

Development of a Machine Vision System for Damage and Object Detection in Tunnels using Convolutional Neural Networks

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Introduction

- Every year, 4700 km of new tunnels are built in the world.
- Germany has:
 - more than 700 km of tunnels,
 - more than 200 tunnels,
 - Road tunnels
 - Railway tunnels
 - Underground tunnels



Introduction

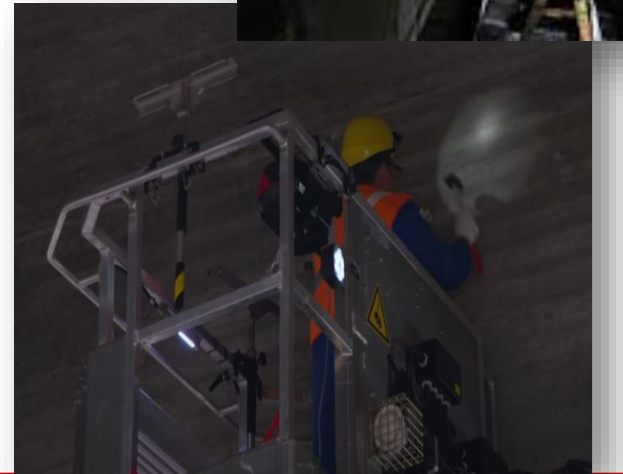
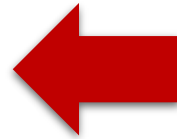
- Tunnel inspection:
 - Monitoring structural reliability
 - Monitoring health conditions
 - Safety management
 - Providing proper maintenance and renovation
 - Providing sustainable urban transportation infrastructures.



Conventional Tunnel Inspection

- **Concept:**
 - On-site inspections using adapted cars
 - Laser scanners
 - Manual data collection

Local, Manual, Expensive !

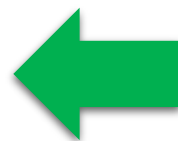


Vision-based Tunnel Inspection

- **Concept:**

- Vision-based systems on the normal vehicles
- Cameras and LED lights
- Synchronized laser sensors

Global, Automatic, Low-cost !



@Huang, 2017



@Dibit, 2019



@Ricoh



@Chapman, 2016



@Jiang, 2019

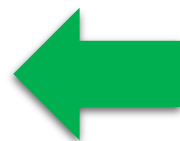


@Terra

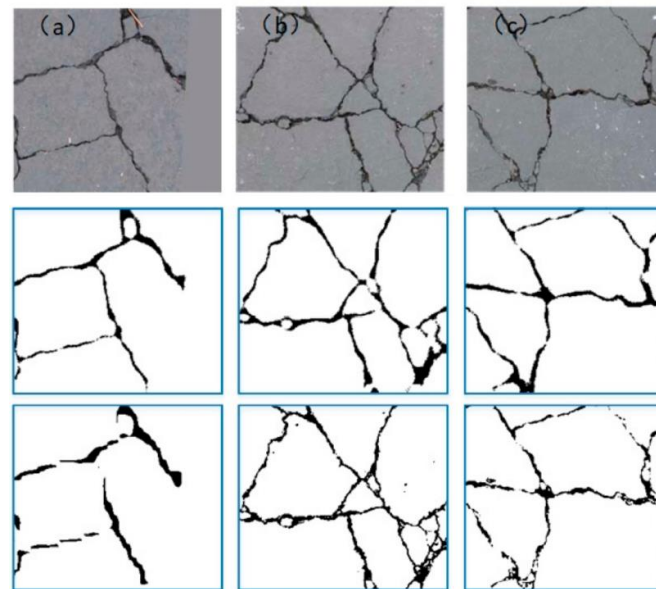
AI-based Inspection

- **Concept:**
 - Image-based segmentation CNNs
 - For damage and object detection tasks

Local, Automatic, Low-cost !



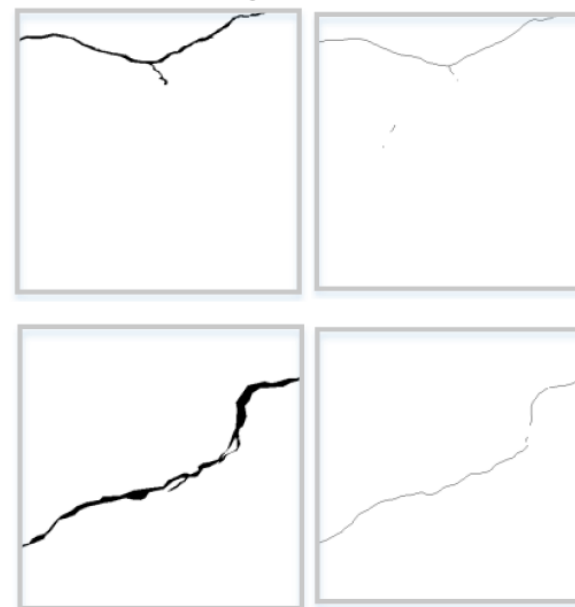
@Qiao, 2021



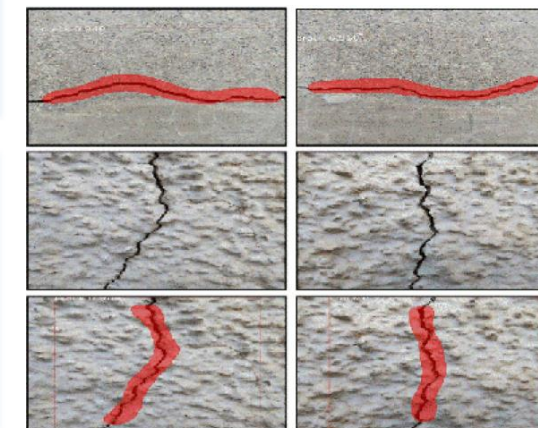
@Kim, 2020



@Li, 2020



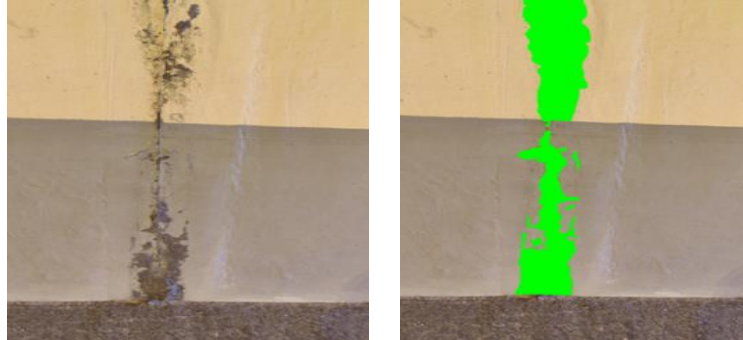
@Kumar, 2021



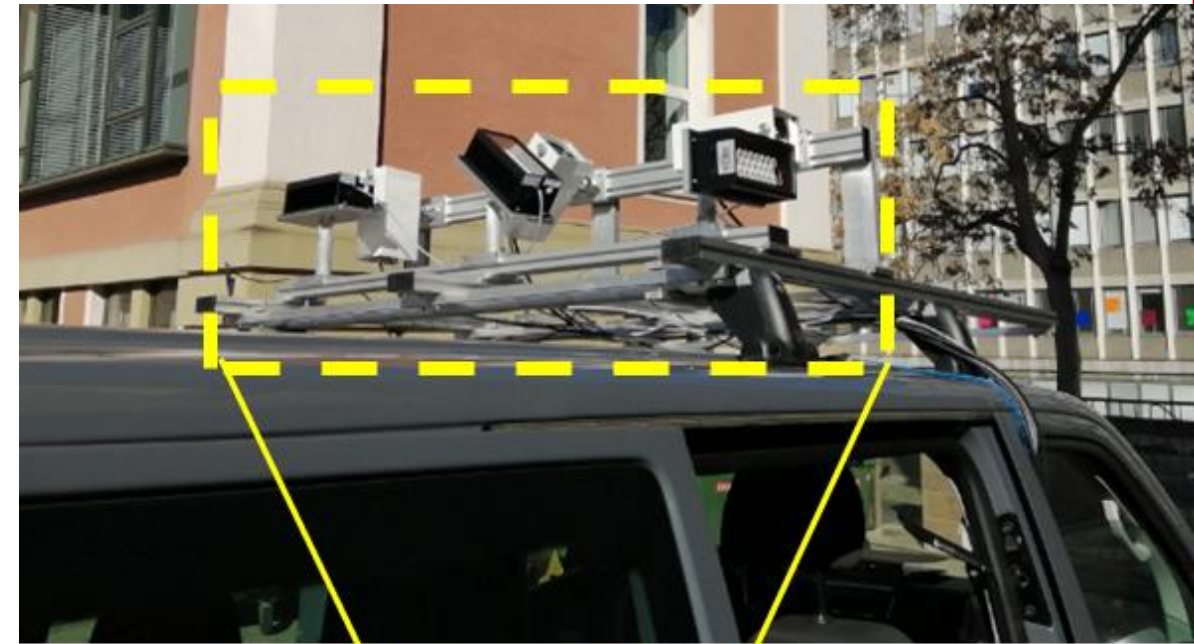
Proposed Method

- **Main goal:**
 - Propose a Machine Vision System (MVS) to capture RGB images from tunnel structures.
 - Propose CNN-based methods to detect damages and objects automatically.

Damage detection



Object detection



Machine Vision System

- Camera Selection:
 - Line scan or Area-scan camera?
 - Rolling shutter or Global shutter?
 - CCD or CMOS?
 - Small buffer or Large buffer?
 - GigE or USB 3.0 interface?
 - Number of cameras? 10, 8, 5?
 - Angle between cameras? 36°, 45°, 56°?
 - Required lens? 6mm, 12mm, 20mm?
 - Required radiometric resolution? 8, 10, 12, 24, 32 bit?
 - Required shutter speed?
 - Cost?

- LED Selection:
 - Linear, spot, or Area-based LED?
 - Constant, switch, flashlight?
 - NIR or White light?
 - Integrated or external controller?
 - Size (FOV) of the LED? 15°, 30°, 50°?
 - Working distance? <1m, >3m?
 - Number of LEDs? 10, 8, 5?
 - Max. flash rate? 1000, 100, 30, 1 Hz?
 - Required pulse width?
 - Cost?

Company	Origin	Brand	Name	MP	Res.	Sensor format	pixel size	Lens (S 200- S 400)	FPS	Shutter	Buffer	Exposure range	Price	Mass (without lens) gram	Picture	Link
FLIR		BLACKFLY USB3	BF5-USB-12054C-C3	12	4000 x 3000	1/1.7"	3.85 µm	TAMRON 8-12 56-25 mm	31	Rolling shutter with global reset	240 MB	10 µs to 30 s	\$575,000	36		https://www.flir.com/products/blackfly-a-smb2/usb3-bf5-usb-12054c-c3
			BF5-USB-12396C-C	12.3	4096 x 3000	1.1"	3.45 µm	TAMRON 8-12 56-25 mm	30	Global shutter	240 MB	10 µs to 30 s	\$1,605,000	36		https://www.flir.com/products/blackfly-a-smb2/usb3-bf5-usb-12396c-c
			BF5-USB-20096C-C	20	5472 x 3648	1"	2.4 µm	TAMRON 8-12 56-25 mm	18	Rolling shutter with global reset	240 MB	...	\$720,000	36		https://www.flir.com/products/blackfly-a-smb2/usb3-bf5-usb-20096c-c
		GRABHOPPER3 USB3	GS3-USB-12096C-C	12	4320 x 2832	1"	3.1 µm	TAMRON 8-12 56-25 mm	7	Global shutter	128 MB	0.040 ms to 32 s	\$1,605,000	90		https://www.flir.com/products/grabbopper3-smb2/usb3-gs3-usb-12096c-c
			GS3-USB-12396C-C	12.3	4096 x 3000	1.1"	3.45 µm	TAMRON 8-12 56-25 mm	30	Global shutter	128 MB	0.01 ms to 32 s	\$1,249,000	90		https://www.flir.com/products/grabbopper3-smb3/usb3-gs3-usb-12396c-c
Basler	Germany	Basler ace USB3	acA4000-30uc	14	4008 x 3288	1/2.1"	3.4 µm	Basler 8-16 mm	10	Rolling Shutter	-	-	\$495,000	80		https://www.baslerweb.com/de/products/ace/ace/ace-scamer/usb3/acA4000-30uc/
			acA4024-20uc	12.2	4024 x 3036	1/3.1"	3.85 µm	Basler 8-16-25 mm	31	Rolling Shutter	-	-	\$595,000	80		https://www.baslerweb.com/de/products/ace/ace/ace-scamer/usb3/acA4024-20uc/
			acA5472-17uc	20	5472 x 3648	1"	2.4 µm	Kowa 8-25 mm	17	Rolling Shutter	-	-	\$790,000	80		https://www.baslerweb.com/de/products/ace/ace/ace-scamer/usb3/acA5472-17uc/usb3-ace-scamer
			acA4112-30uc	12.3	4096 x 3000	1.1"	3.45 µm	Kowa 8-25 mm	30	Global shutter	-	-	\$1,195,000	80		https://www.baslerweb.com/de/products/ace/ace/ace-scamer/usb3/acA4112-30uc/
Stemmer Imaging	United Kingdom	Optimas CamPerform Cyclone	CP-CYCLONE-56-294-C	16	4672 x 3456	4/3"	3.9 µm	-	294	Global shutter	-	-	-	400		https://www.stemmer-imaging.com/en/products/camperform-cyclone-56-294-c/
		AltRad Vision Borlio PRO	X-1250C	12.5	4069 x 3072	-	4.5 µm	-	142	Global shutter	-	-	-	500		https://www.stemmer-imaging.com/en/products/borlio-pro-x-1250c/
IDS	Germany	USB 3.1 Gen. 1	UIS-3000SE	12.25	4096 x 3000	1.1"	3.45 µm	-	32	Global shutter	128 MB	0.032 ms - 2000 ms	-	105.5		https://en.ids-imaging.com/en/products/uis-3000se.html
SIS Vision	Germany	EKO	ewo353C13	12.3	4096 x 3000	1.1"	3.45 µm	-	30	Global shutter	256 MB	28 µs - 1 s	-	118		https://www.sis-vision.com/en/produkte/ewo353c13/
			ewo387C13	16.8	5456 x 3078	21.7mm (8/5)	3.45 µm	-	22	Global shutter	256 MB	29 µs - 1 s	-	120		https://www.sis-vision.com/en/produkte/ewo387c13/

Metaphase	USA		Long Range Strobe	LR5608	Integrated	Flash	2-250 µs	up to 50kHz	30	160 x 160			12" - 28"		https://www.metaphase-tech.com/wp-content/uploads/2018/03/LR5608-v20190605.pdf
Gardasoft	USA	1,600.00 € *	High-speed LED controllers	FP200	2 channels	Flash	1 µs - 5 s	10kHz	—	—	—	—	—		http://www.gardasoft.com/LED-Controllers/FP/
Gardasoft (Stemmer Imaging)	DE	400.00 € *	Entry-Level Controllers	RC120	1 channels	Flash	100 µs - 100 ms	100 Hz	—	—	—	—	—		https://www.stemmer-imaging.com/en/products/gardasoft/rc120/
Gardasoft (Stemmer Imaging)	DE	1,800.00 € *	High Speed and High-Power Controllers	TR-HT220	2 channels	Flash	20 µs - 5 s	30kHz	—	—	—	—	—		http://www.gardasoft.com/LED-Controllers/TR-HT/
BASLER	DE	349.00 €	SLP Strobe Controller	121040	?	Flash/Const.	50µs - 5ms	200 Hz	—	—	—	—	—		https://www.baslerweb.com/en/products/vision-components/basler-lighting/basler-slp-strobe-control-121040/
1	Company	Country	Price	Type	Name	Controller	Light	Flash time (pulse width)	Flash frequency	Working Distance	Size [mm]	Illumination	Lens	Photo	Link
2	LUMIMAX	DE	1.190,00 €	Area Flood	LQ100FL-49-W-220	Integrated	Flash	20-220 µs	35 Hz	2	65 x 65	268 w/m2 @ 0.5m	49°		https://www.lim-ag.com/en/lumimax/products/art/area-flood-lights/ls100fl-49-w-27385.html
3	LUMIMAX	DE	525,00 €	Mini Bar	LSB200FL-48x19-W	External (335,00 €)	Flash/Const.	100 µs	10-35-100 Hz	2	195 x 15	140 w/m2 @ 0.5m	48x19°		https://www.lim-ag.com/en/lumimax/products/art/led-bar-lights-1/lsb200fl-48x19-77392.html
4	LUMIMAX	DE	2.050,00 €	Bar	LSB00FL-48x19-W-220	Integrated	Flash	20-220 µs	35 Hz	2	490 x 22	359 w/m2 @ 0.5m	48x19°		https://www.lim-ag.com/en/lumimax/products/art/led-bar-lights-3/lsb00fl-48x19-220-7553.html
6	Metaphase	USA	890,00 € 1.400,00 €	Area Flood	MB-FLD	External (540,00 €)	Flash/Const.	7µs - 60ms	up to 50kHz	5.5	210 x 90 380 x 90	600,000 Lux	11° - 30°		https://www.metaphase-tech.com/wp-content/uploads/2018/04/MB-FLD-PDS-v20190528.pdf
7	Metaphase	USA		Area Front	MB-FL	Integrated	Constant	Need external controller for flash		?	200 x 100		11° - 30° - 34°		https://www.metaphase-tech.com/wp-content/uploads/2018/03/MB-FL-PDS-v20190611.pdf
8	Metaphase	USA		Line	MB-CCL	Integrated	Constant	Need external controller for flash		?	140 - 3100	1.5 million Lux	no		https://www.metaphase-tech.com/wp-content/uploads/2018/03/MB-CCL-PDS-v20191014.pdf

Machine Vision System

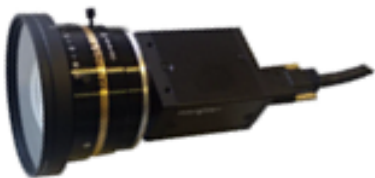
- Main components:
 - Machine vision camera from FLIR Co. (x3)
 - Flash LEDs from Metaphase Co. (x3)
 - Self-made synchronization (x1)

$$FOV_w [deg] = 2 \times \arctan \left(\frac{w[mm]}{2 \times f[mm]} \right) \times 180 [deg]/\pi$$

$$FOV_h [deg] = 2 \times \arctan \left(\frac{h[mm]}{2 \times f[mm]} \right) \times 180 [deg]/\pi$$

$$ET [s] = \frac{(D[m] \times B [px] \times PS [mm])/f[mm]}{V[m/s]}$$

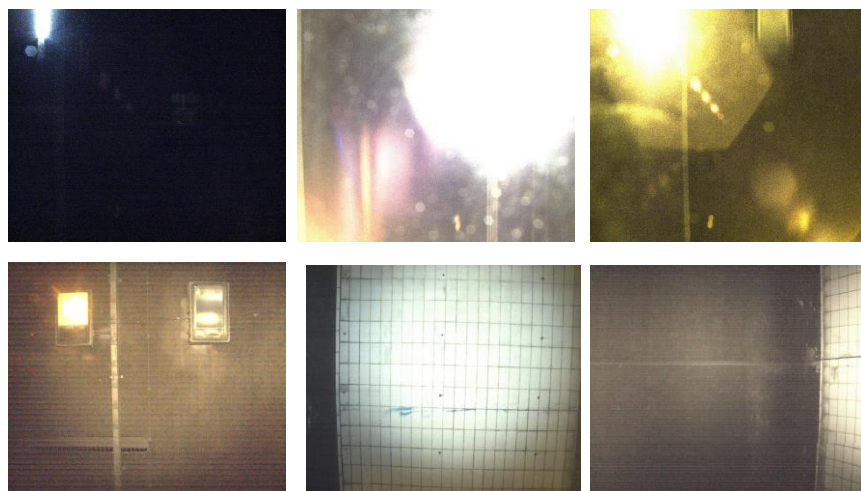
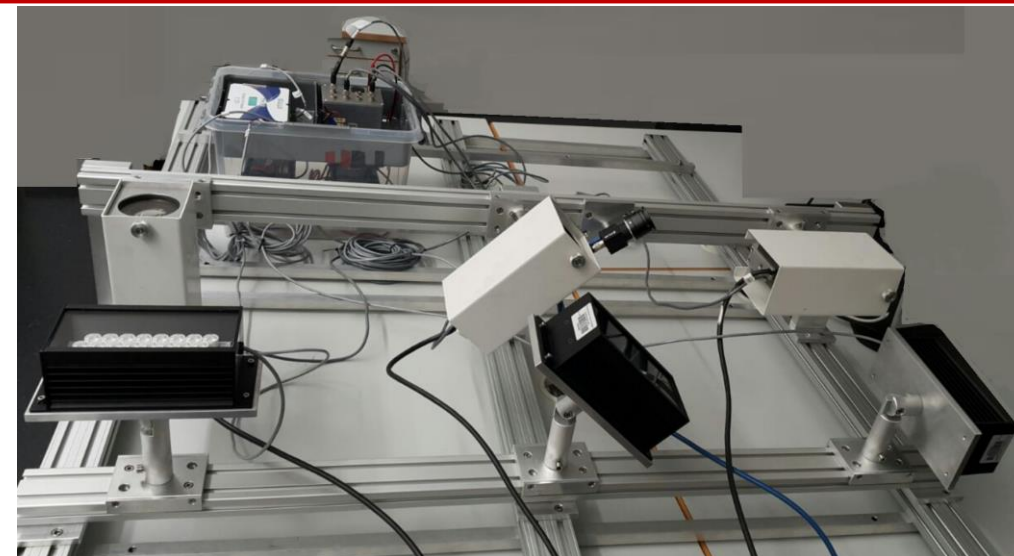
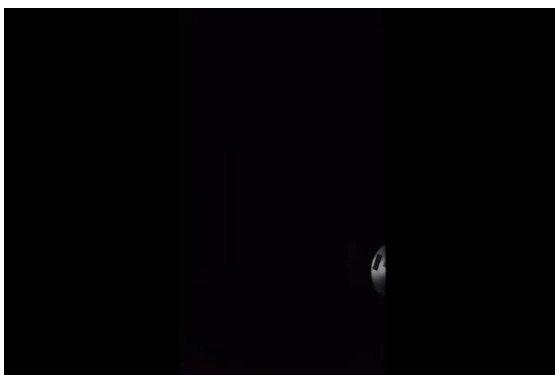
$$E [W/m^2] = E_o[W/m^2] \times \left(\frac{R_o[m]}{R[m]}\right)^2$$



Settings	Parameters	Values
Camera	Sensor	CMOS, Area Scan
	Resolution	5 MP
	Pixel size	3.45 μm
	Sensor size	2448 x 2048 pixels
	Focal length (lens)	6 mm
	Shutter	Global
	Required frame rate	5 Hz and 15 Hz
	Interface	USB 3.0 (400 MB/s)
	Pixel Bit Depth	8 bits
	Chroma	color and mono
	Exposure Time	250 μs
	Price range	\$1500
LED	LED shape	Area based
	Operation mode	Flash
	Wavelength	White
	Flash Pulse width	250 μs
	Flash rate	5 Hz and 10 Hz
	Irradiance at 2m	878 W/m2
	Price range	\$1000
Car	The driving speed	36 km/h
	Working distance	5 m
	Installation angle	45°
Operations	Irradiance at 5m	140 W/m2
	FOVw x FOVh	70° x 60°
	Vertical overlap	~ 35 % of FOVw
	Horizontal overlap @ 2Hz	~ 23 % of FOVh
	Actual frame rate	2 Hz and 4 Hz
	Exposure Time	~ 250 μs

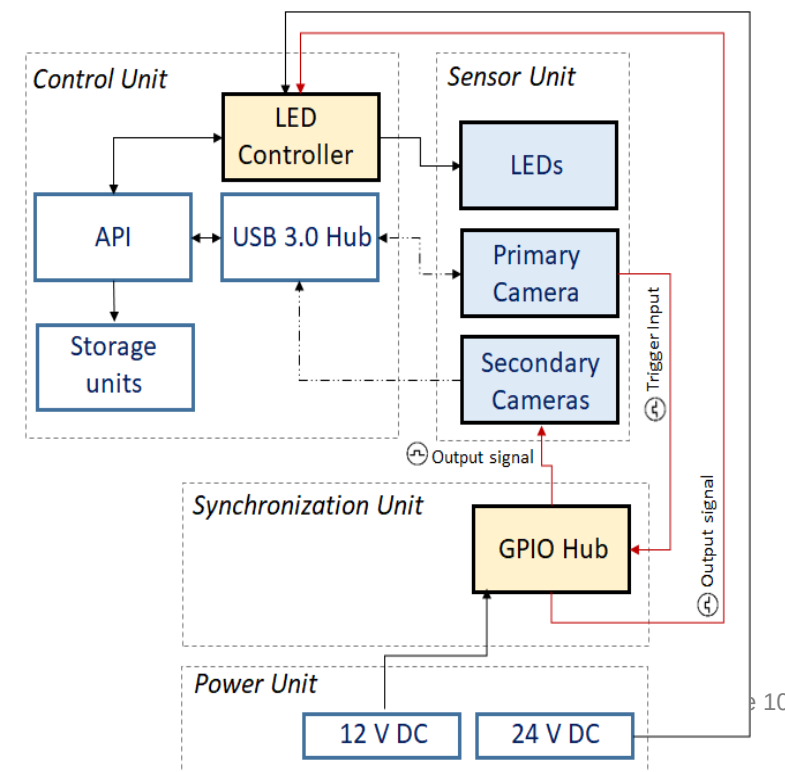
Synchronization

- To avoid motion blur and other illumination artifacts
 - Between cameras? **By Hand-made sync. unit**
 - Between the cameras and LEDs? **By LED controller**

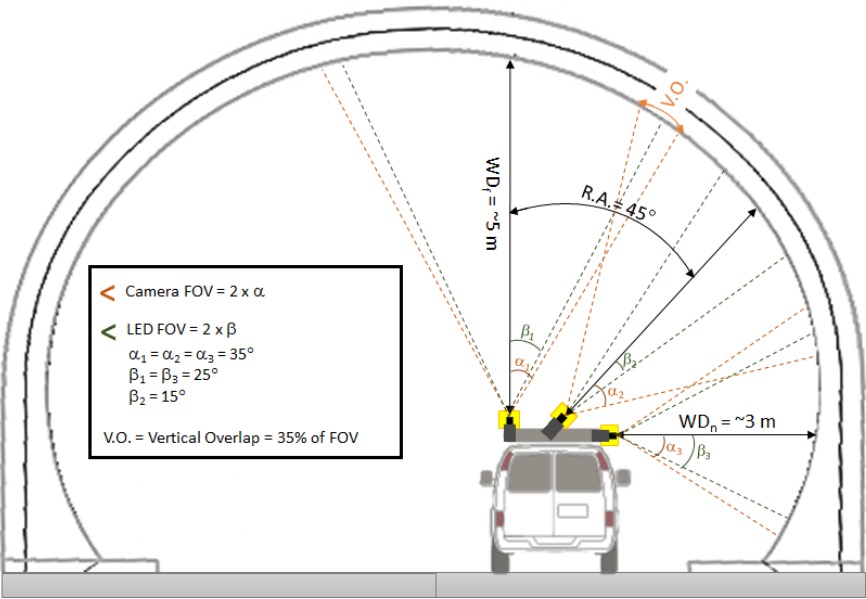


✗ non-synchronized system

✓ synchronized system

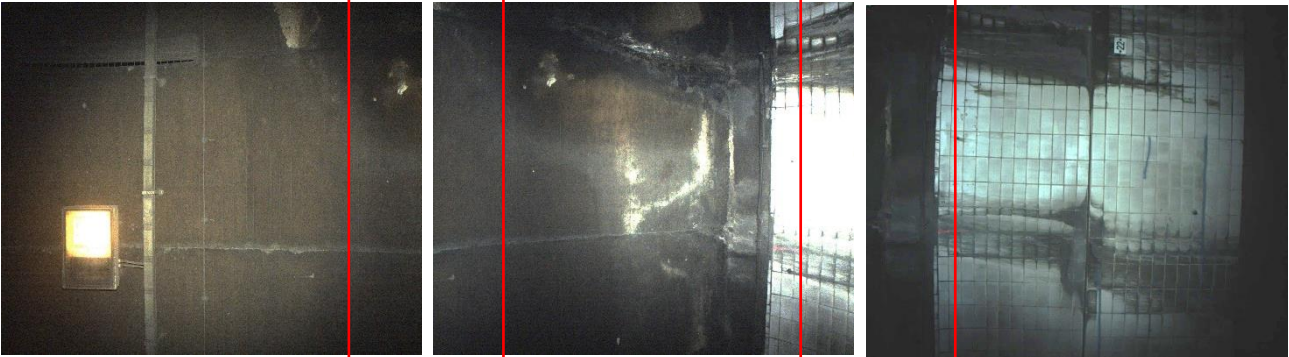


Data Capturing



H.O.

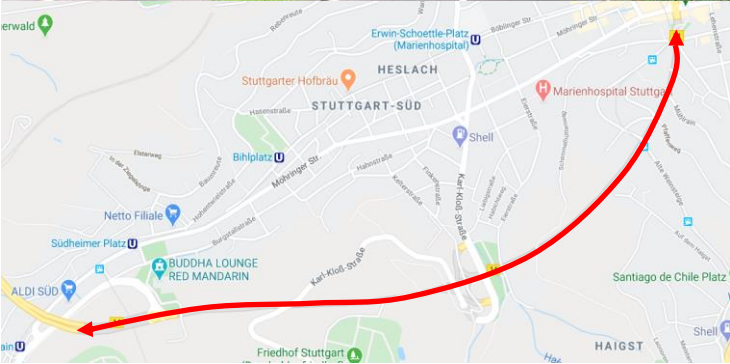
H.O.



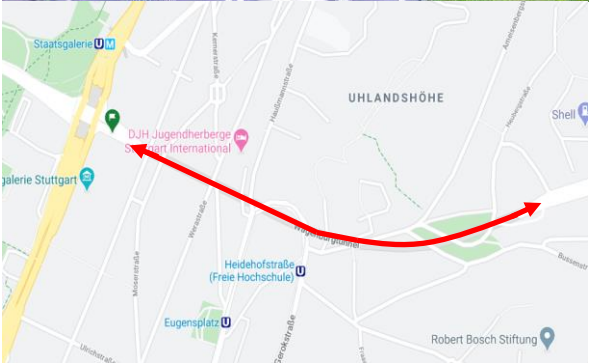
Cam. 1 the ceiling

Cam. 2 the corner

Cam. 3 the wall



Heslacher Tunnel
(Hauptstätter Straße)
very long tunnel



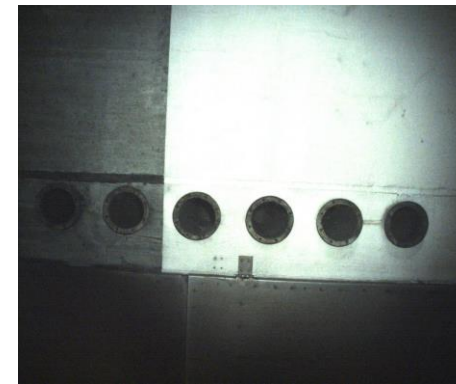
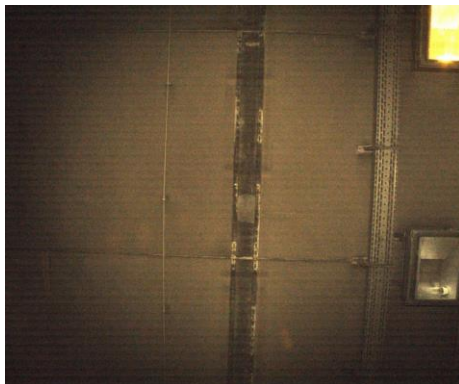
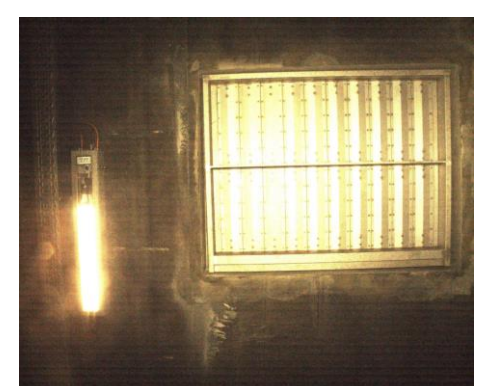
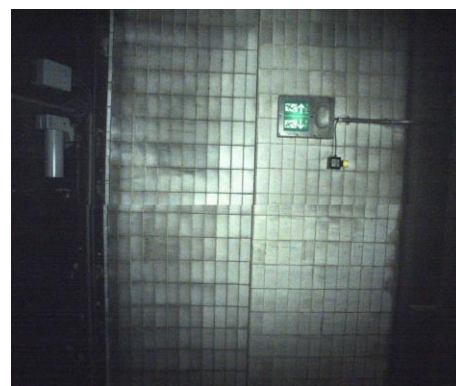
Wagenburg Tunnel
(Gebhard-Müller-Platz)
short tunnel

$$VerticalOverlap [\%] = \left(1 - \frac{\alpha[deg]}{FOV_w[deg]}\right) \times 100$$
$$HorizontalOverlap [\%] = \left(1 - \frac{V[m/s] \times f[mm]}{FPS[Hz] \times h[mm] \times D[m]}\right) \times 100$$

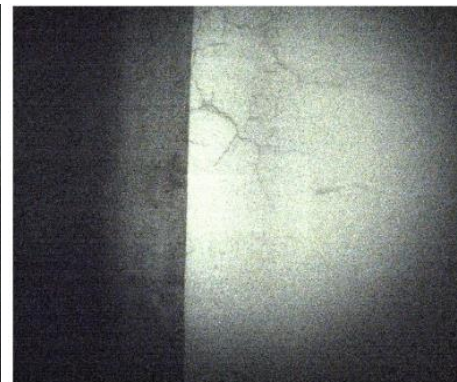
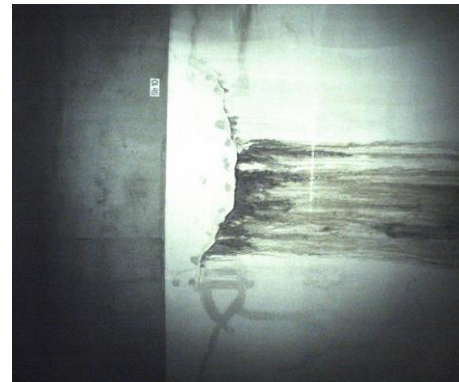
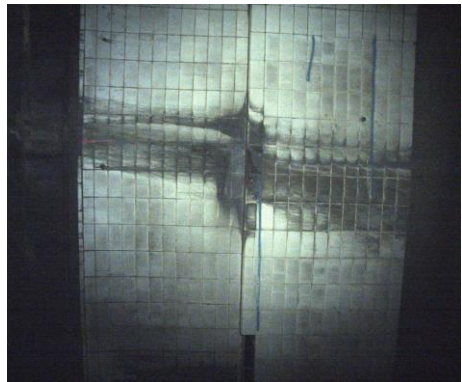
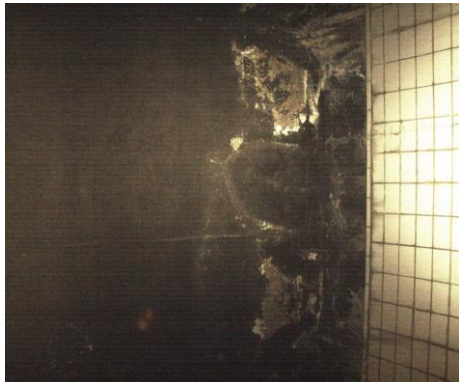
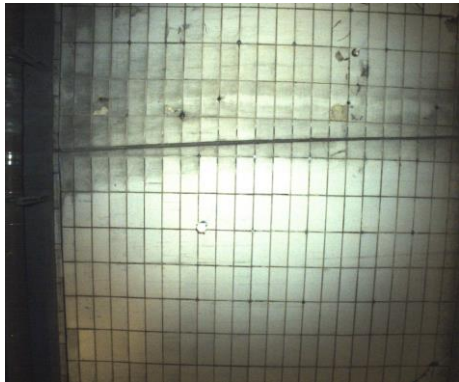
Data Capturing



Objects in the Tunnel



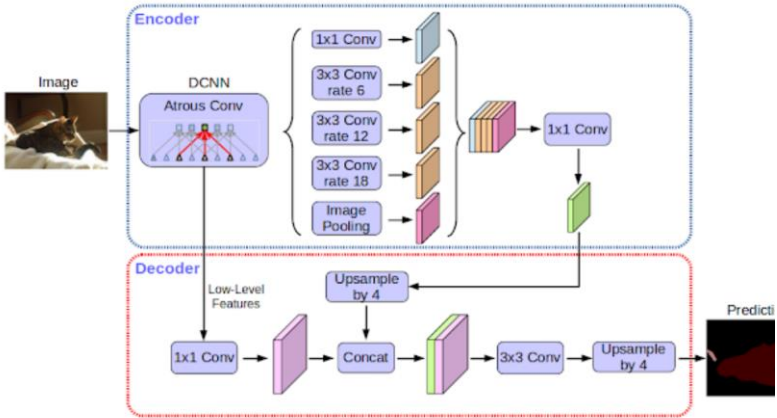
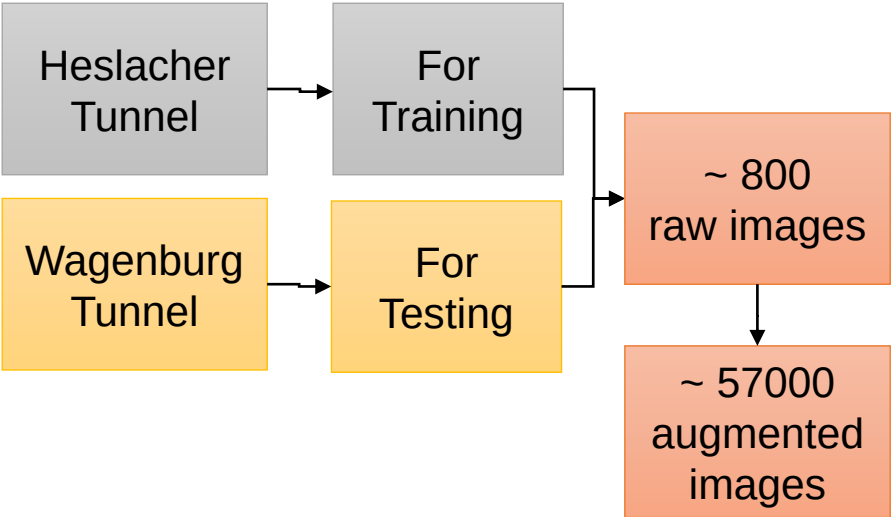
Damages in the Tunnel



AI-based Image Segmentation

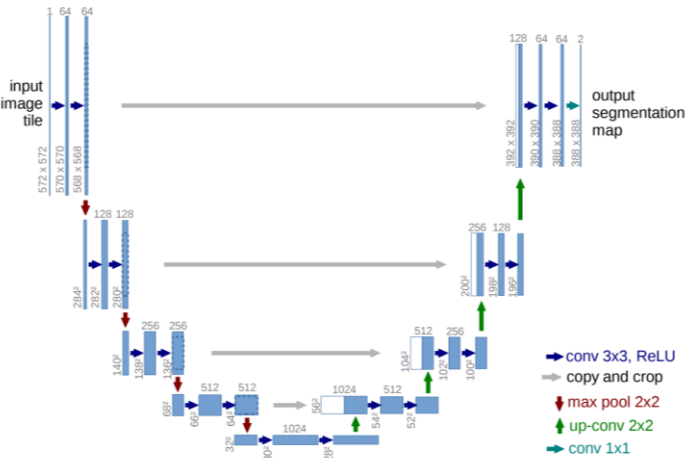
- **CNNs:**
 - DeepLab and U-Net
- **Data sets:**

Dataset	All	Training	Testing	Augmented data
Damages	220	200	20	23751
Objects	522	473	49	33583

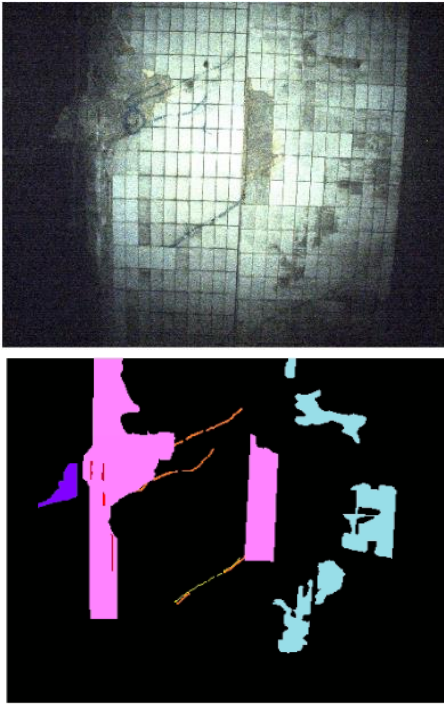
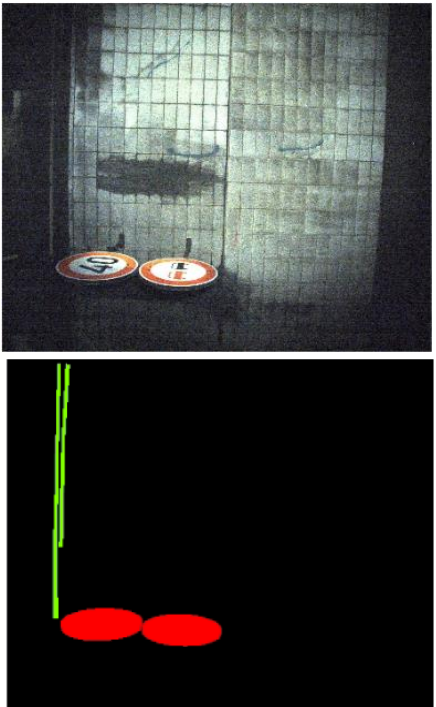


<https://ai.googleblog.com/2018/03/semantic-image-segmentation-with.html>

https://link.springer.com/chapter/10.1007/978-3-319-24574-4_28



- CableBoxes
- ElectronicBoxes
- AirVent
- AlarmSpeaker
- Cable
- TrafficLight
- AxialFan
- Sensors
- Lights
- Signs
- Background



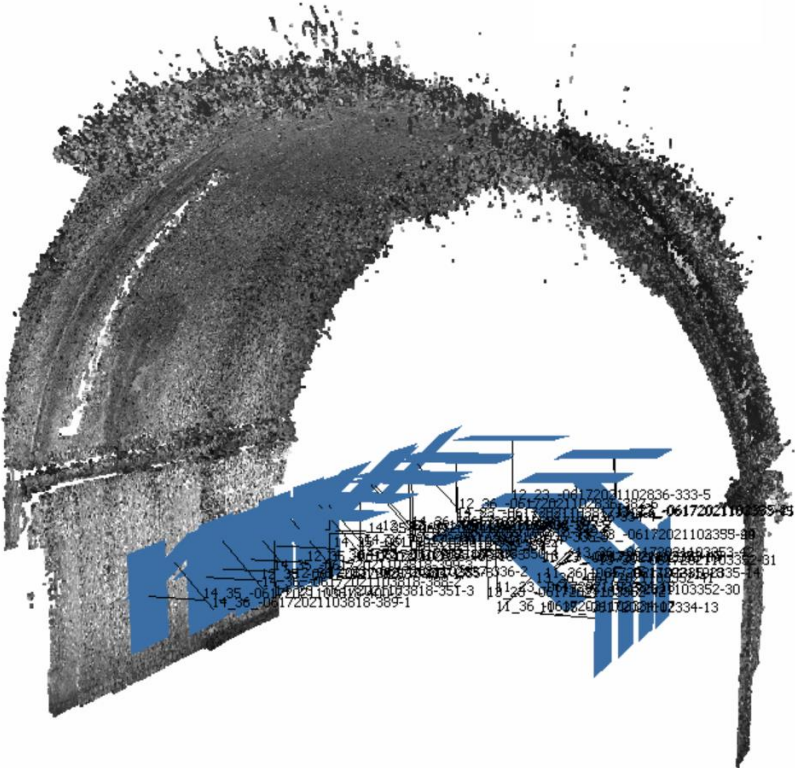
- Moss
- Efflorescence
- Delamination
- Spalling
- RustFlag
- Rust
- Rebar
- Cracks
- Background

Results

- **3D Model:**
 - The image overlap of 23% in the direction of travel and 35% in the transverse direction are not enough for point cloud generation.
 - Low illumination and a texture-less environment.

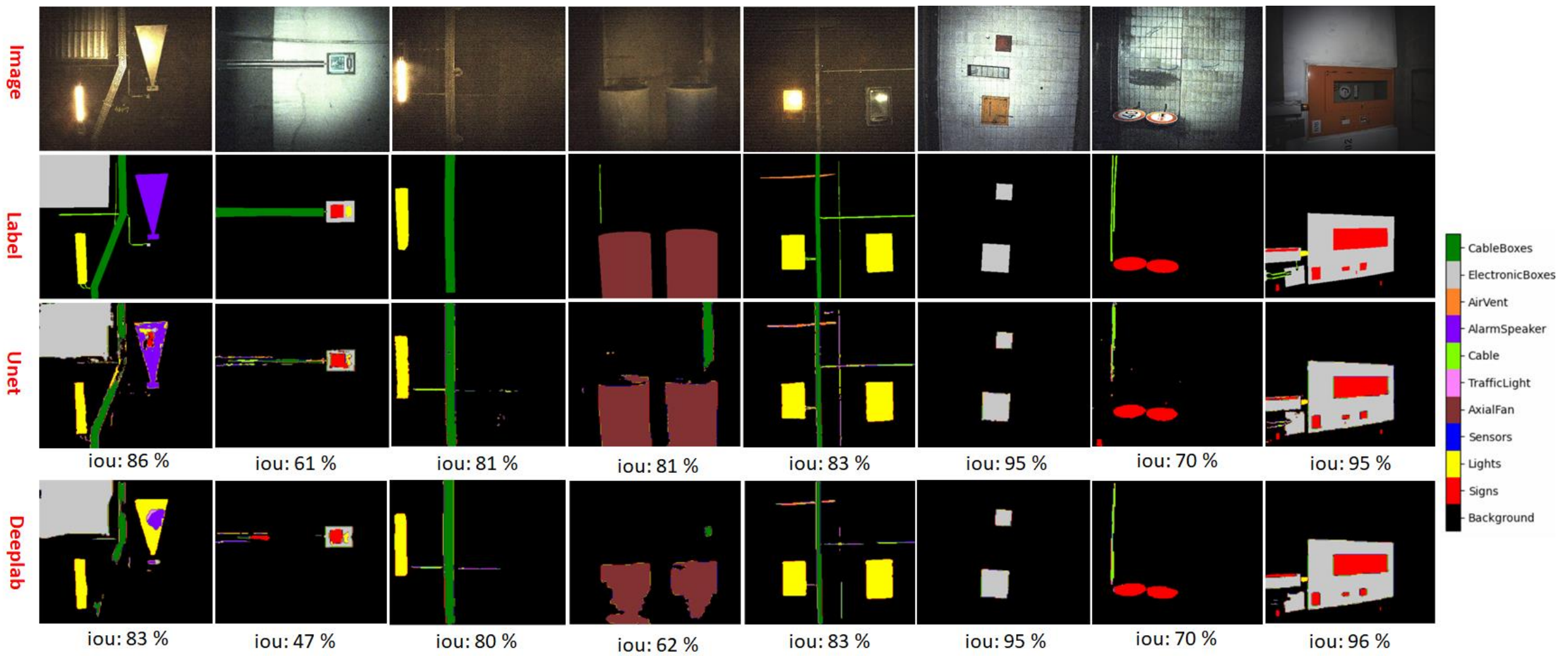
- **Image Segmentation:**

Model	IoU on object detection (%)	IoU on damage detection (%)
U-Net	78.6	49.3
DeepLab	75.9	48.5



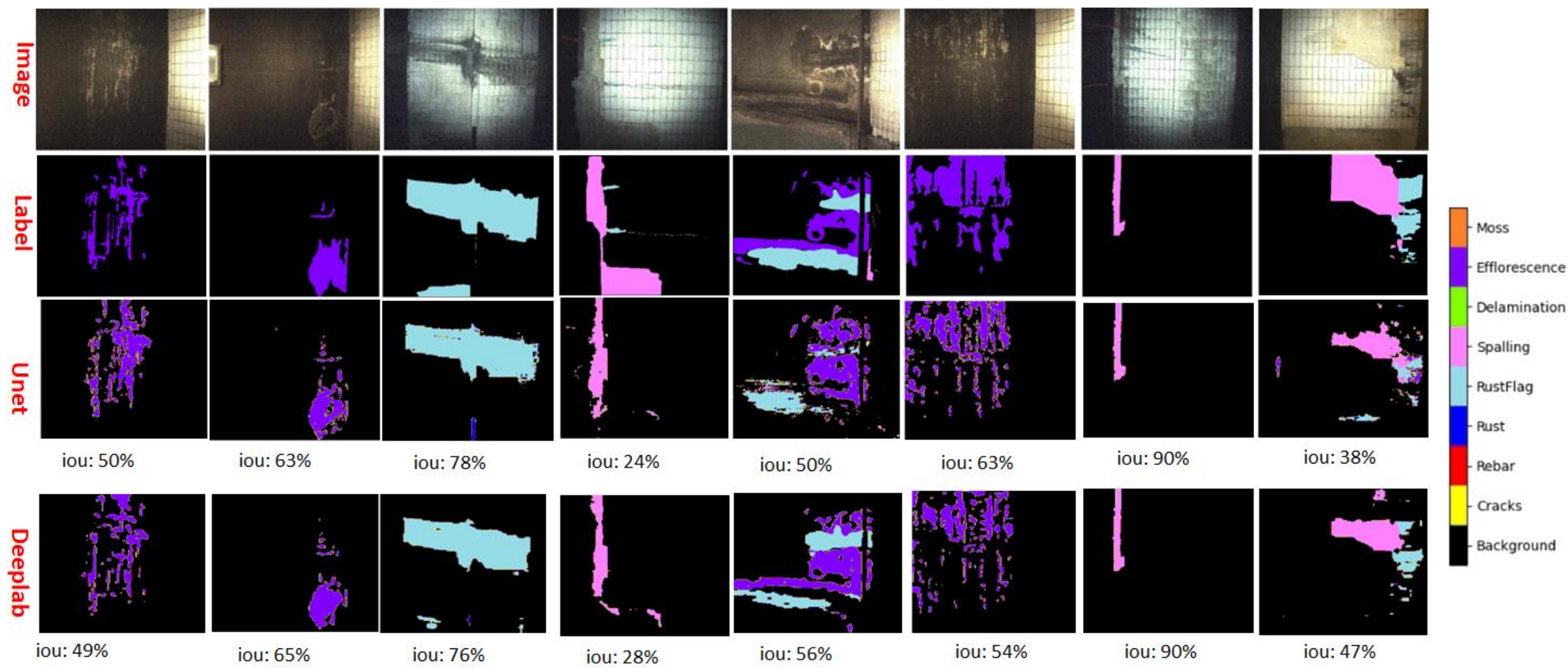
Results

- Object Detection



Results

○ Damage Detection



Conclusion

- Proposed a data automation approach for object/damage detection in tunnels using a combination of machine vision and machine learning techniques.
- The key parameters: the synchronization unit and the geometric design of the system so that well-illuminated images with sufficient coverage of the tunnel surfaces are captured.
- The data is used to train two CNNs to extract objects and damages from RGB images.
- The results show that U-Net outperformed the DeepLab model with IoUs of 78.6% and 49.3% for object and damage detection tasks, respectively.
- This research is funded by the Federal Ministry for Economic Affairs and Energy (BMWi) as part of the ZiM project ABOUT. The project partner is Viscan Solutions GmbH (www.viscan.de).

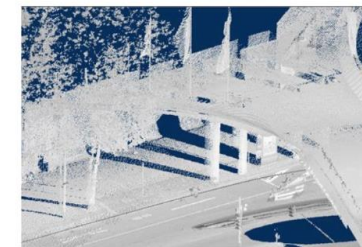


Completed projects



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Completed projects



ABOUT

Tunnelmonitoring

<https://www.hft-stuttgart.com/research/projects/completed#subnavigation>

Thanks for your attention