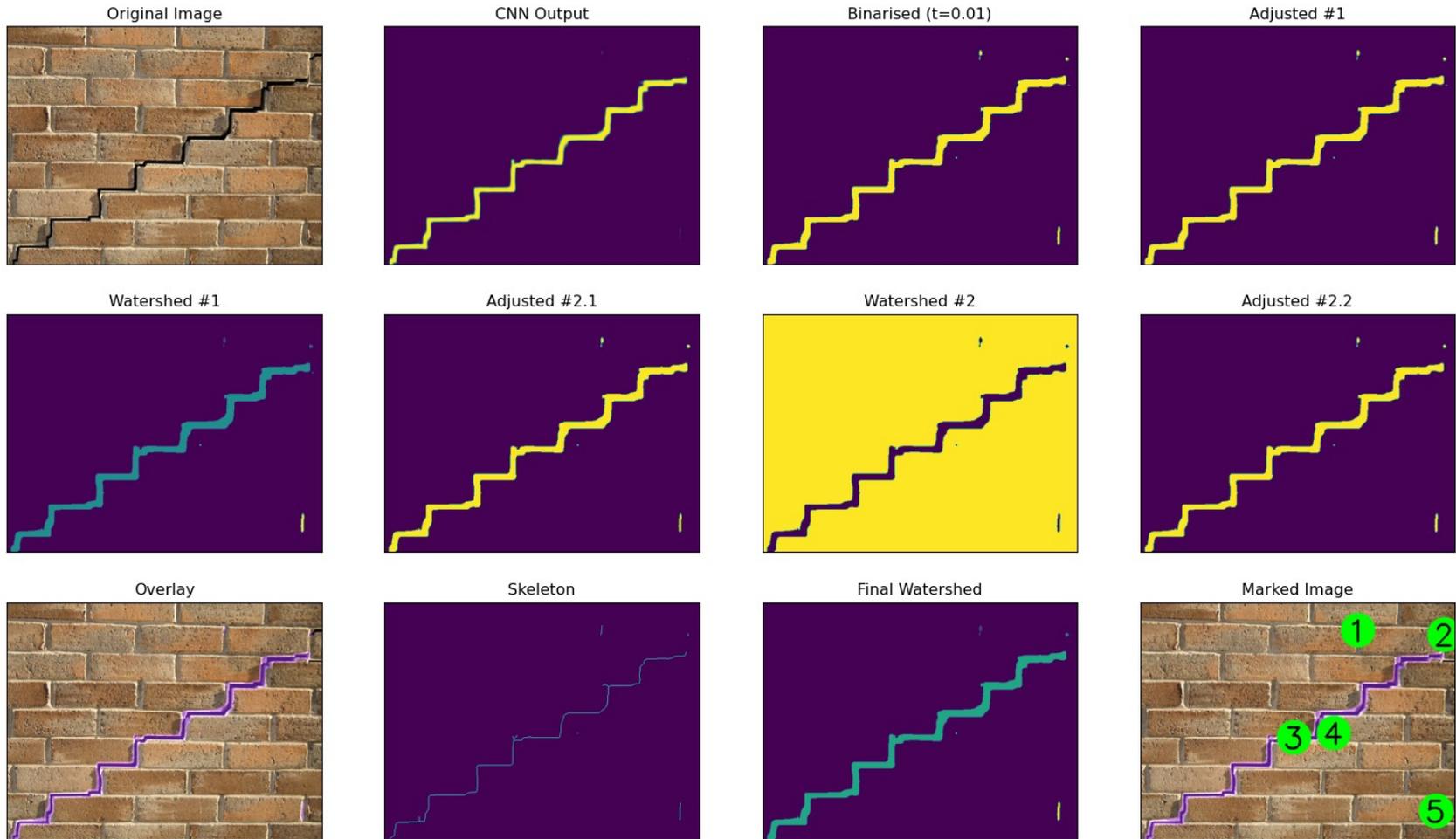
## Example #1

- A very simple case
- Low intensity photo (641x480px)
- No noise, no background
- Clean single crack



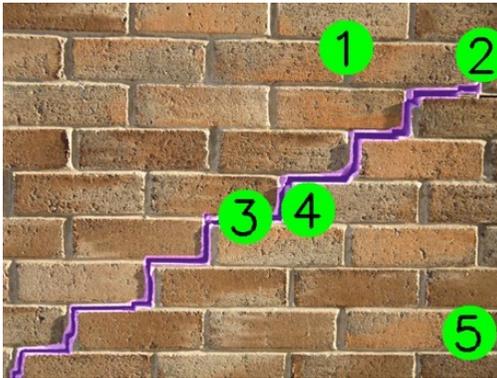
# AI-based Crack Detection

## Example #1

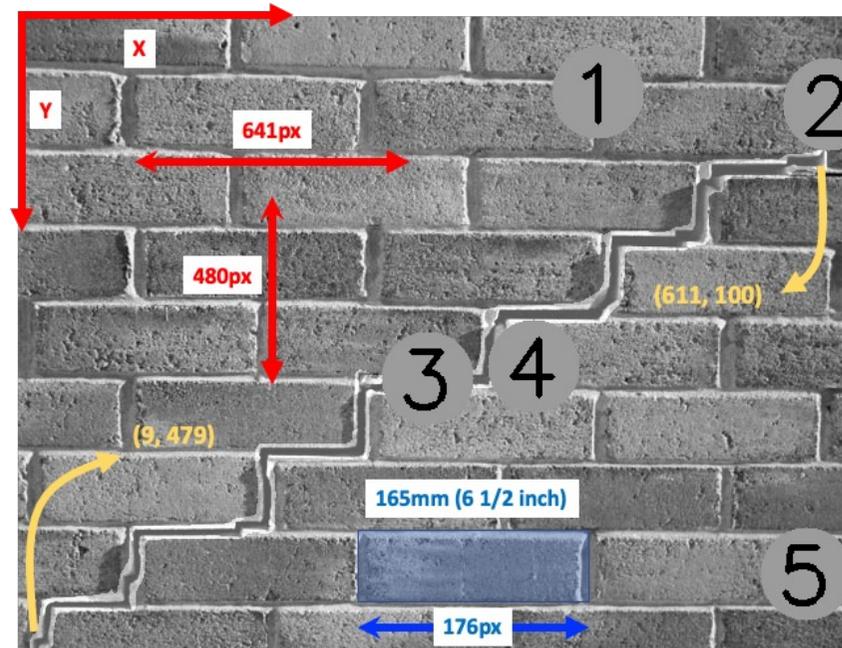


# AI-based Crack Detection

## Example #1



Label	LocTop (x,y)	LocBot (x,y)	Loc (xmin,ymin)	Loc (xmax,ymax)	Loc (xp,yp)	Area (pxls)	Skeleton (pxls)	Length (pxls)	Width (pxls)
1	[442, 48]	[440, 67]	[440, 48]	[445, 67]	[442, 57]	70	19	19.24	3.64
2	[616, 63]	[616, 69]	[615, 63]	[621, 69]	[618, 66]	39	5	4.83	8.08
3	[611, 100]	[9, 479]	[9, 100]	[616, 479]	[312, 273]	12795	903	957.28	13.37
4	[393, 263]	[393, 266]	[392, 263]	[394, 266]	[393, 264]	9	2	1.00	9.00
5	[602, 403]	[600, 440]	[598, 403]	[604, 440]	[601, 421]	182	35	34.83	5.23



Average crack width  
along Area 3: 13.37px

165mm=176px  
1px=0.9375mm  
1px=0.037inch

Crack width= 0.9375x13.37  
= 12.5mm

Crack width= 0.037x13.37  
= 1/2 inch

# AI-based Crack Detection

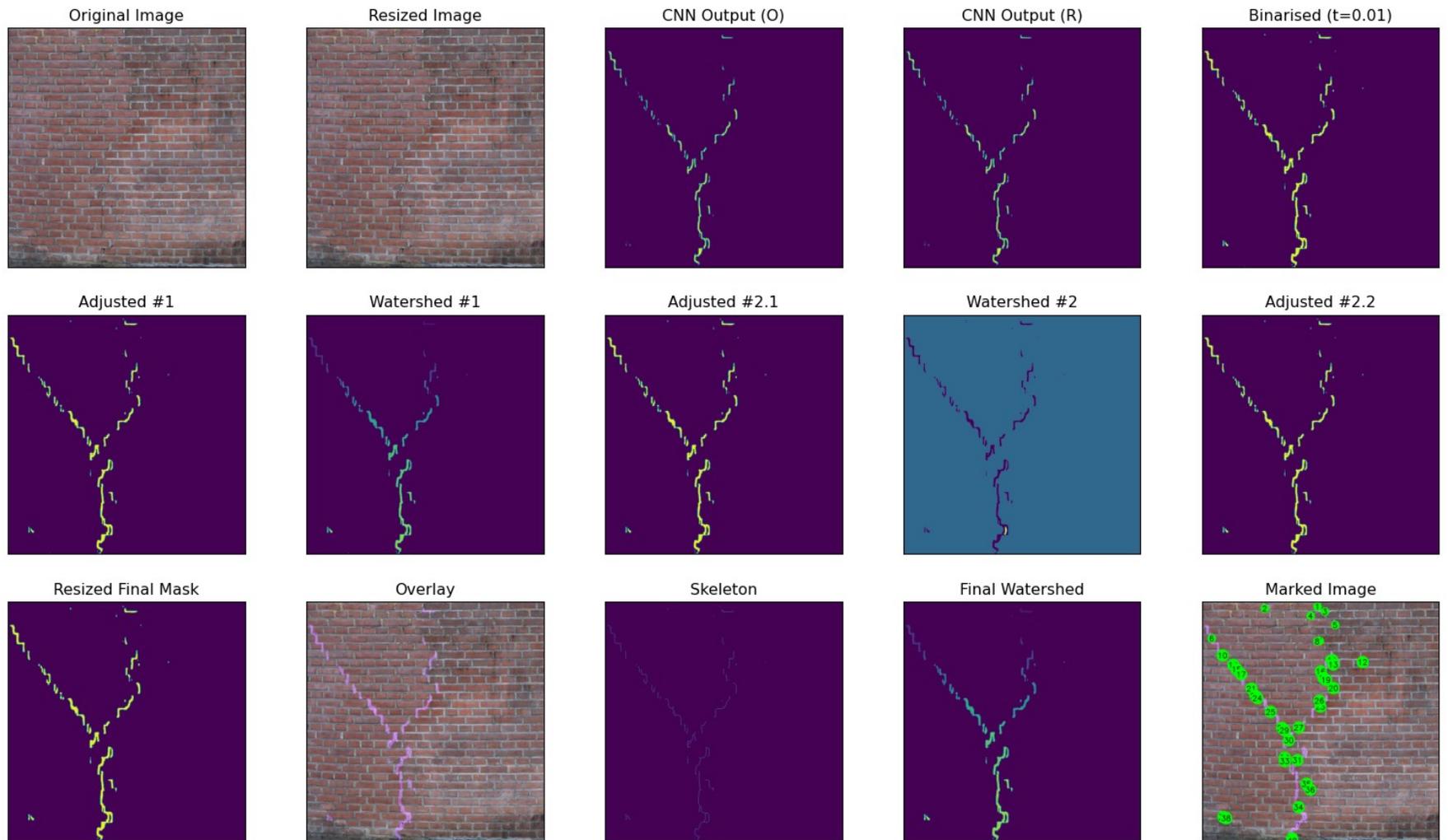
## Example #2

- Quay wall Amsterdam
- High intensity photo (1939x1939px)
- Some noise, no background
- Several cracks



# AI-based Crack Detection

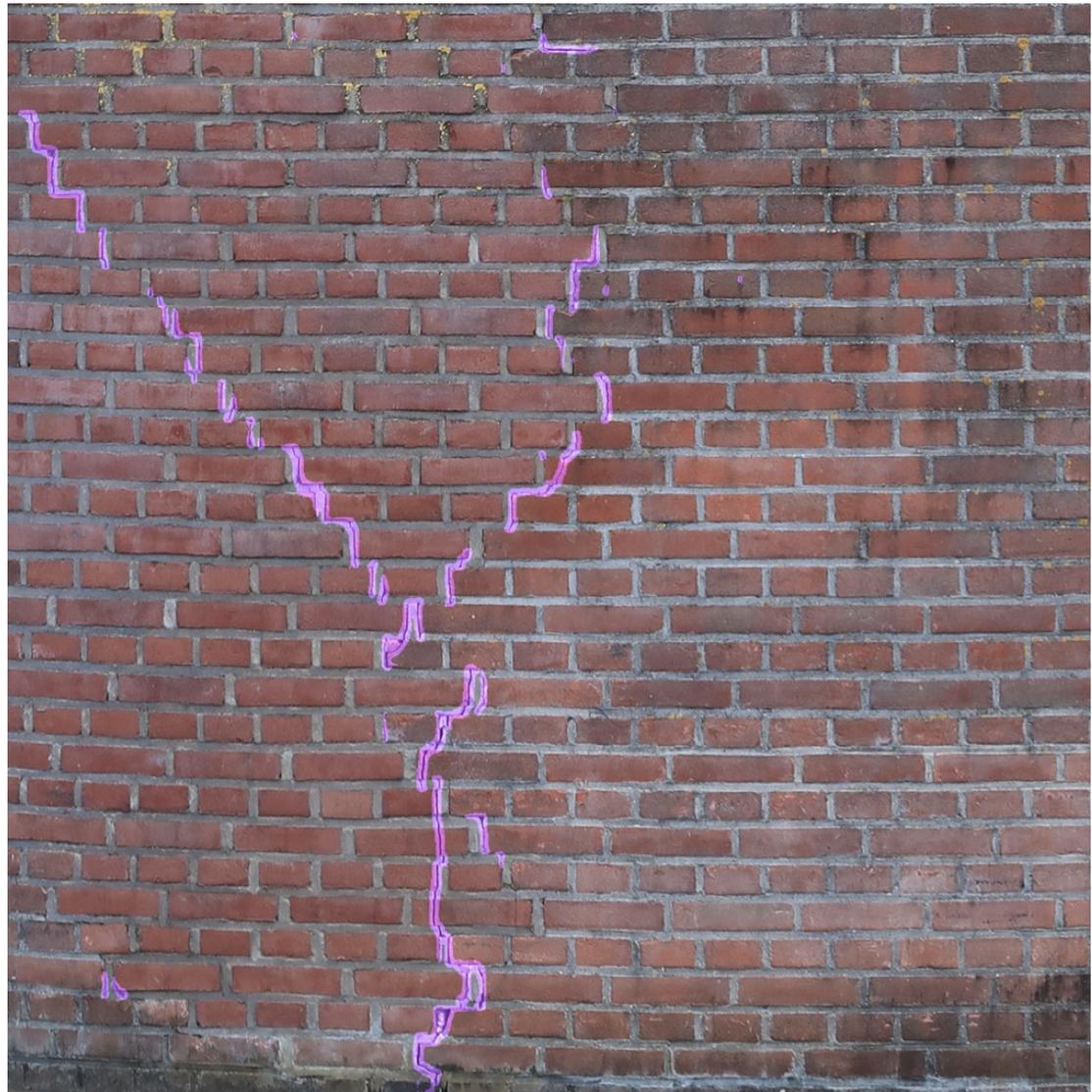
## Example #2



# AI-based Crack Detection

## Example #2

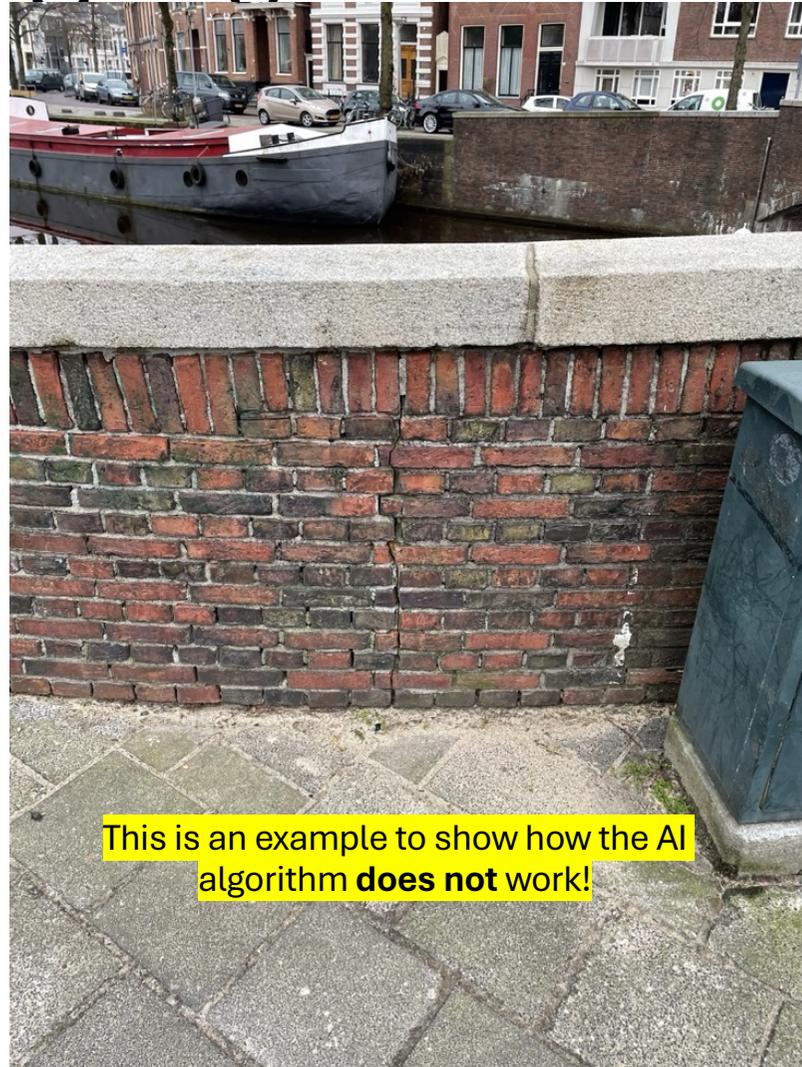
- Auto-detection of more than 90% of the cracks
- Use of single photo
- Image taken from distance
- Higher accuracy in length and position



# AI-based Crack Detection

## Example #3

- Parapet wall Groningen
- Very high intensity photo (3024x4032px)
- High noise, high background
- Cracks and crack-like features



# AI-based Crack Detection

## Example #3

- Confusion in the background
- Confusion in crack-like features
- Confusion in the noise

**The actual gap between the “crack detection papers” and “real engineering problems” is the false positives.**



## How an actual problem looks like?



Almost clean 2D  
crack



Crack with occlusion



Actual crack in 3D



Actual crack in 3D  
taken from height

Most papers (if not all!)

Very few, very targeted trials on data fusion

## **Generation of 3D synthetic data**

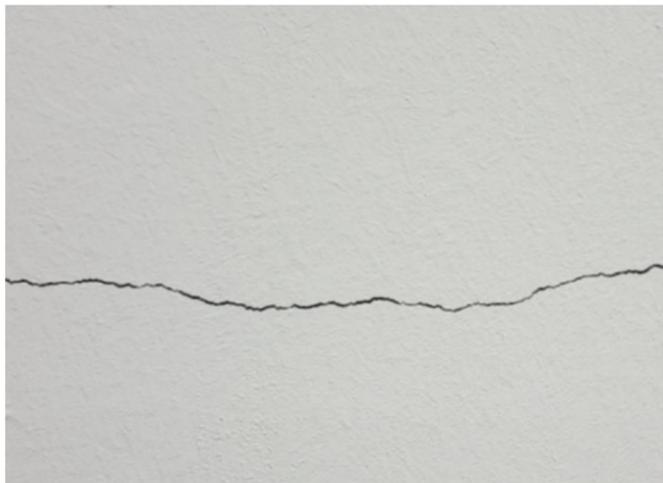
# The problem

- ❑ The data is scarce in (some) of the image-based surface anomaly detection problems
- ❑ The 3D rendering and gaming tools have reached an extreme reality, so much that modern GPUs produce more material than the human eyes can detect
- ❑ Could this advanced technology be used for producing realistic 3D synthetic data, which is learnable and useful for scarce-data problems?

# Our dilemma

- ❑ We picked the masonry surface crack detection problem for benchmarking, because it is very well studied.
- ❑ But... at the same time, the combination of existing datasets and methods have already reached very high levels of prediction accuracy in this particular problem, so synthetic data generation has little to offer.
- ❑ So, don't expect miracles! Our aim is to show that the framework actually is able produce useful data, not superior performance.

# Existing solutions for synthetic image generation



Gaussian convolutions +  
Brownian Motion  
[Lee et al.]



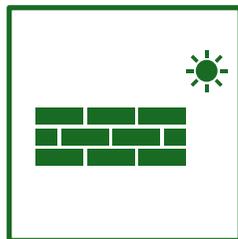
Perlin Noise  
[Rill-García et al.]



Overlaying cracks  
[Xu et al.]

# Dataset generation framework

Input

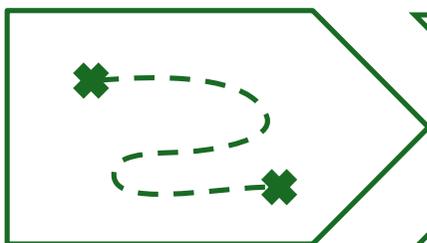


3D scene

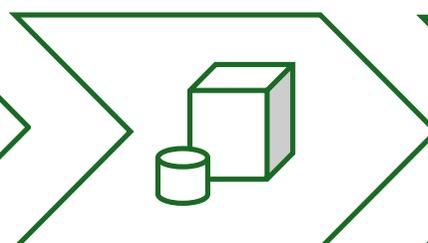


Configuration

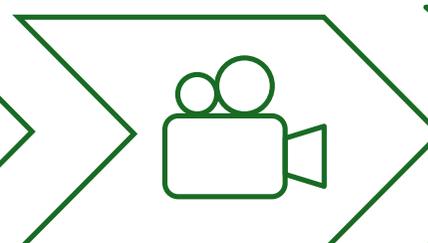
Pipeline



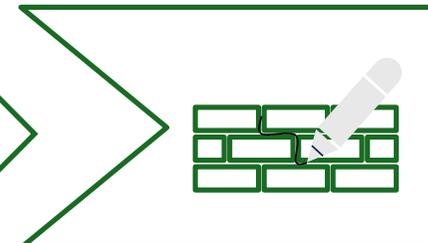
Crack generation



Scene composition



Rendering



Annotation

Output



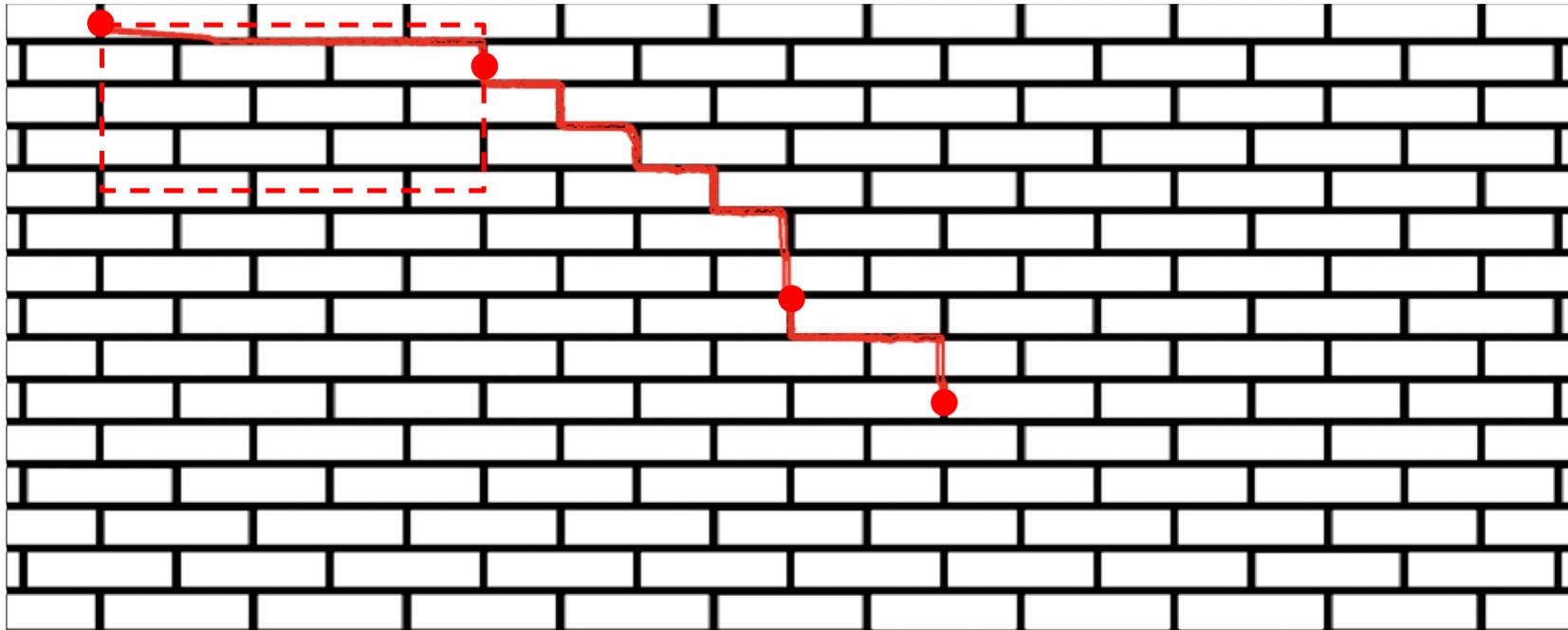
Images



Labels

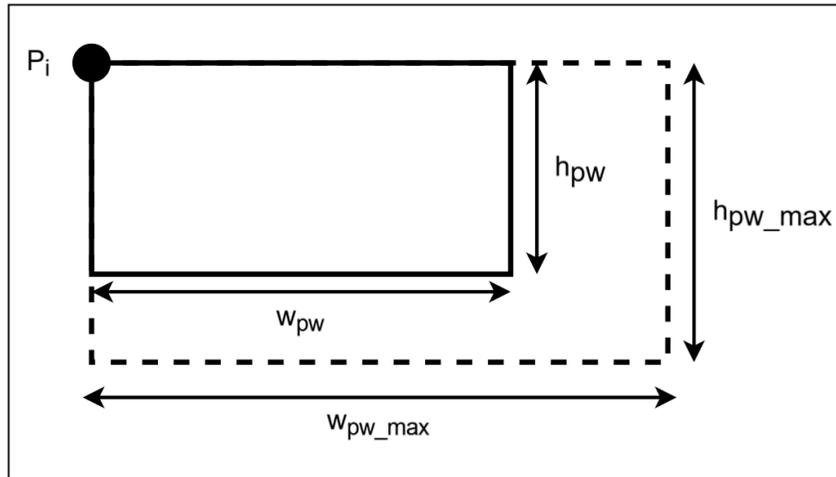


Crack generation

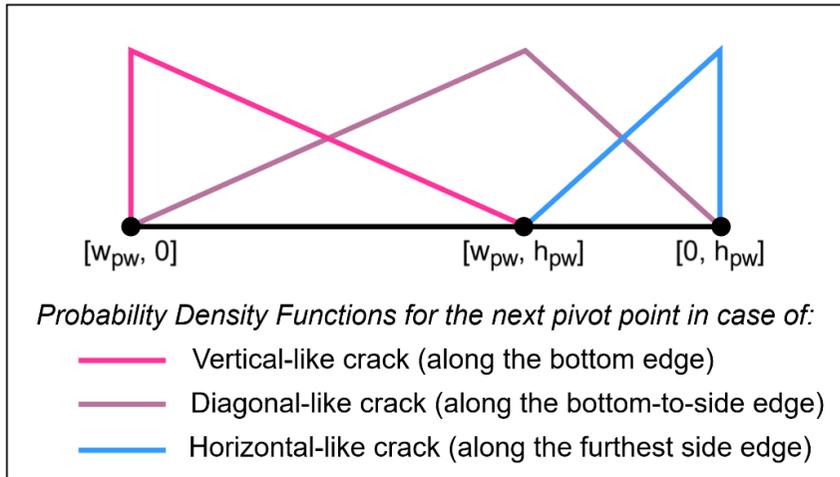


Grid size in bricks: H x W

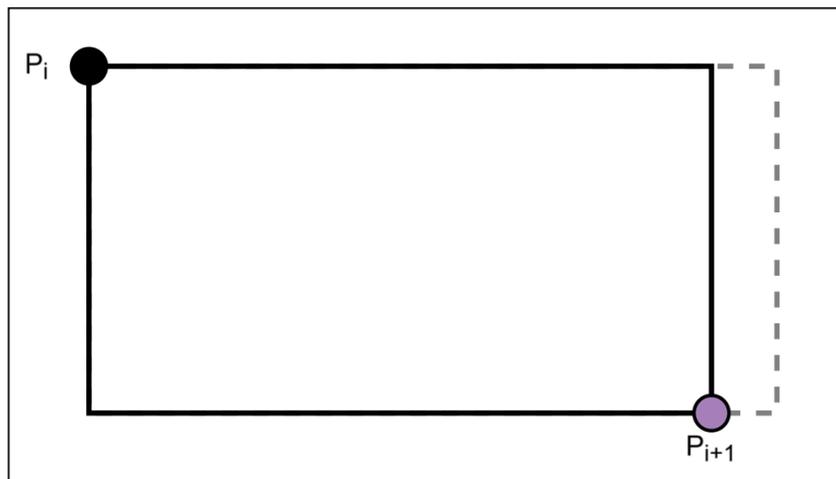
### Step 1: Determine pivot window size



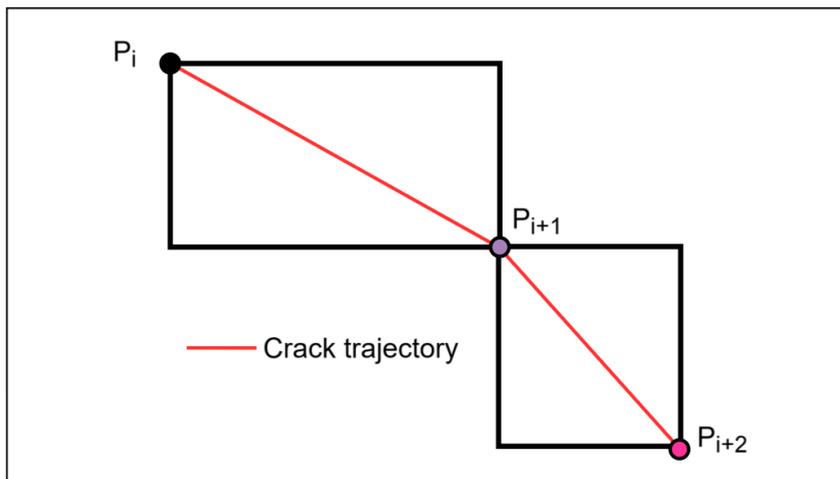
### Step 2: Randomly choose crack type and distribution



### Step 3: Place the next pivot point

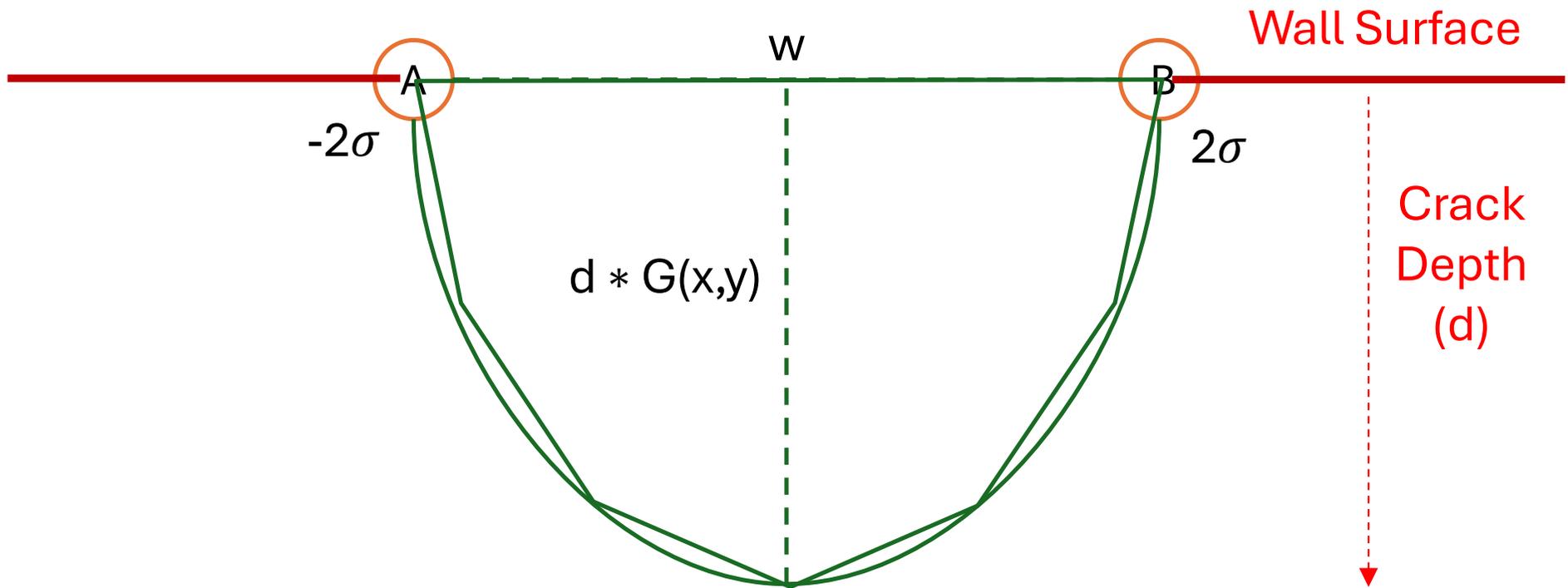


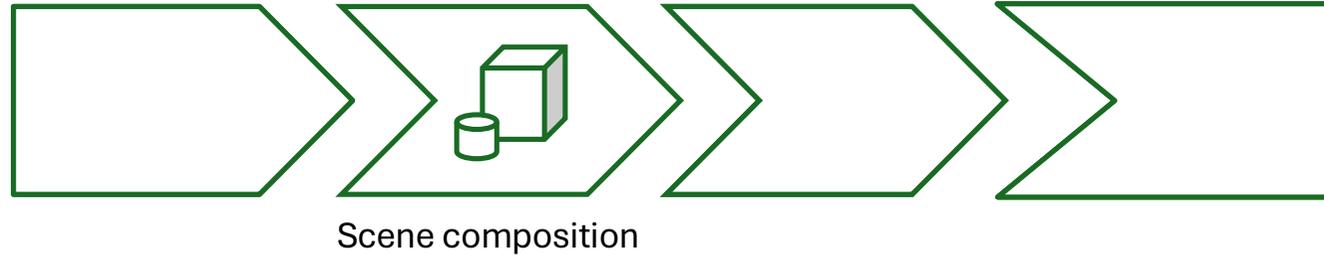
### Step 4: Repeat



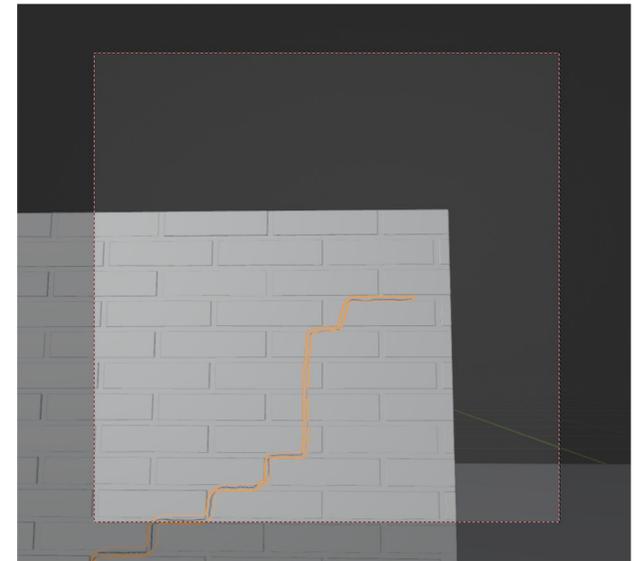


Crack generation





- Reset scene
- Randomize scene
- Import crack model
- Subtract crack from wall geometry





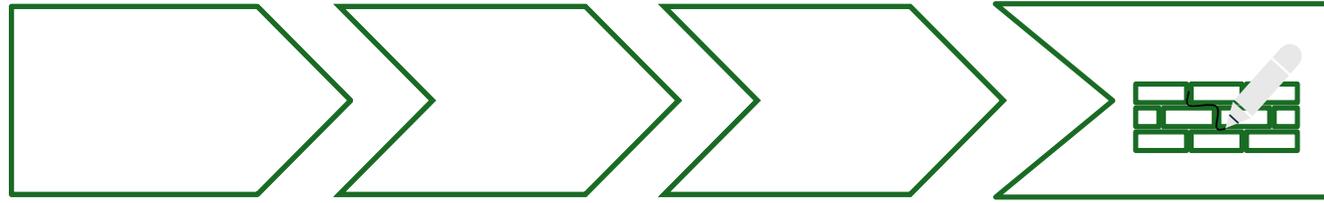
Rendering



Image



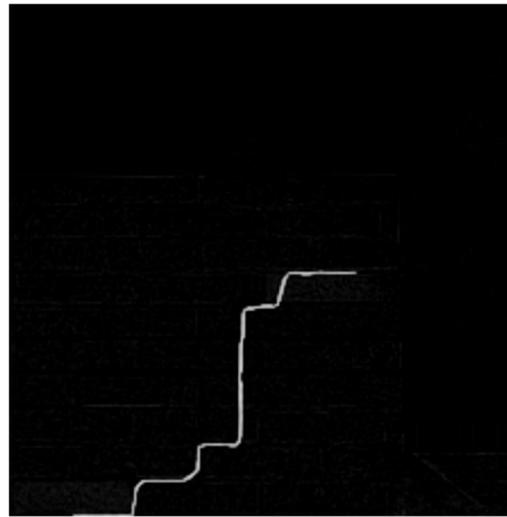
Label



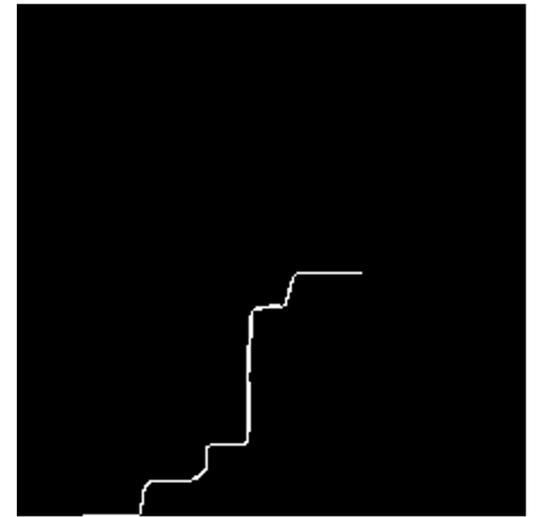
Annotation



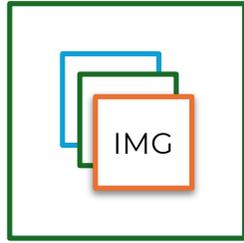
Label



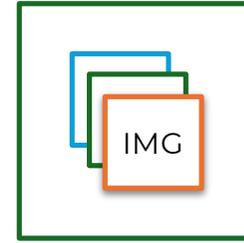
Difference



Thresholded



Images



Labels



# Testing setup

## Networks

U-Net [Ronneberger et al.]

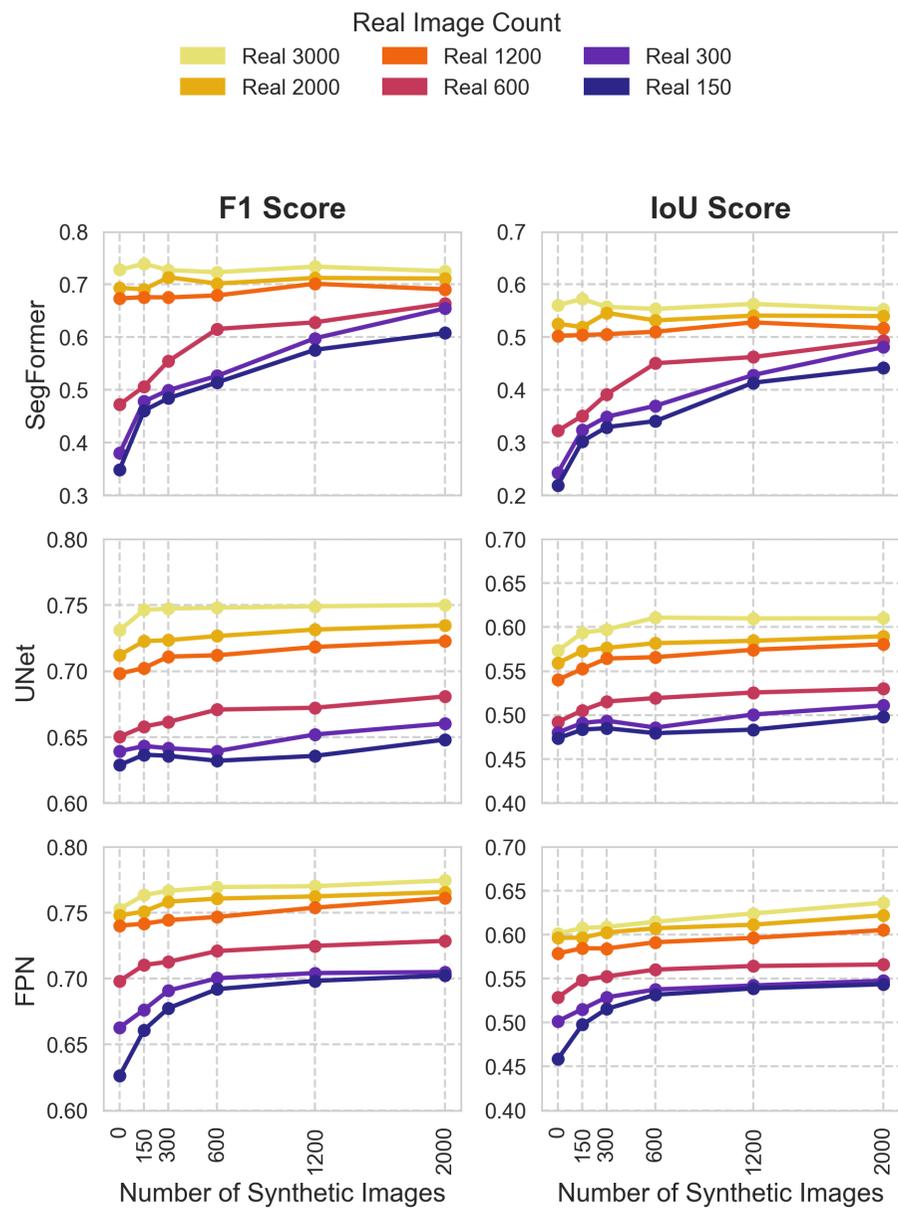
FPN [Lin et al.]

SegFormer [Xie et al.]

## Dataset

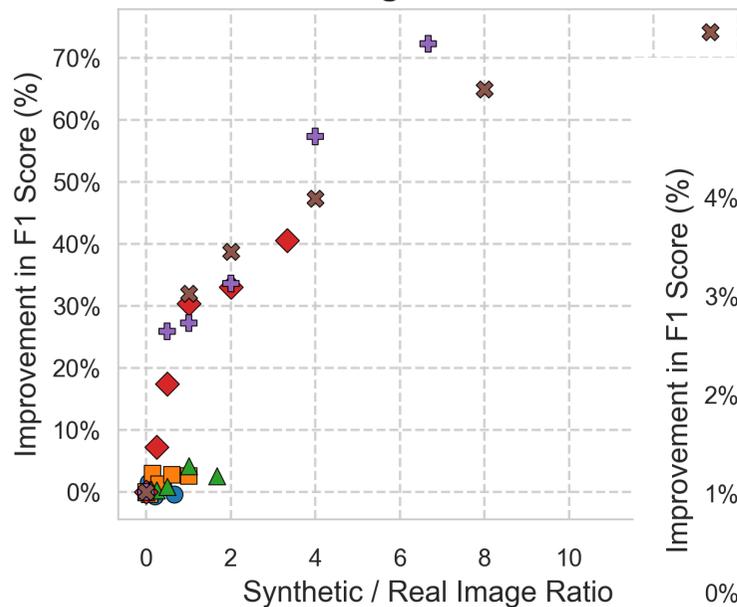
- ❑ A real dataset with 4000 available images and labels [Dais et al.]
- ❑ Real images of 150, 300, 600, 1200, 2000 and 3000
- ❑ Synthetic images in combination with the real ones, 150, 300, 600, 1200, 2000 and 3000

# Results

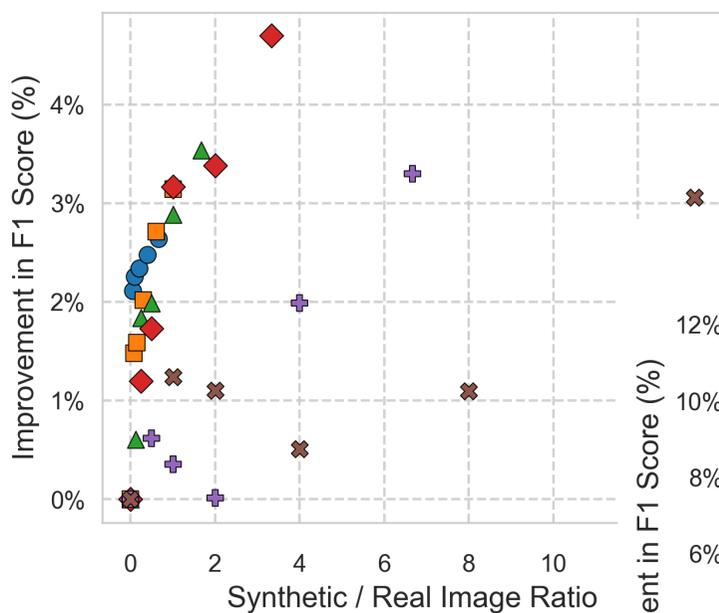




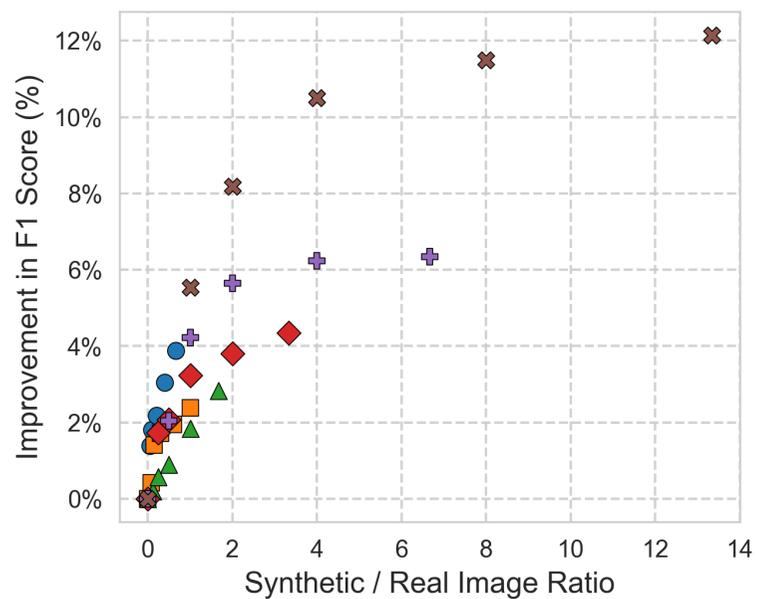
**SegFormer**



**UNet**



**FPN**



*Boerema, D., Bal, I., Smyrou, E., & Kosinka, J. (2025). A framework for generating a 3D synthetic dataset for automatic crack detection in masonry surfaces. In Proceedings of the 14th International Conference on Structural Analysis of Historical Constructions.*

*Boerema, D. H., Bal, I. E., & Smyrou, E. (n.d.). Noise-resistant crack segmentation through the application of transfer learning on the Segment Anything Model 2. In Digitalisation of the Built Environment: 4th 4TU/14UAS Research Day (pp. 104–107).*

# Future Work

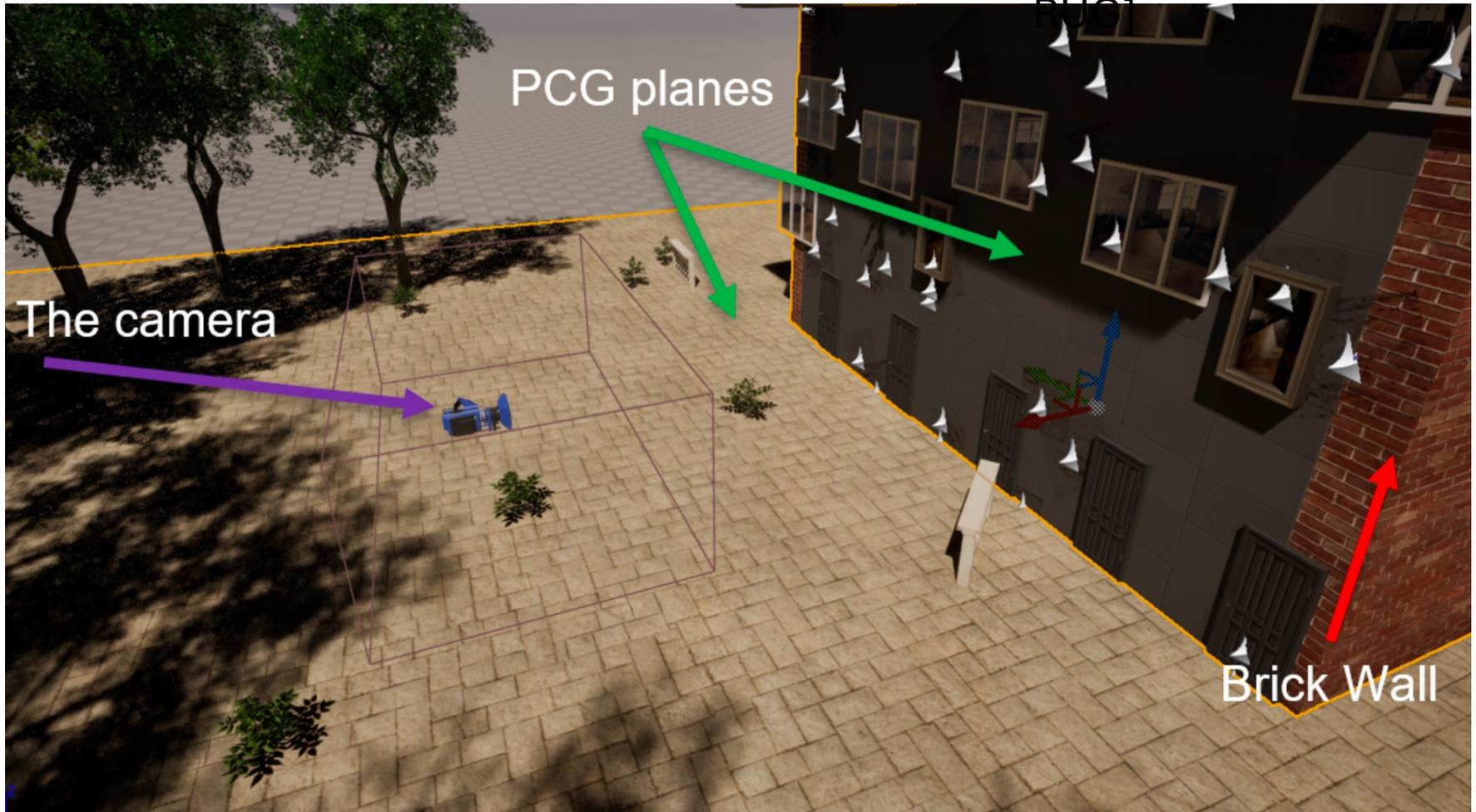


**UNREAL  
ENGINE**

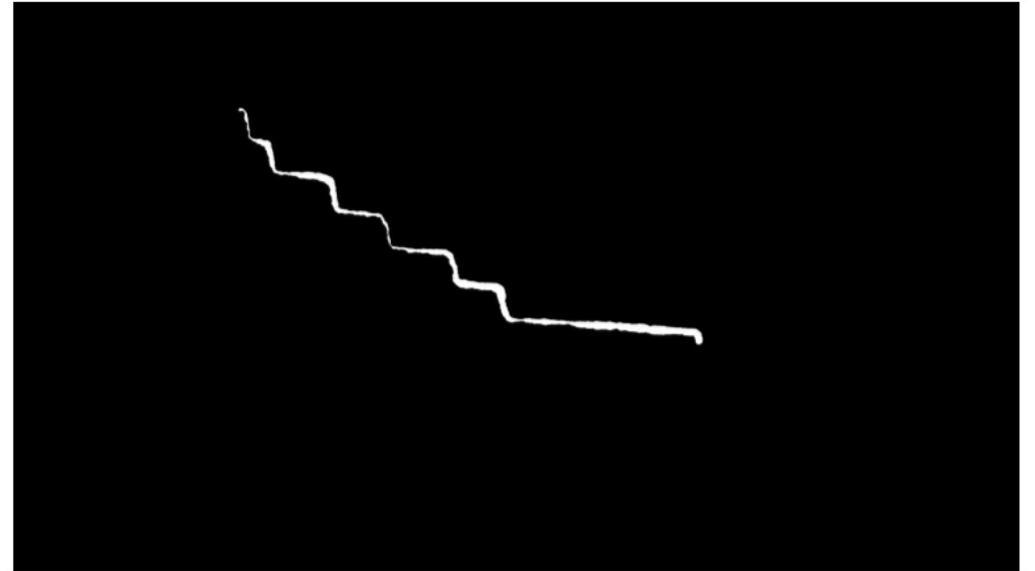
We use the most famous gaming engine for generating realistic built environments

# Future Work

[Muscoi et al., 2025, FIG. 1]



# Future Work



[Muscoi et al., 2025, RUG]

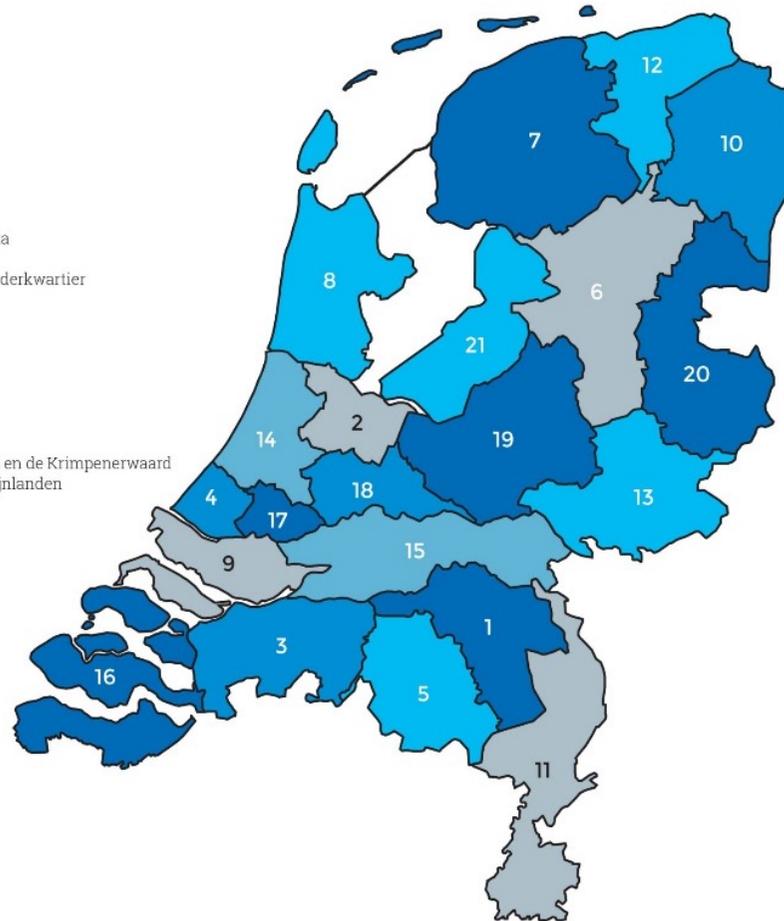
## **3D point cloud data – Use case of water defence dykes**

# Water protection administration in the Netherlands

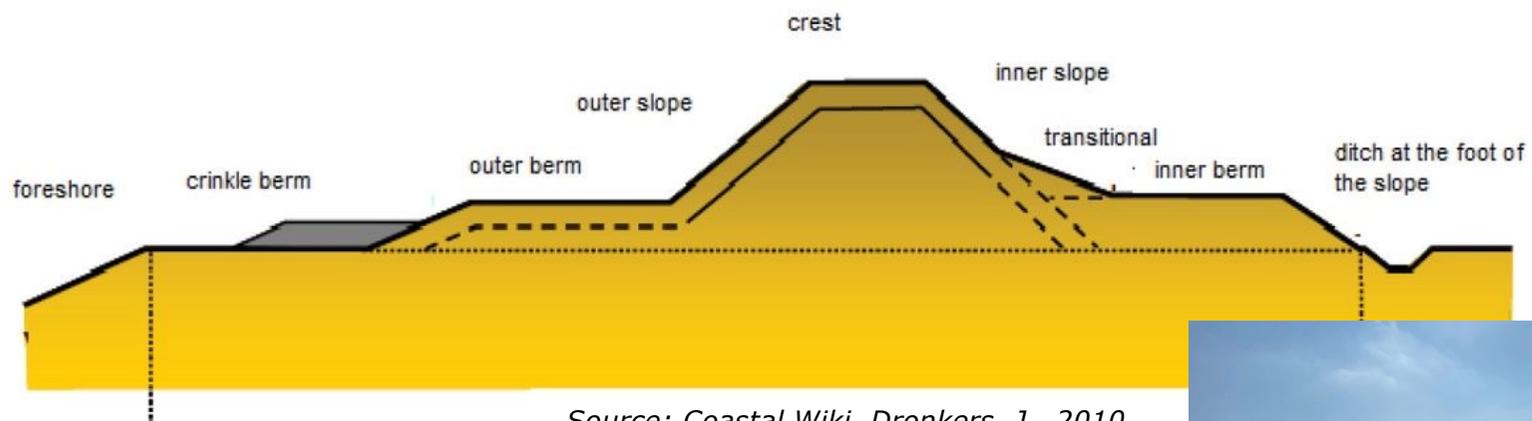
## UNIE VAN WATERSCHAPPEN

### LEGENDA

1. Waterschap Aa en Maas
2. Waterschap Amstel, Gooi en Vecht
3. Waterschap Brabantse Delta
4. Hoogheemraadschap van Delfland
5. Waterschap De Dommel
6. Waterschap Drents Overijsselse Delta
7. Wetterskip Fryslân
8. Hoogheemraadschap Hollands Noorderkwartier
9. Waterschap Hollandse Delta
10. Waterschap Hunze en Aa's
11. Waterschap Limburg
12. Waterschap Noorderzijlvest
13. Waterschap Rijn en IJssel
14. Hoogheemraadschap van Rijnland
15. Waterschap Rivierenland
16. Waterschap Scheldestromen
17. Hoogheemraadschap van Schieland en de Krimpenerwaard
18. Hoogheemraadschap De Stichtse Rijnlanden
19. Waterschap Vallei en Veluwe
20. Waterschap Vechtstromen
21. Waterschap Zuiderzeeland



# Water protection administration in the Netherlands



Source: Coastal Wiki, Dronkers, J., 2010



## Dyke inspections in the Northern Netherlands



- Various damage types and anomalies need to be inspected
- Weekly light & quick inspection
- Annual walk-down inspection
- Increasing number of problems, decreasing personnel!
- New materials, aging, climate change effects...

*Rozemarijn, C., Veenstra, A., Bal, I. E., & Smyrou, E. (2026). Towards data-driven inspection methods with artificial intelligence of the primary dikes in the Netherlands. In Proceedings of the International Conference on Natural Hazards and Infrastructure (ICONHIC 2026), Crete, Greece.*

## Dyke inspections in the Northern Netherlands

- North Netherlands has 60km of main dykes
- The water authorities under pressure for the inspections
- We are trying to incorporate drone images to accelerate the inspection processes
- The drone images give 3 types of information;



Individual images



Stitched TIFF



3D Point Cloud



3D Point Cloud

## Dyke inspections in the Northern Netherlands

- AI can pre point potential problems and support predictive maintenance by enabling more frequent scans, but **it cannot replace actual inspection** or maintenance work.
- Single images can detect individual issues, but **geo referenced TIFF orthomosaics** allow better localization and mapping, requiring some GIS skills.
- **Combining orthomosaics with 3D point clouds** is more powerful for detecting deformation, erosion, and surface changes.
- The use of drones and ground robots improves coverage, resolution, and safety during inspections.

## **Future research**

# FLOIRO

Use Floor (B)IM (Information Model)

## 3D Model of the geometry

The screenshot displays the FLOIRO software interface. On the left, a 3D model of a floor slab is shown in a perspective view, with a green dashed outline indicating a selection. The software's ribbon menu is visible at the top, with the 'VIEW' tab active, showing options for 3D, 2D, and camera controls. On the right, the 'Modify Setup' dialog box is open, showing the 'Advanced' tab. The 'Advanced' tab contains various checkboxes for export settings, such as 'Export parts as building elements' and 'Use visible Revit name as the IFC entity name'. Below the dialog, a tree view shows the project hierarchy, including 'Building Storey', 'Site', and 'Building Element Proxies'. At the bottom, a properties table is visible, showing details for the selected 'Element Specific' object.

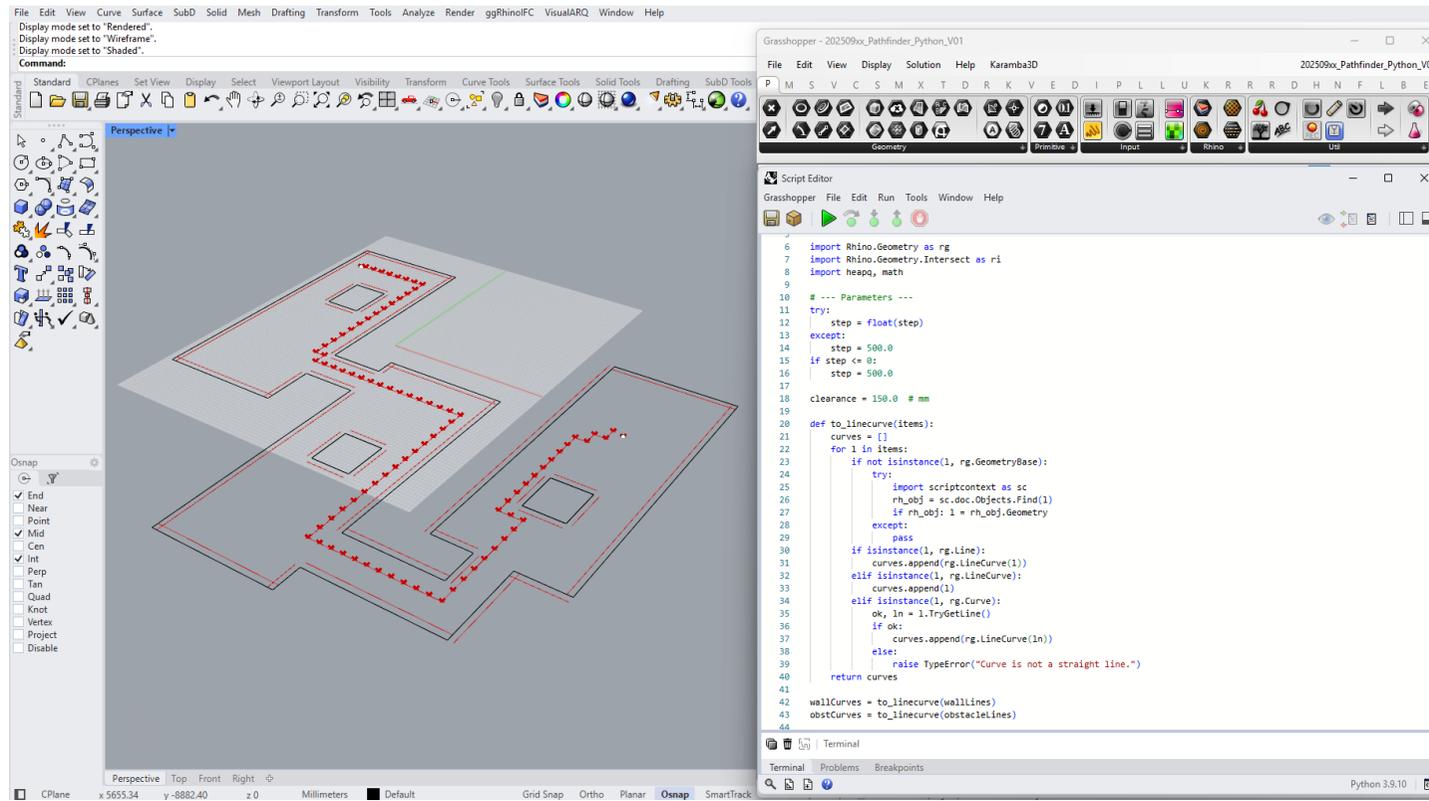
Properties	Location	Classification	Relations
<b>Element Specific</b>			
Guid		19b2qD9116Pj9W0LwpVcz	
IfcEntity		IfcBuildingElementProxy	
Name		Generic Models : 202509xx_ProjectRover : Floor_02	
ObjectType		202509xx_ProjectRover:Floor_02	
Tag		971617	
<b>Profile</b>			
ProfileName		Floor_02	
XDim		3 000	mm
YDim		6 000	mm
<b>IFC.GenericSchedule</b>			
Family		202509xx_ProjectRover	
FloorLength		6 000	mm
FloorThickness		200	mm
FloorWidth		3 000	mm
Type		Floor_02	
Volume		3.6	m3

Project funded by:



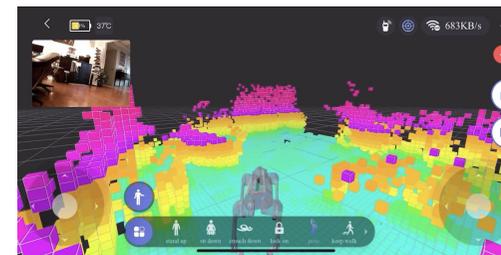
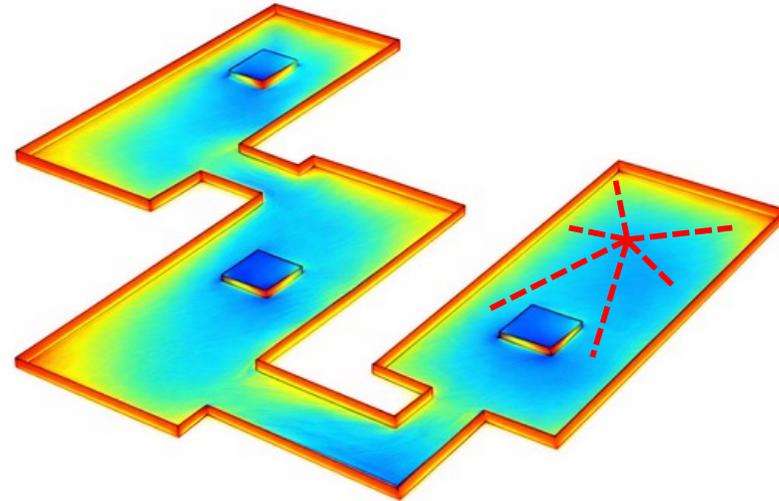
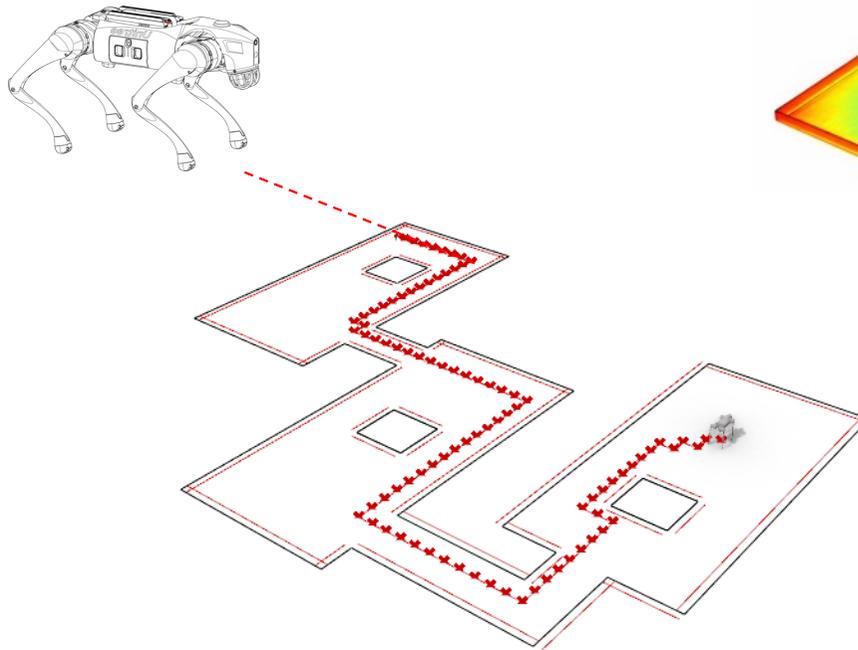
# FLOIRO

Pathfinding with Rhino / Python



# FLOIRO

Place Robot at entrance of to be inspected site,  
robot finds its way autonomous to test site based on on-board lidar

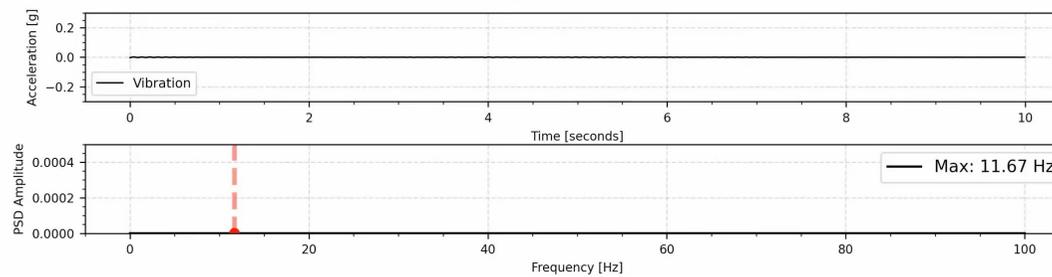


Robot uses own lidar heatmap to compare real situation  
with (B)IM model to define the test locations.

# FLOIRO

How do we do these tests normally?

*Smyrou, E., Özdemir, K., Veenstra, R., Bal, İ. E., Roijackers, R., & Tesfamariam, S. (2026, in press). Experimental evaluation of static and vibration performance of three timber floor systems with and without bonded topping layers. Journal of Performance of Constructed Facilities. American Society of Civil Engineers (ASCE).*



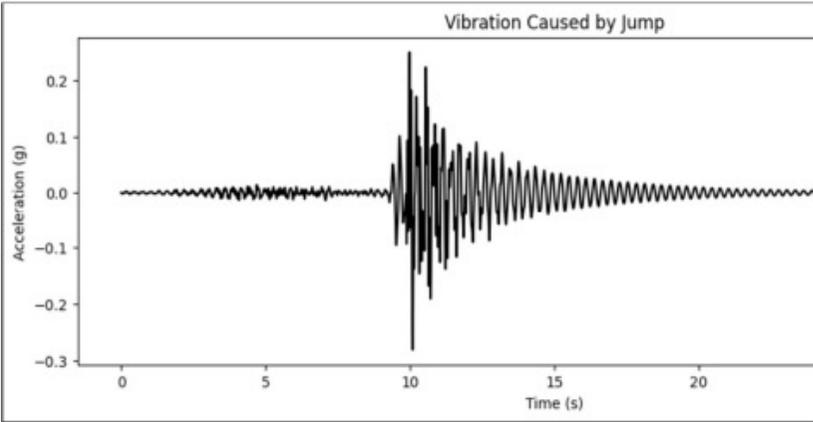
# FLOIRO

Robot applying impact by using stamping leg



Using 'live' robot sensor data from IMU to measure, record and transmit vibration event for further (off site)analysis

```
Mode: 1
progress: 0.0
gait_type: 1
foot_raise_height: 0.0
position:
- 1.2441953420639038
- 0.8927316665649414
- 0.30695709586143494
body_height: 0.30695709586143494
velocity:
- -0.0008932886994443834
- 0.003539283061400056
- 0.0001954567269422114
yaw_speed: 0.0010652643395587802
range_obstacle:
- 2.0
- 2.0
- 2.0
- 2.0
foot_force:
```



## Our Conclusions...

- AI and digital technologies in the built environment are still in their early stages of development.
- Understanding both the opportunities and the limitations of these methods is essential before applying them in practice.
- Current AI tools cannot fully replace human expertise, and complete automation may never be realistic.
- Human-in-the-loop (HIL) approaches remain essential for reliable decision making.
- The key challenge is to combine human expertise with AI capabilities, allowing computers to handle repetitive tasks while experts focus on interpretation and judgment.
- A useful analogy is the evolution of finite element analysis (FEA): initially experimental and limited, but now a mature and indispensable engineering tool.

**Thank you ...**