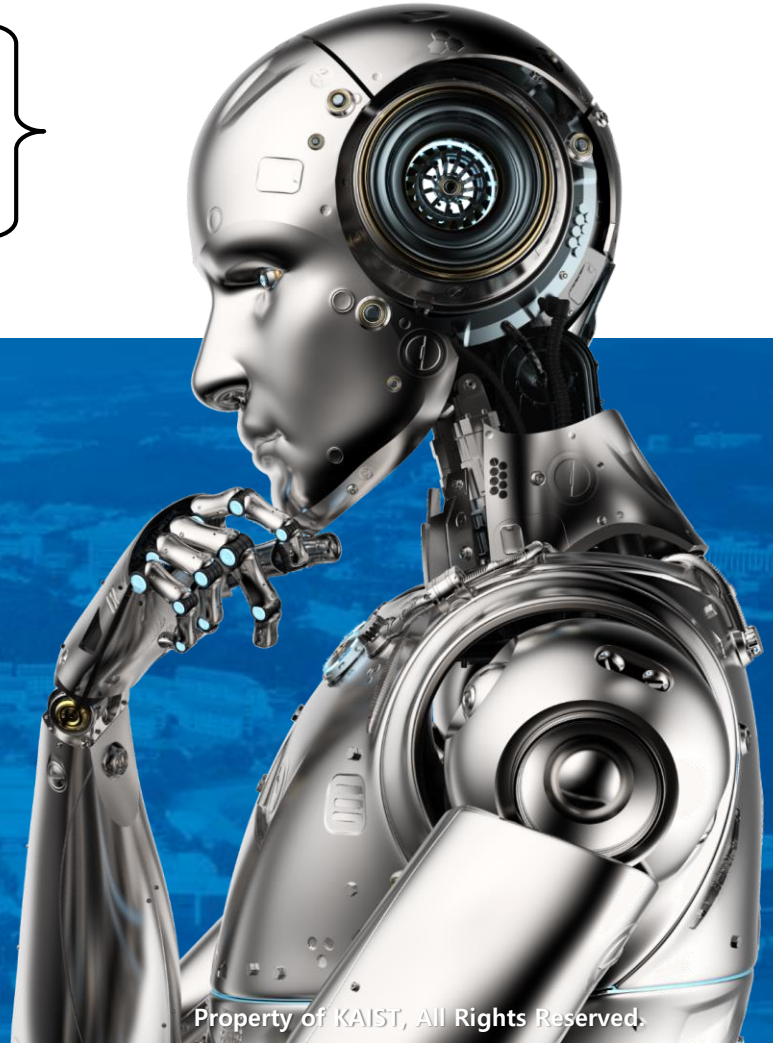
KAIST

HUMAN LAB
HUMAN-MACHINE INTERACTION

진동 음향, 3D정보 기반 센서 및 인식 기술

인간-기계 상호작용 연구실 소개
Human-Machine Interaction LAB



HUMAN LAB 연구소개
2023년 10월 6일

박 용화 교수
HUMAN LAB
NOVIC+ (Center for Noise and Vibration Control Plus)
Department of Mechanical Eng., KAIST

"본 영상은 실험 동영상 외에는 무음으로 제작 되었습니다."

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Prof. Yong-Hwa Park

(1987~1999)	BS, MS, Ph.D at Mechanical Eng., KAIST Structural Vibration and Optimization
(2000~2003)	Post Doc. Of Univ. of Colorado at Boulder Microelectromechanical System Design
(2003~2016)	Research Master of SAIT, Samsung Electronics 미래 센서 연구 개발 Published 70+ US Patents

- NOVIC+ 센터장 (2023~)
- KAIST 기계공학과 산학협력위원장 (2017~)
- KAIST ILP(산학자문위원회) Prog. Director (2021~)
- AI 연구소 운영위원, 로봇학제 참여교수 (2022~)
- 대한기계학회, 소음진동공학회 부회장 (2023~)
- KAIST Tennis Championship (1996, 2000)

Research Topics

- Mechanical Vibration, Condition Monitoring (PHM)
- Auditory Intelligence, Acoustic Recognition
- Human Sound and Vibration, Health Sensors
- 3D Measurements (Lidar), AI-base Recognition

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주인공 토니스타크를 도와주는 **인공지능 집사 Jarvis**



3D 계측 및 인식

음향인식, 청각지능

진동 해석 및 상태진단

[스타크]
"자비스, 심장 체크해봐. 내 뇌가 이상한거야?"

[자비스]
"심장이랑 뇌에는 전혀 문제가 없어요."

생체 건강 진단

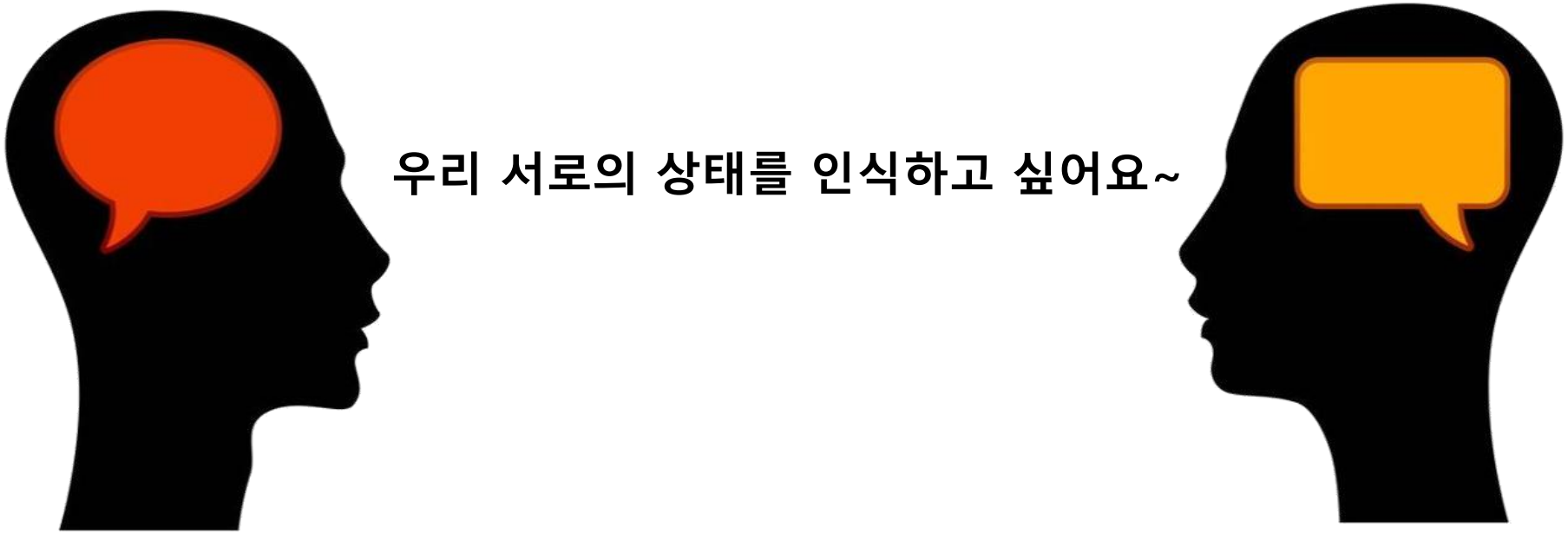
[스타크]
"그럼, 독극물에 중독됐어?"

[자비스]
"제가 보기엔 심각한 불안증세예요."

HUMAN LAB's Motivation!

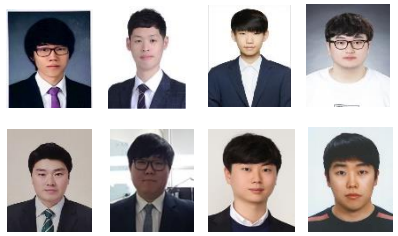
“진동, 음향, 3D계측을 통해 **인간과 기계의 상태를 인식하는 센서, AI에 대해 연구합니다”**

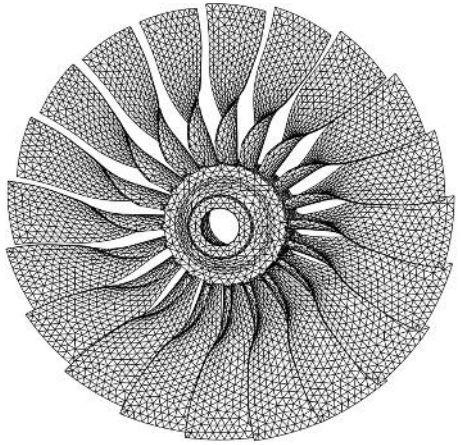
2023년 가을 기준, 박사과정 17명, 석사과정 10명 (27명)

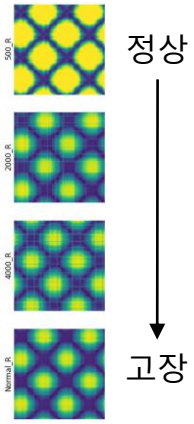


Research Topics & Members

진동해석 상태진단
Vibration Analysis & Condition Monitoring

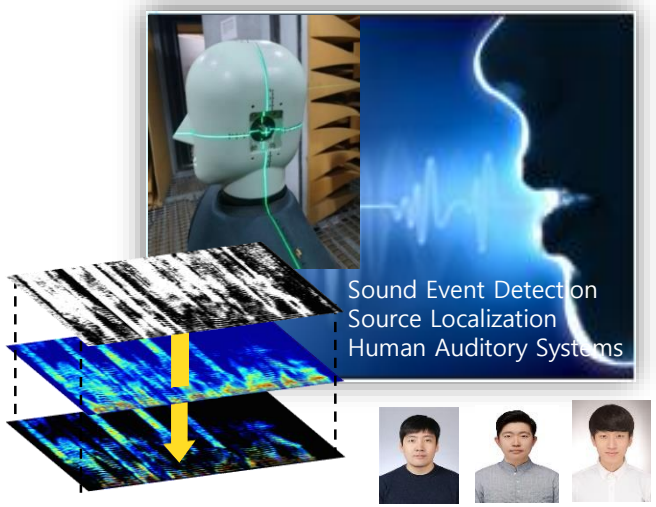


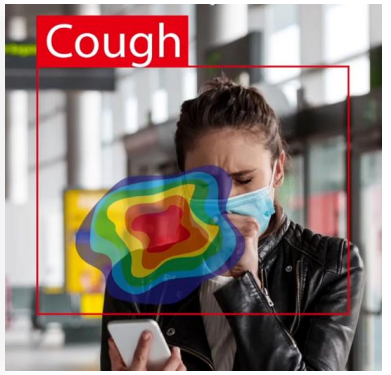


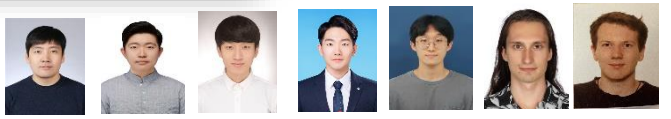


Hi-Fidelity Vibration Analysis
AI-based Condition Monitoring

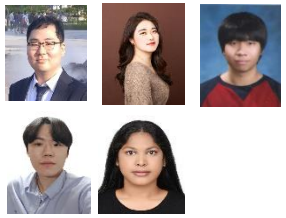
청각지능 · 음향인식
Auditory Intelligence & Acoustic Recognition



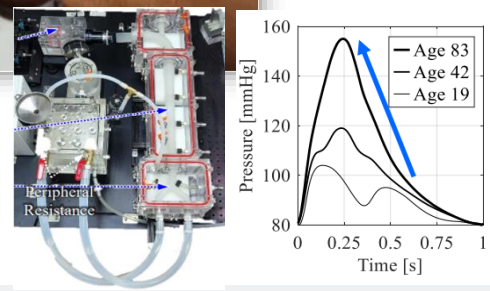




인체진동 건강센서
Human Vibration & Health Sensors







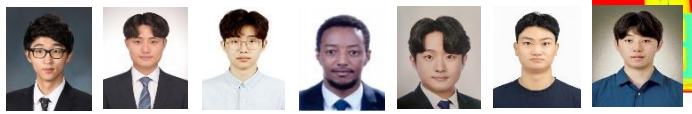
Non-invasive
Health Sensor

3차원 공간 인식
3D Scene Recognition

Full HD 3D Map from 3D Lidar
(KAIST Human Lab)

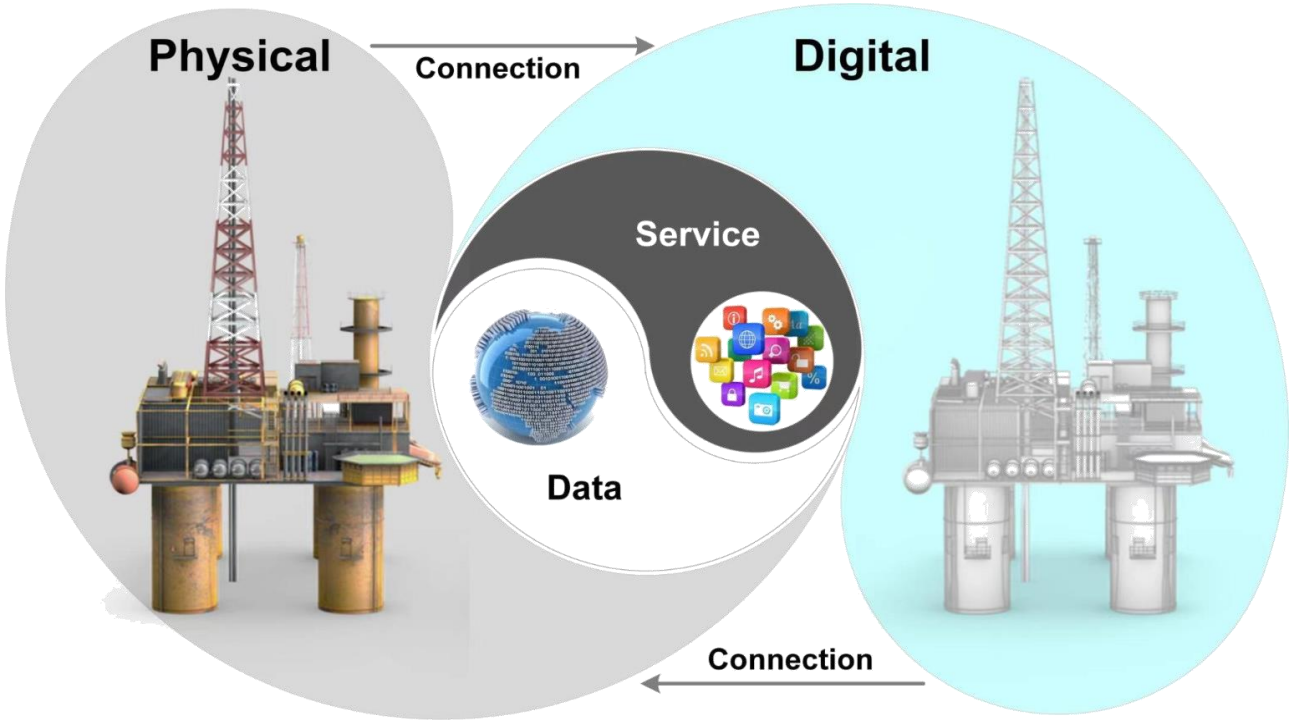






High-Fidelity Digital Twin for Condition Monitoring

- A virtual presentation of a real **dynamical** structure



1. What?

A digital twin is a digital representation of a physical object, process or service. A digital twin can be **a digital replica of an object in the physical world**, such as a jet engine or wind farms, or even larger items such as buildings or even whole cities.

2. Why?

As well as physical assets, the digital twin can be **used to replicate dynamical behaviour in order to collect synthetic data** to predict how they will perform dynamically.

Hi-Fi Digital Twin in Human LAB

Problem to Solve

Insufficient fault data

Fault data is harder to collect practically than the normal data. The **insufficient fault data** significantly **degradade the accuracy** of the trained classifier. Accurate and sufficient fault data should be generated from the Hi-Fi Digital Twin.

Experiment from Physical Systems



"Data Imbalance"

Normal

Fault

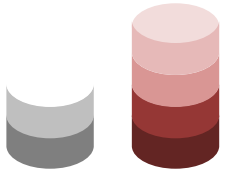


Synthetic Data from Digital Twin



Data

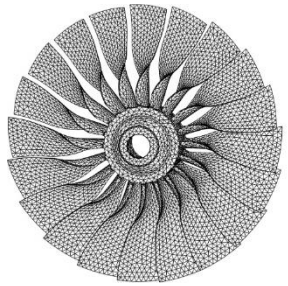
Normal Fault



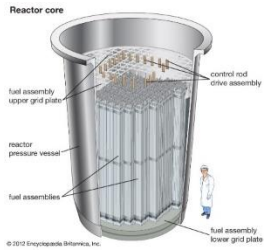
Performance to Achieve

Precision

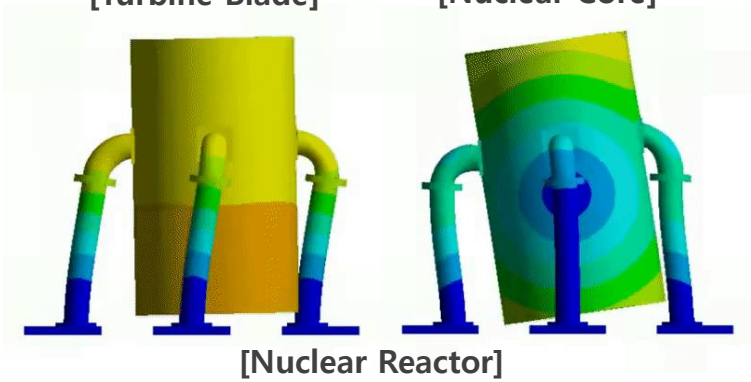
The fault diagnosis is required for power plants, turbine, nuclear reactors, engine, transmissions, motor, and compressors which are **complicated and coupled-physical systems** with **uncertainties** and **nonlinearities** (contact, localities…).



[Turbine Blade]



[Nuclear Core]

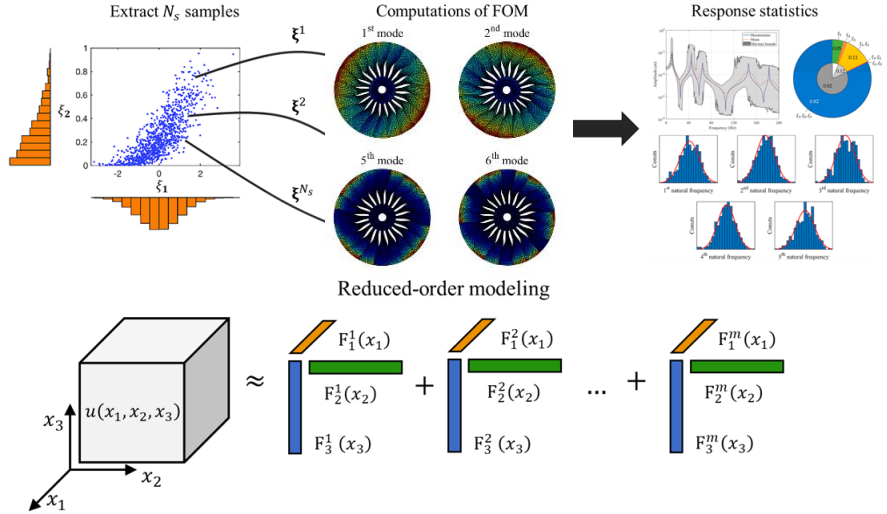


[Nuclear Reactor]

Computational Efficiency

Due to so-called **"curse of dimensionality"** The computational efficiency required for digital twin application is limited in using commercial softwares (ANSYS, ABAQUS,…)

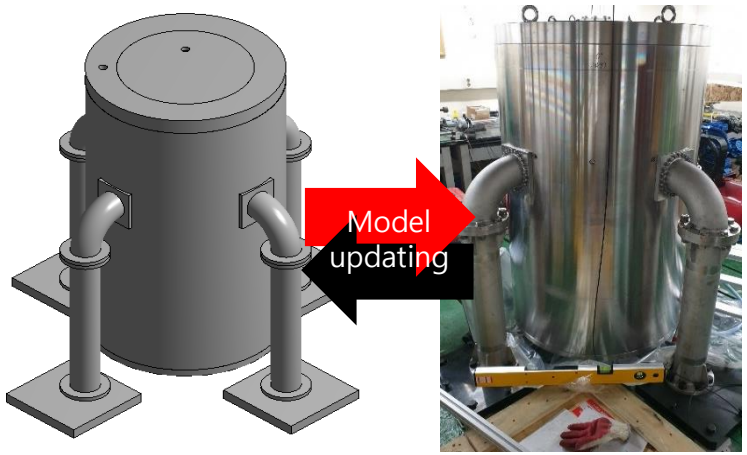
Reduced order model(ROM) and **decomposing of dimensions (PGD)** to tackle the computation limitation is being actively conducted (3 to 5 folds more efficient than the previous methods)



Projects for Hi-Fi Digital Twins in Human LAB

Project #1 FEM Model Updating and Experimental Modal Analysis for safety assessment of nuclear reactor vessel

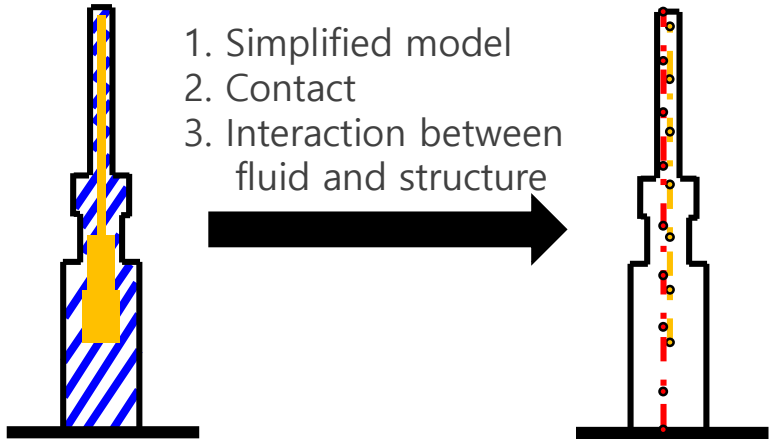
Modal test and FEM model updating were conducted **to validate robustness of the nuclear reactor vessel**, especially nuclear coolant considered as acoustic fluid and simplified as **added mass effect**.



Example 1. Nuclear Reactor **Vessel**

Project #2 Nonlinear Transient Analysis with Fluid-Structure Interaction in Nuclear Reactor

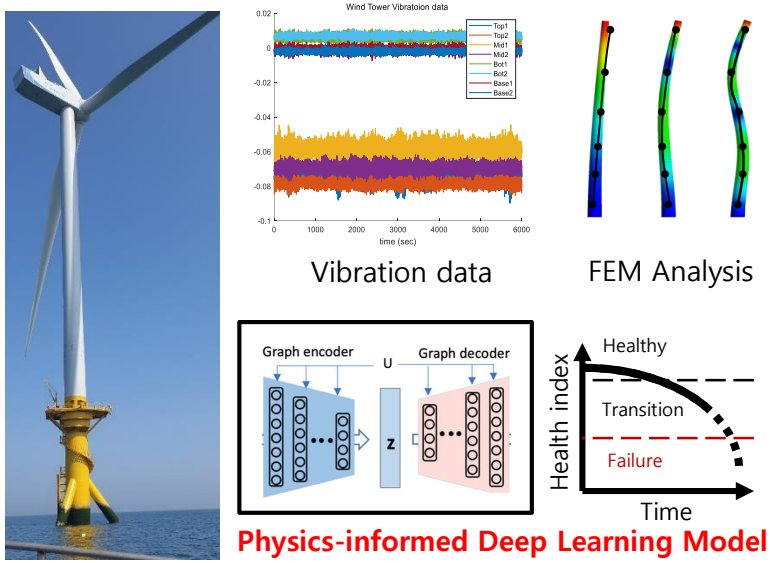
In order to evaluate the **drop time of the control rod**, which falls in an emergency in the nuclear reactor, a nonlinear dynamical analysis was performed **considering the interaction between fluid and structure**.



Example 2. Nuclear Reactor **Control Rod**

Project #3 Fault diagnosis for Offshore Wind Turbine Tower using Physics-informed Deep Learning

To achieve **fault diagnosis** of offshore wind tower flanges, HI-Fi Digital Twin combined with **Physics-informed AI-model** is developed to tackle the **lack of failure data.**

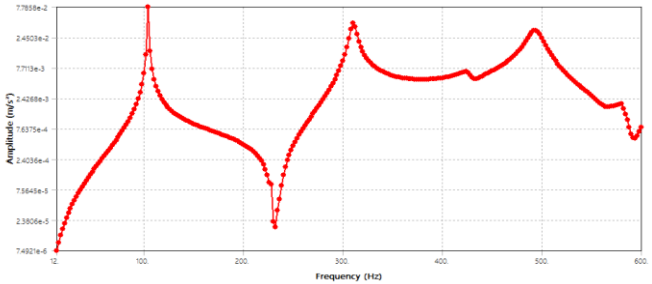


Example 3. Wind Turbine Tower

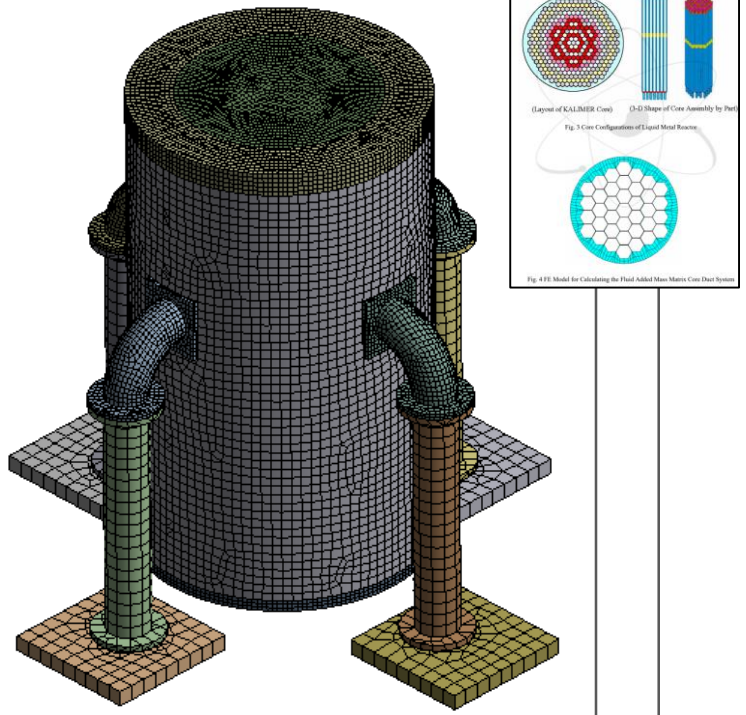
High Fidelity Digital Twin (고정밀 진동해석)

Finite Element Model,
Experimental
Modal Analysis of Reactor

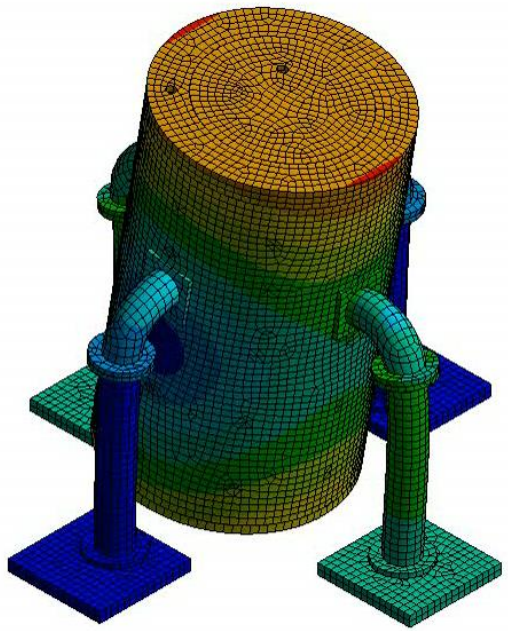
Frequency Response Functions (FRF)



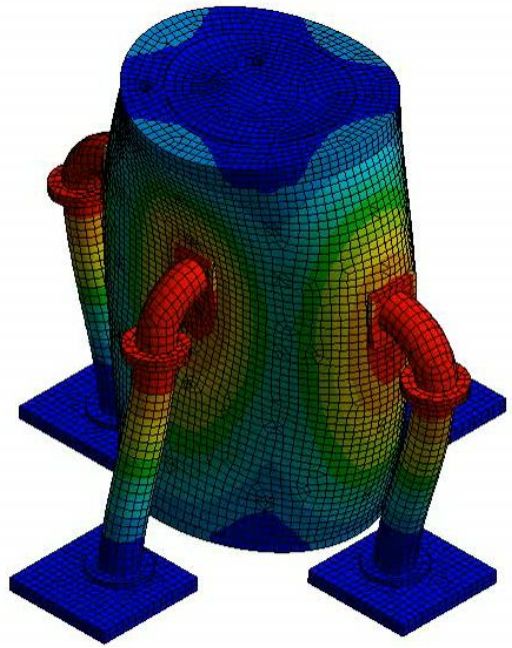
FEModel of Reactor



Vibration Motion of Reactor from Finite Element Method

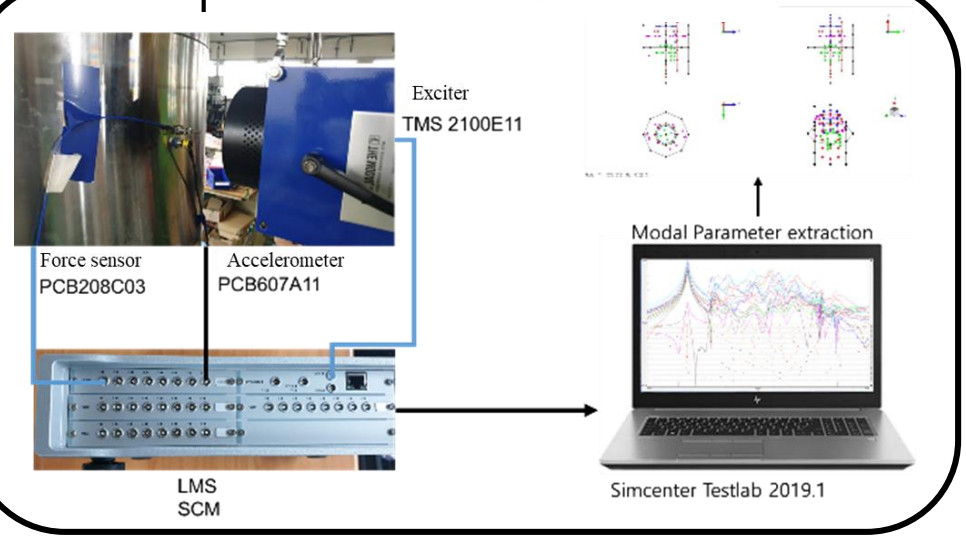


64.6 Hz

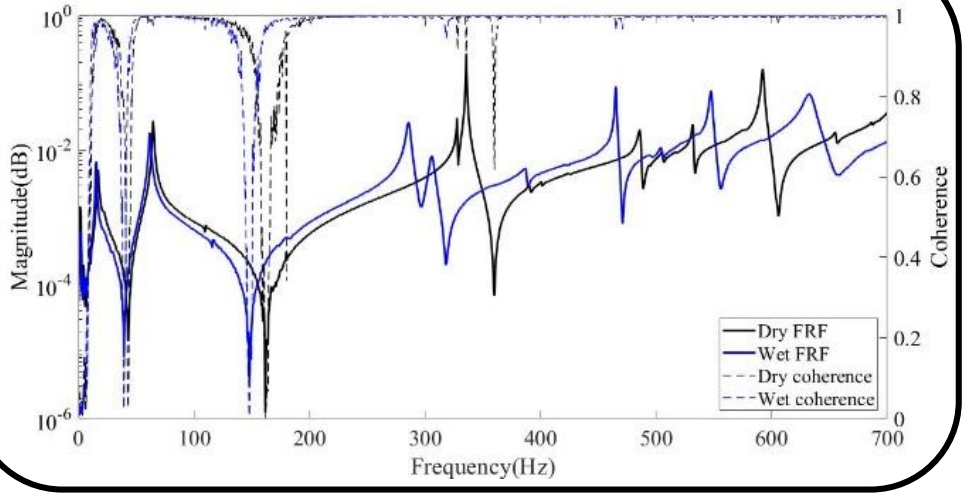


308.5 Hz

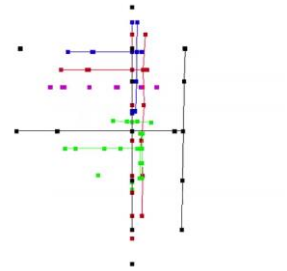
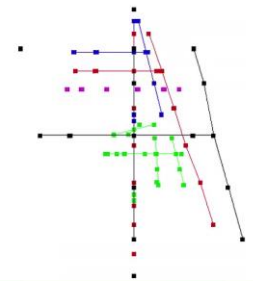
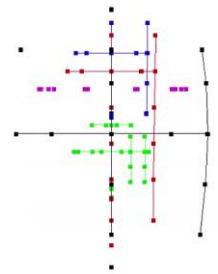
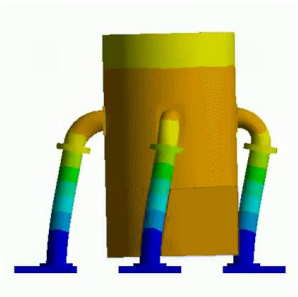
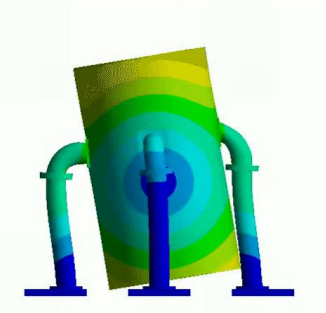
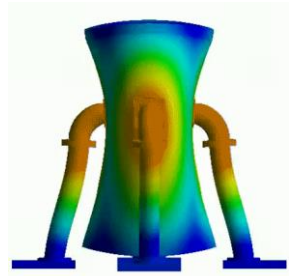
Experimental Modal Test



FRF Identification Results



FE Model Updating

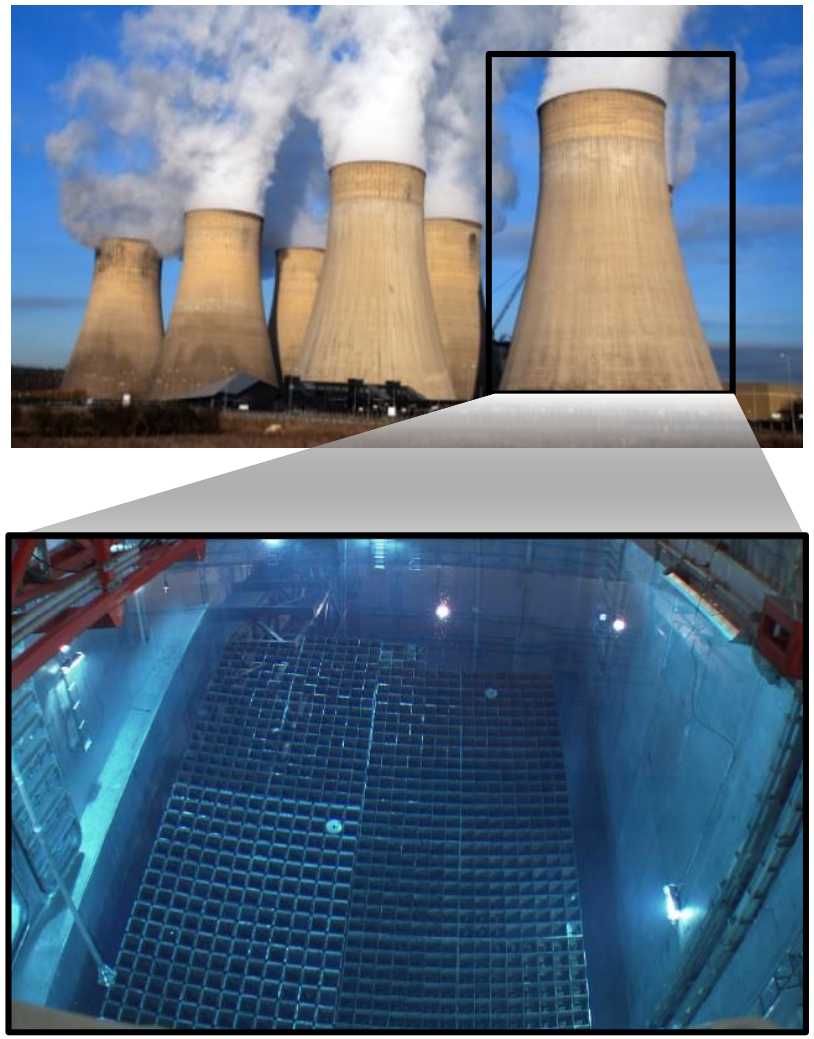
Mode	Translation	1st Bending	(2,1) shell
EXP			
FEM			

Mode	Dry condition(f_d)				Wet condition(f_a)			
	EXP	FEM	Error	MAC	EXP	FEM	Error	MAC
Translation	16.2	16.3	0.62	0.954	14.9	14.5	-2.68	0.949
Rotation	63.4	64.6	1.89	0.898	59.9	60.9	1.67	0.941
(2,1) shell	312	308.5	-1.12	0.946	282	276.8	-1.84	0.842

*In addition, the results of the other 13 modes also have errors **of 5%** in both dry and wet condition

지진에 의해 낙하하는 원자력 연료봉의 낙하 해석 (Time Domain Vibration Analysis)

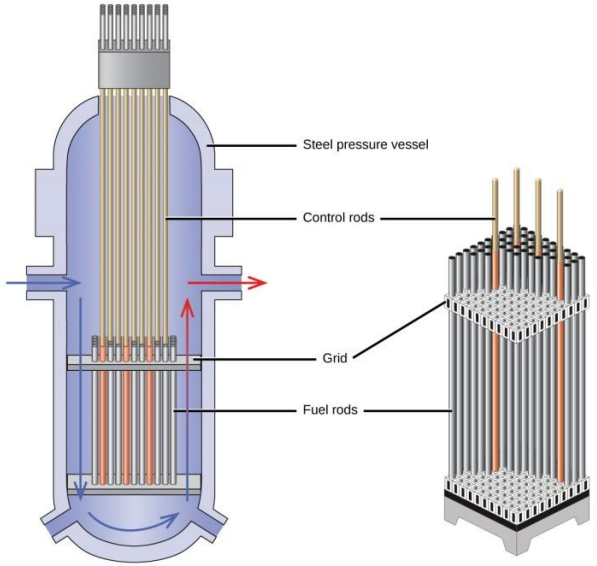
A Nuclear Power Plant



Time response analysis under highly-nonlinear characteristics such as **fluid-structure interaction** and **Contact** is required. Accuracy and computational efficiencies are extremely challenging

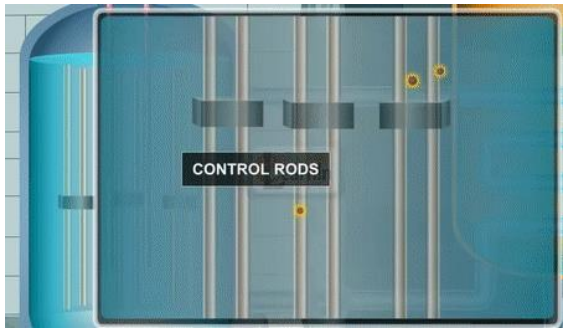
[Element]
Solid → Beam or Shell

[Reduced Order Model]
Proper Generalized Decomposition



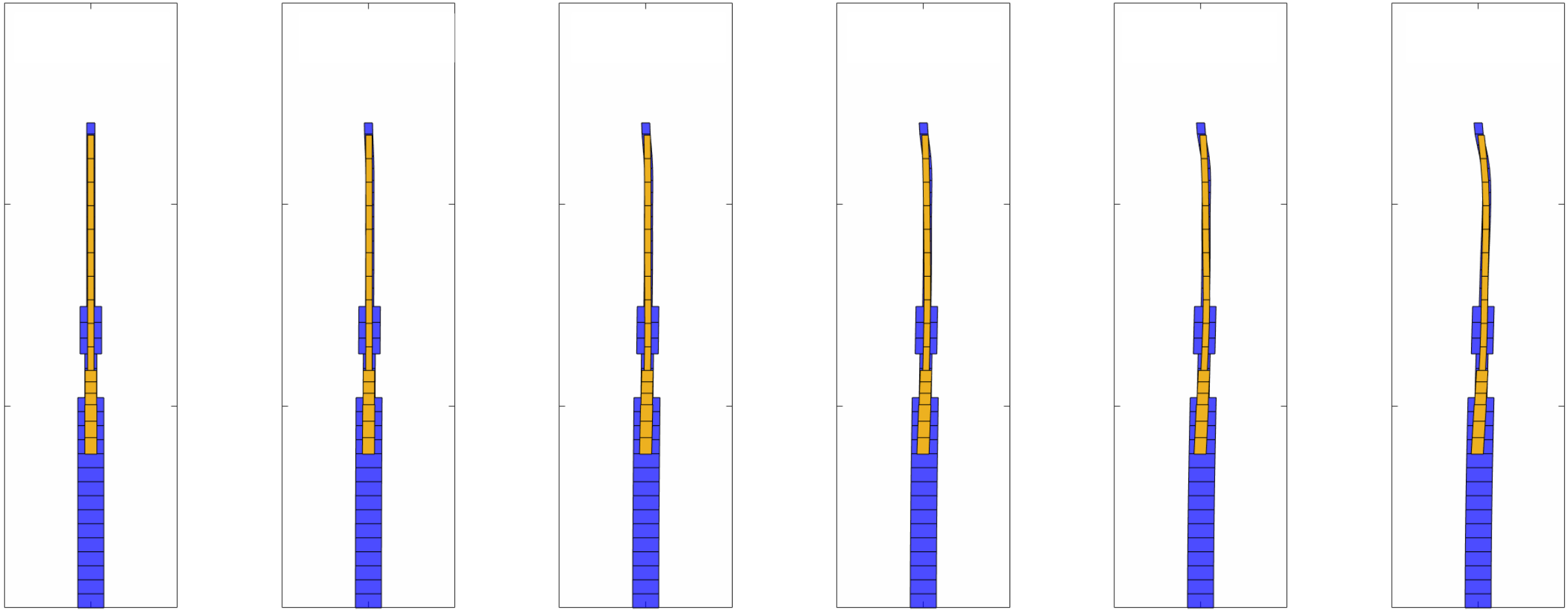
The material of the control rod is **cadmium or boron**, which absorbs neutrons well.

● : Neutron



지진에 의해 낙하하는 원자력 연료봉의 낙하 해석 (Time Domain Vibration Analysis)

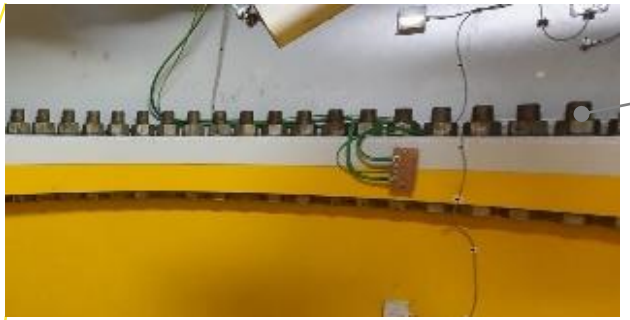
Stage 0 Stage 1 Stage 2 Stage 3 Stage 4 Stage 5



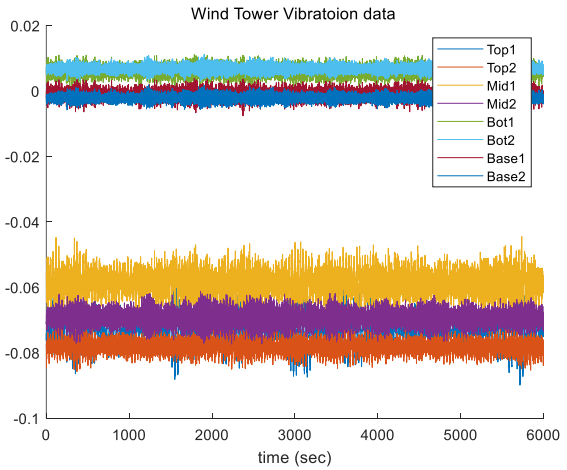
Condition Monitoring of Wind Turbine Tower with Physics-informed AI

Fault diagnosis of offshore wind turbine tower

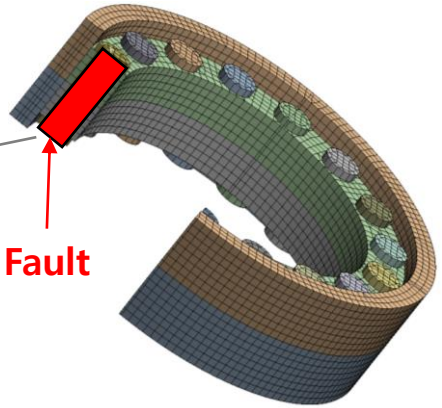




Bolt flange with sensor

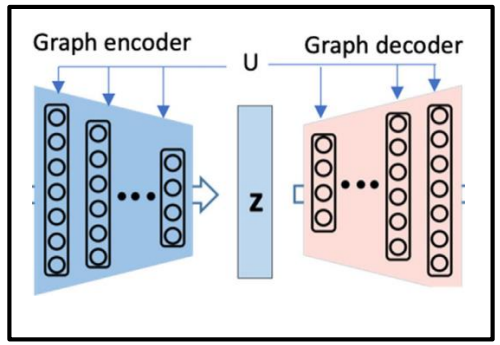


Measured data

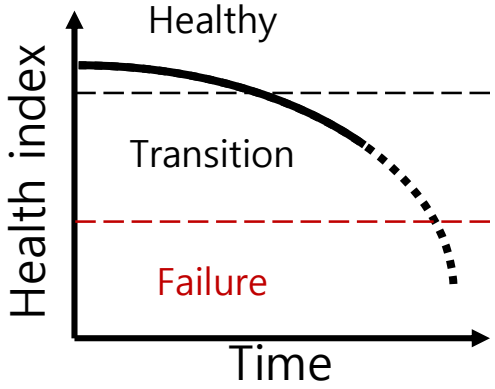


Bolt flange with fault

To achieve **fault diagnosis** of offshore wind tower flanges, HI-Fi Digital Twin combined with **Physics-informed AI-model** is developed to tackle the **lack of failure data.**



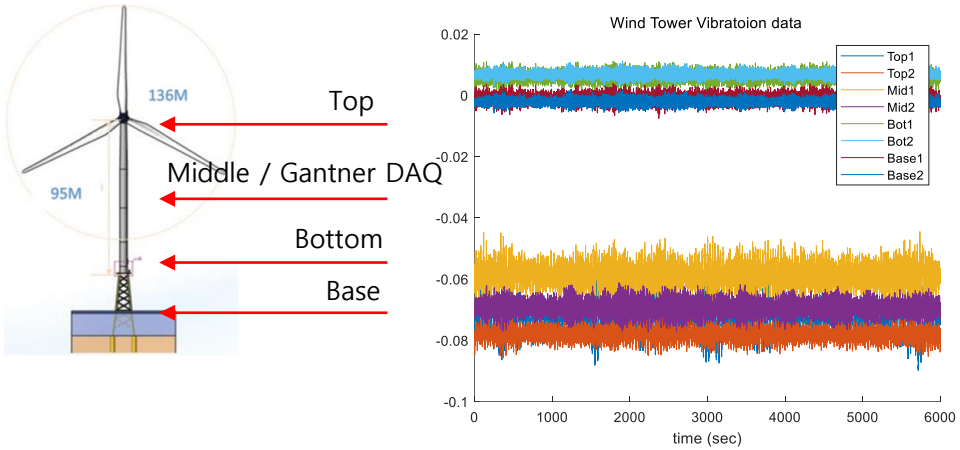
Physics-informed Deep Learning Model



Condition Monitoring

Digital Twin of Offshore Wind Turbine Tower

A. Data-Driven System Identification (Experiment)



Structure

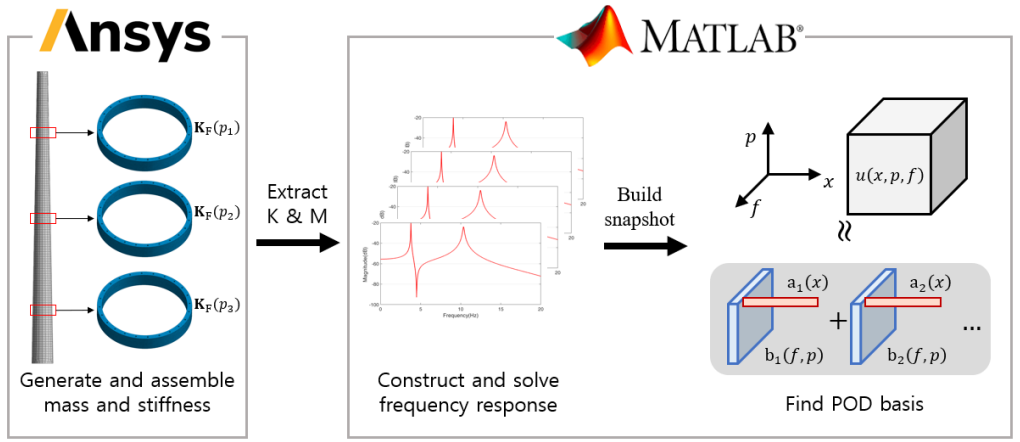
Sensor data

Experimental Feature Extraction
(ex. modal parameters, FRF)

Correlation

Updated Model

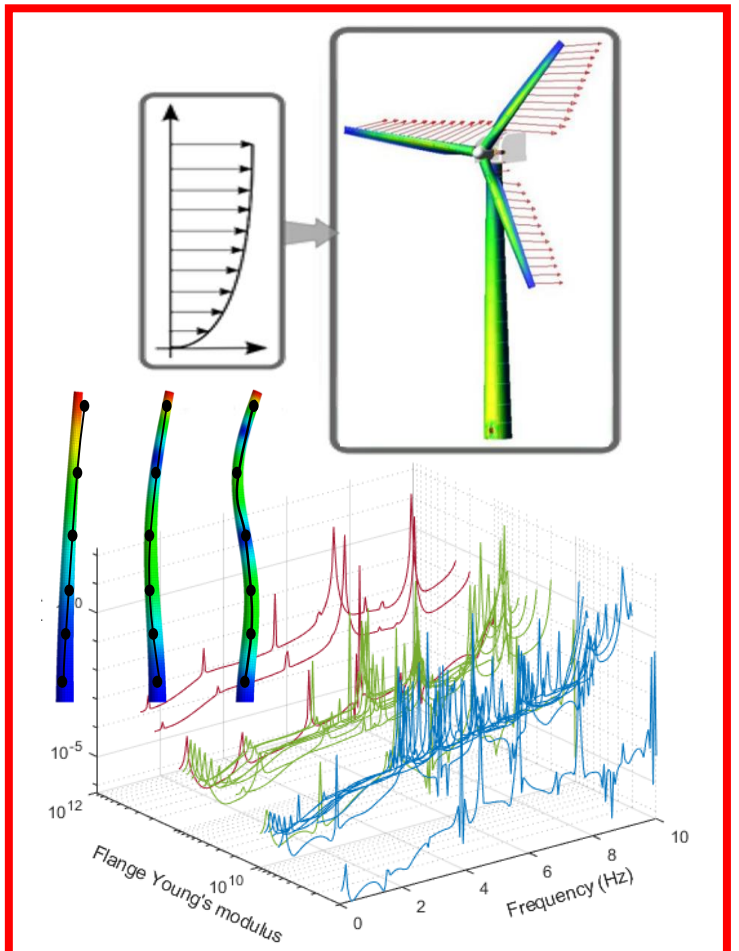
B. Model-Driven System Identification (FEM)



Analytical Feature Extraction
(ex. M, C, K, modal parameters, FRF, ...)

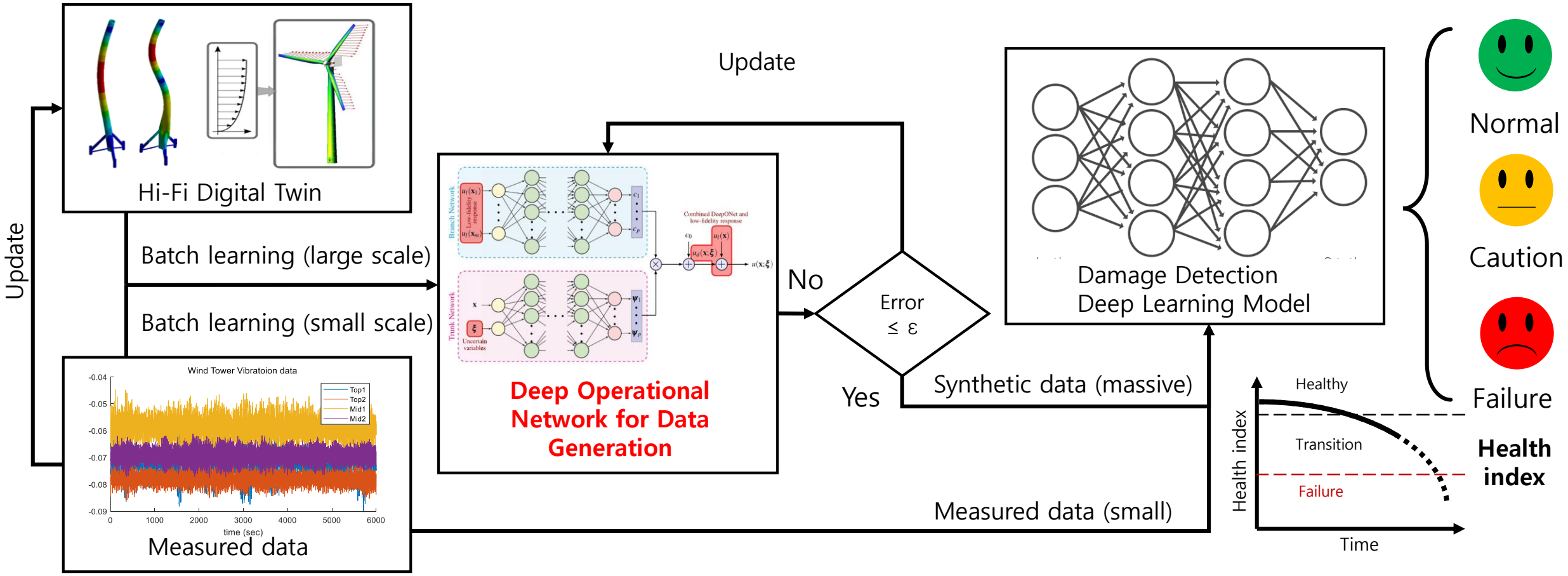
Hi-Fi Digital Twin:

Build a reliable model that can generate massive failure data



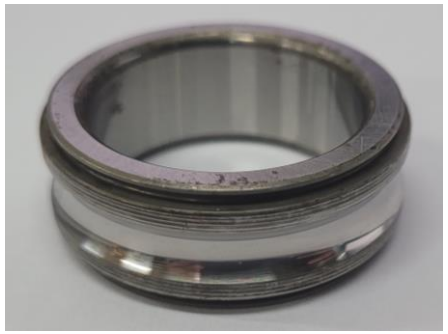
Virtual Tower response

- **Damage detection algorithm using Physics-informed Neural Net**
  - Development of data generation deep learning model through real and virtual data.
  - Development of damage detection model through flange failure model and deep learning algorithm.

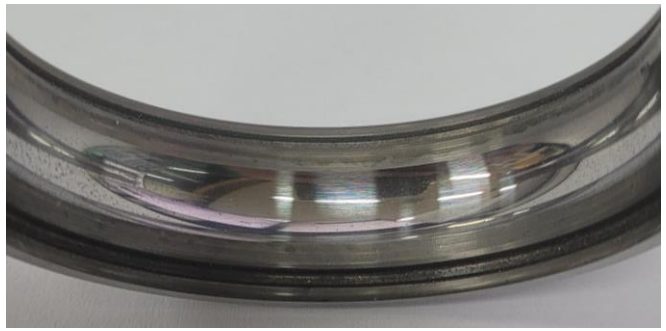


Deep learning based rotating machinery diagnosis using time-series data imaging (신호 시각화와 딥러닝을 이용한 고장진단)

- Bearing vibration signals of full life cycle



Normal stage (inner race)



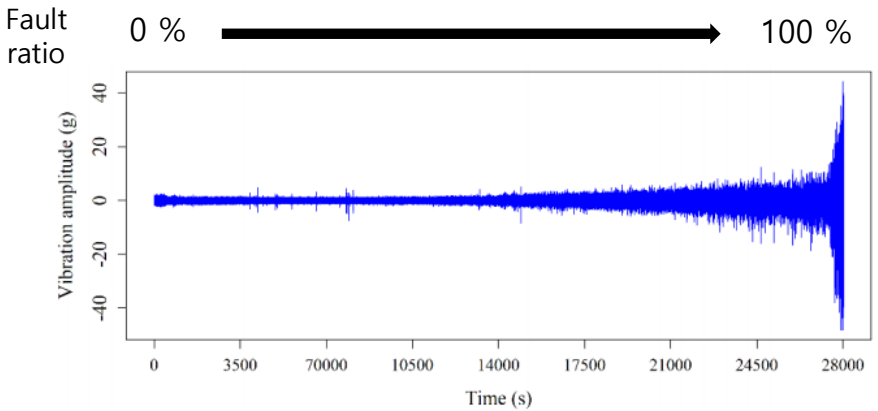
Normal stage (outer race)



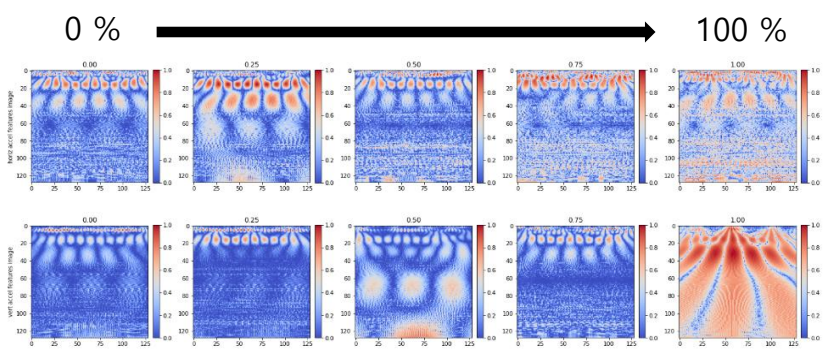
Failure stage (inner race)



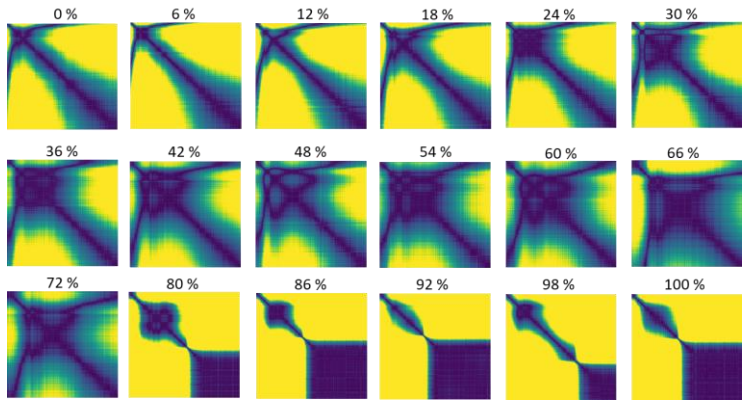
Failure stage (outer race)



Vibration signals



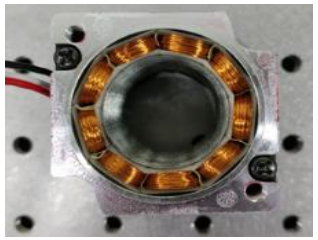
Wavelet transform of vibration signals



Proposed Signal imaging method

Deep learning based rotating machinery diagnosis using time-series data imaging (신호 시각화와 딥러닝을 이용한 모터 고장진단)

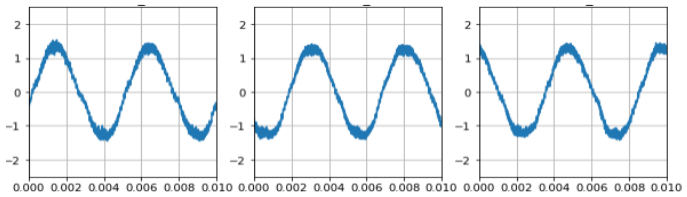
Data Acquisition | **Time-Series Imaging** | **Unsupervised Learning**

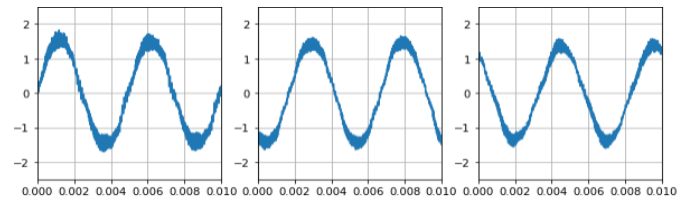


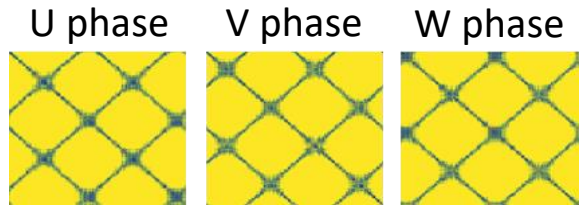
Normal



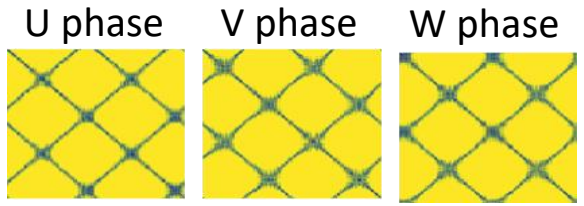
Abnormal



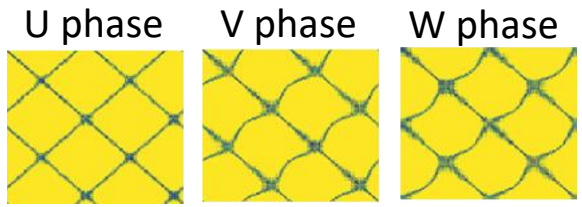




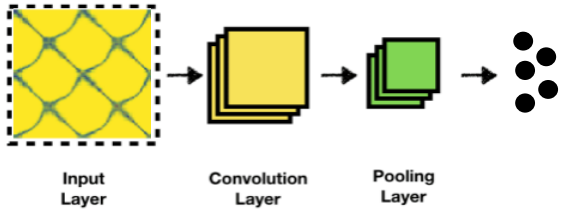
Normal



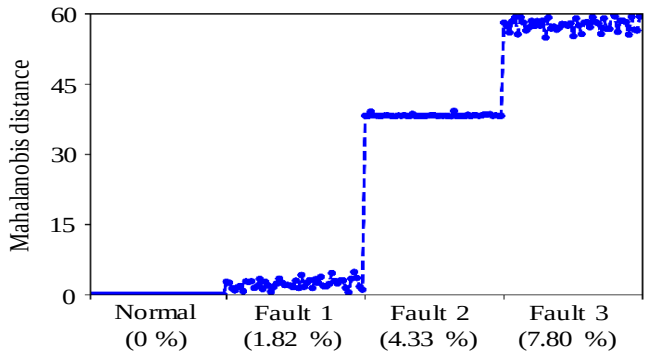
Abnormal 1



Abnormal 2



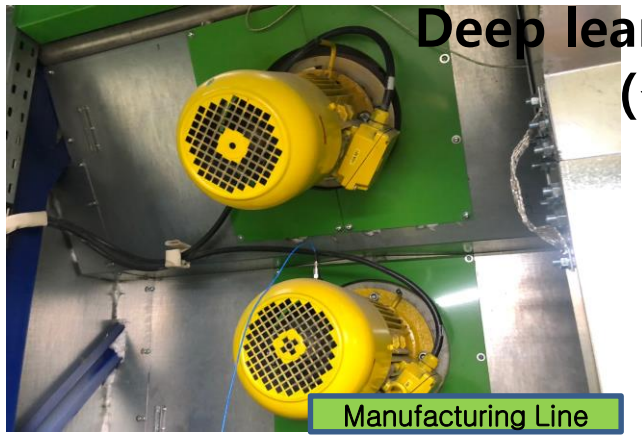
Feature extraction by CNN

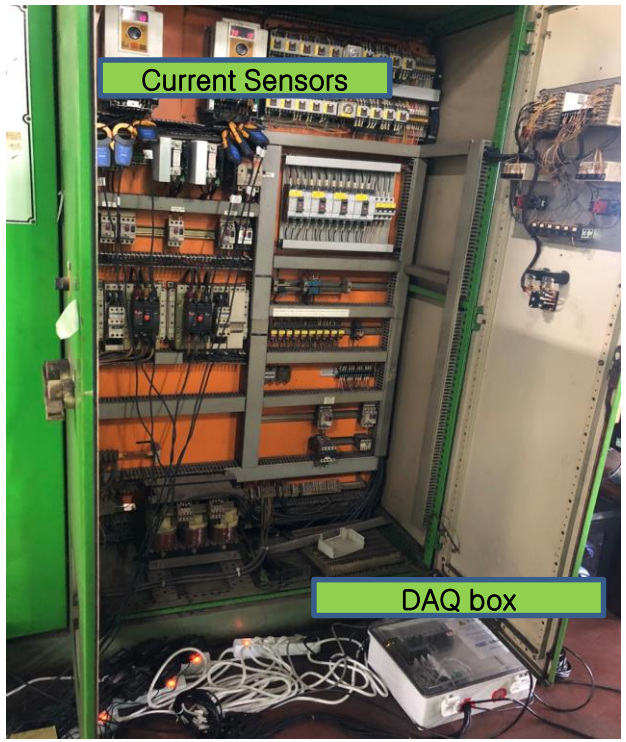


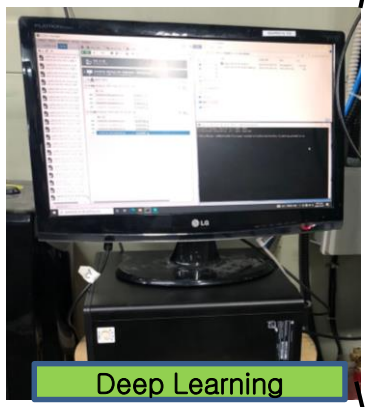
Status graph by MD*

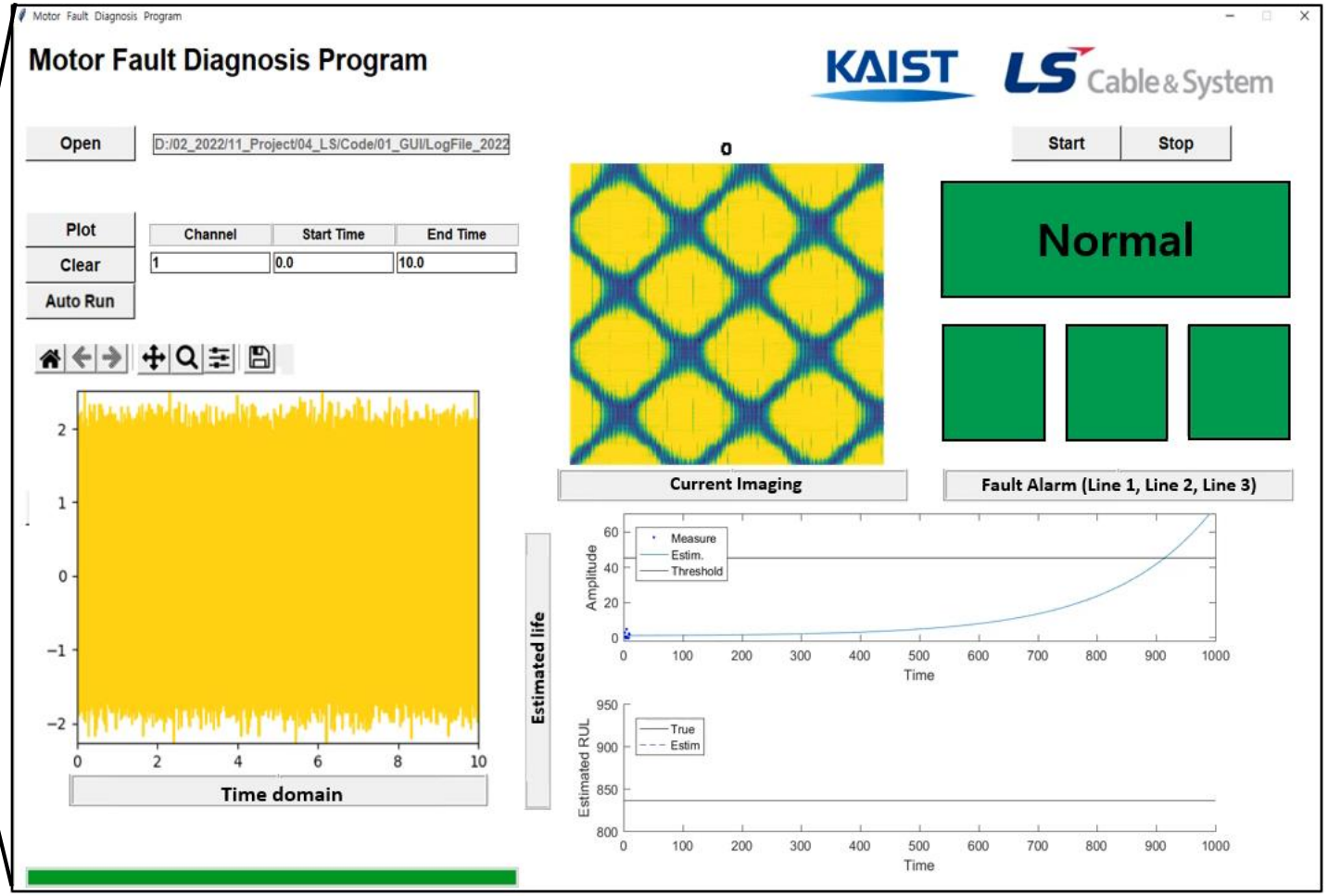
*Mahalanobis distance

Deep learning based rotating machinery diagnosis using time-series data imaging (신호 시각화와 딥러닝을 이용한 모터 고장진단 – 제조 공정 실제 적용)


Manufacturing Line




Deep Learning

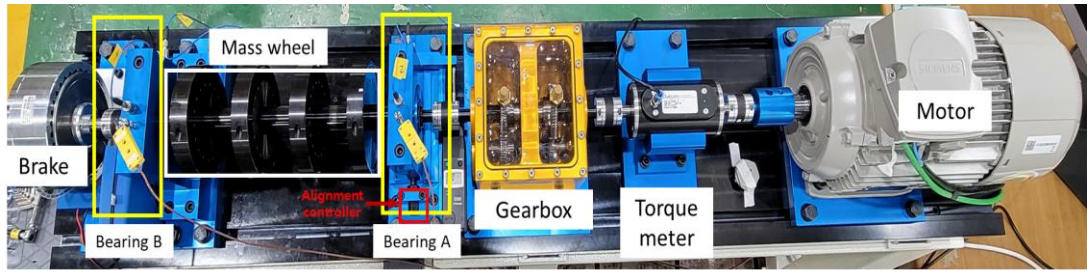


Motor Fault Diagnosis Program Prototype

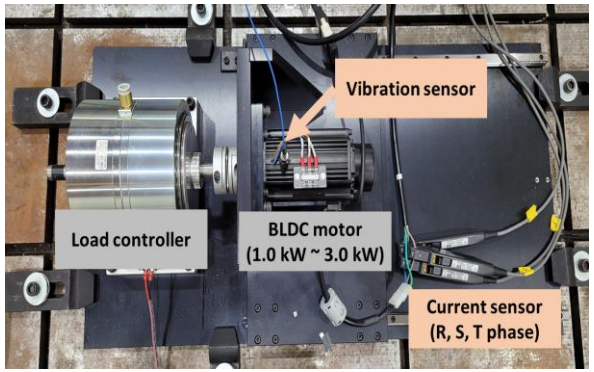
KAIST Fault Database done by Human LAB

Human 랩에서 생산한 대량의 고장 데이터는 Public에 공개해 놓았습니다. 학술용으로 사용 가능합니다.

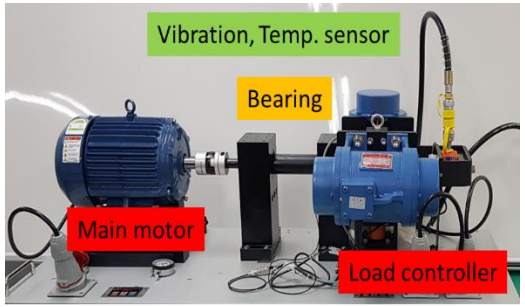
- **Bearing/Rotor Testbed**
  - Title: Vibration, Acoustic, Temperature, and Motor Current Dataset of Rotating Machine Under Varying Load Conditions for Fault Diagnosis
  - DataLink: https://data.mendeley.com/datasets/ztmf3m7h5x
- **Motor Testbed**
  - Title: Vibration and Motor Current Dataset of Permanent Magnet Synchronous Motors for Stator Fault Diagnosis
  - DataLink: https://data.mendeley.com/datasets/rgn5brrgrn
- **Bearing Testbed**
  - Title: Vibration and Motor Current Dataset of Rolling Element Bearing Under Varying Speed Conditions for Fault Diagnosis: Part 1, Part 2, Part 3
  - DataLink: https://data.mendeley.com/datasets/vxkj334rzv
    https://data.mendeley.com/datasets/x3vhp8t6hg
    https://data.mendeley.com/datasets/j8d8pfkvj2
- **Bearing Run-to-Failure Testbed, HVAC Testbed**
  - Title: Vibration and Motor Current Dataset of Bearing
  - DataLink: TBA (maybe open on December 2022)



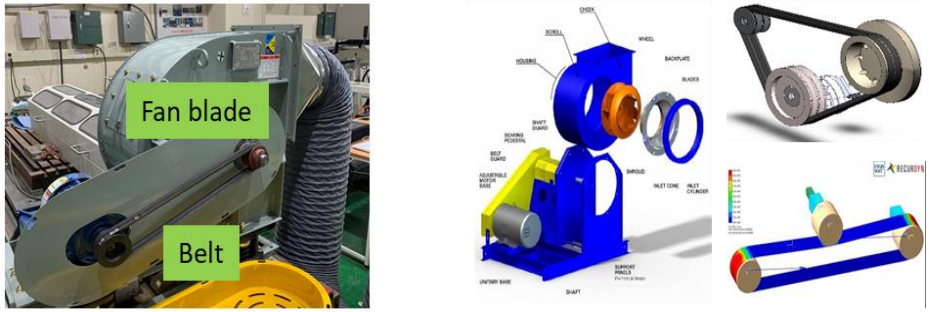
Rotor & Bearing Testbed



Motor Testbed



Bearing Accelerated Life Testbed



HVAC (heating, ventilation, & air conditioning) Testbed

Motion Amplification (Vibration Modal Analysis + Dynamic Vision Processing)

for remote vibration sensing



Original video



Motion Amplified

Spatiotemporal slices



Original video



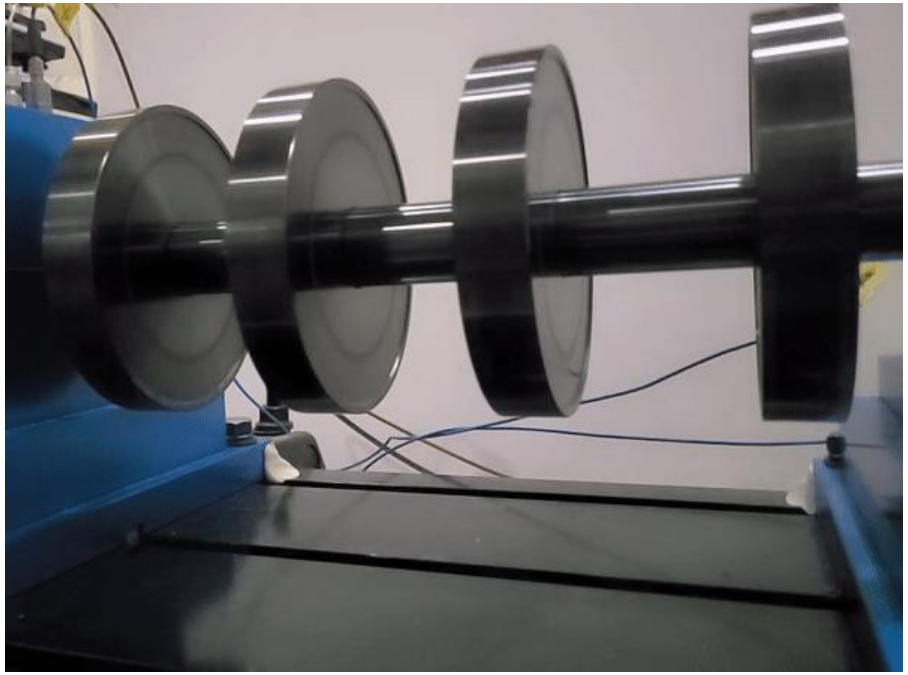
Wadhwa et al.2013



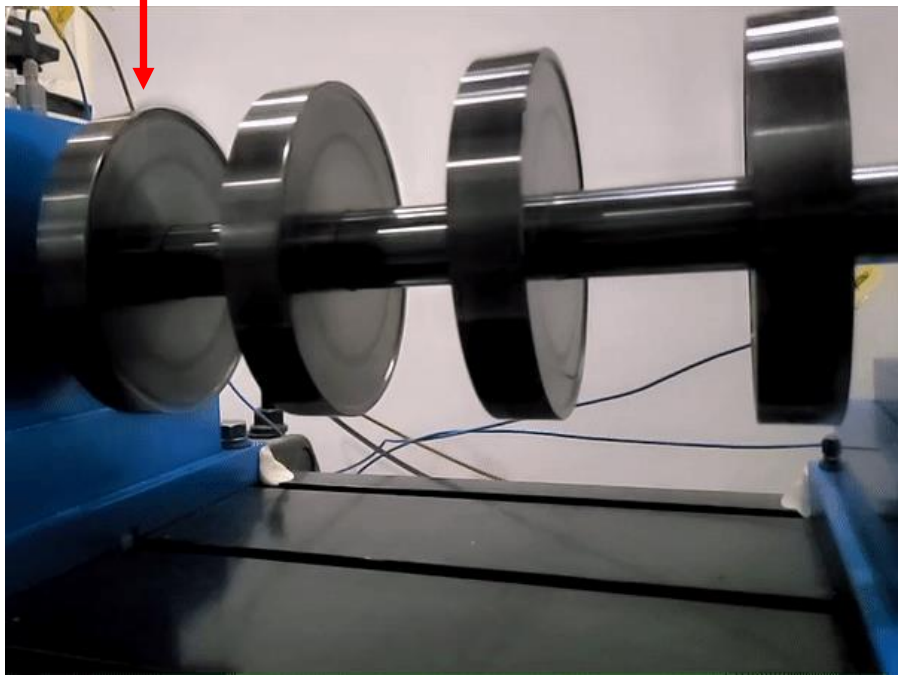
Proposed Method

Motion Amplification (영상 증폭을 이용한 고장진단)

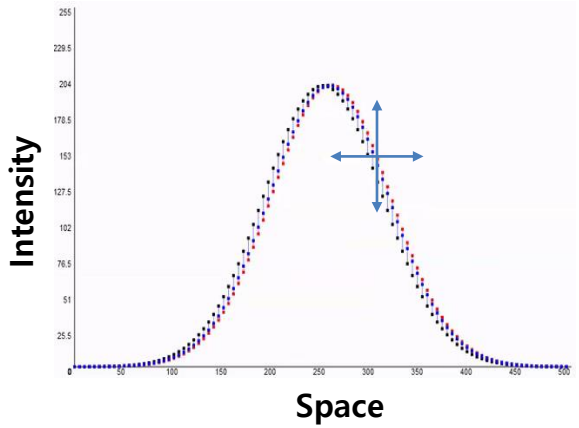
고장 부위 검출 (이상 움직임 관측)



원본 휴대폰 영상



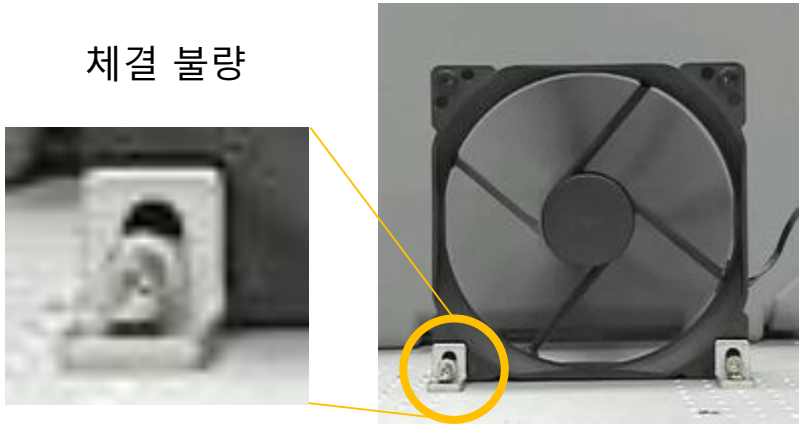
증폭영상



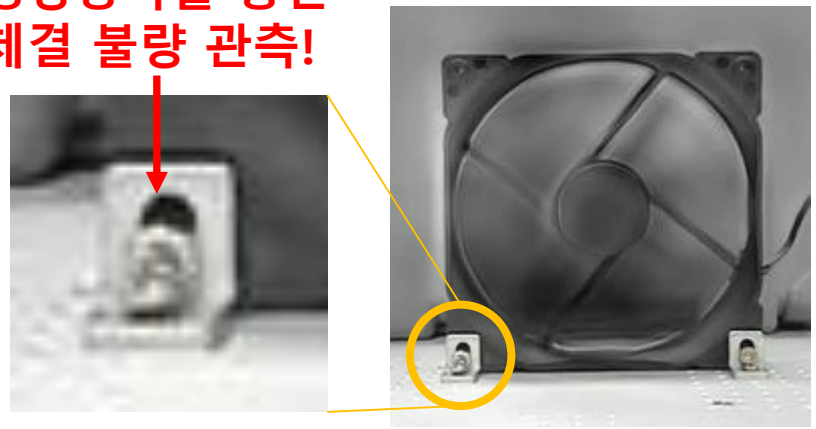
Motion Amplification (Vibration Modal Analysis + Dynamic Vision Processing)

10~20 Hz

체결 불량



영상증폭을 통한
체결 불량 관측!



원본 휴대폰 영상

증폭영상

5~10 Hz





악조건 속에서의 영상 데이터를 이용한 공조기 Looseness 판별

김정민
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Korea Advanced Institute of Science and Technology (KAIST),
Mechanical Engineering, Daejeon, South Korea

SAMSUNG
삼성중공업

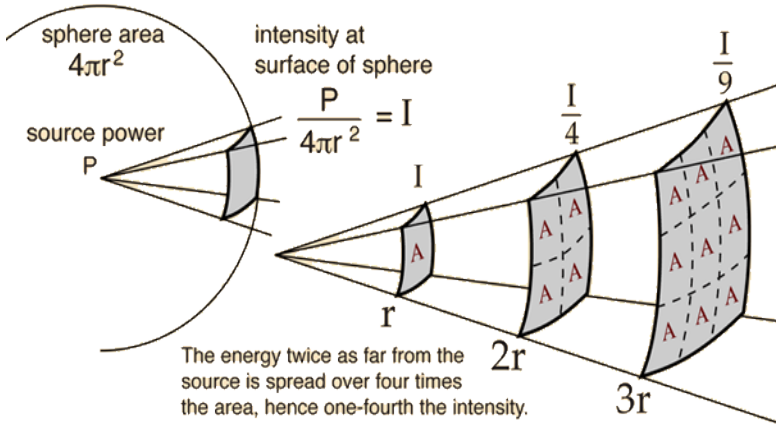
KAIST

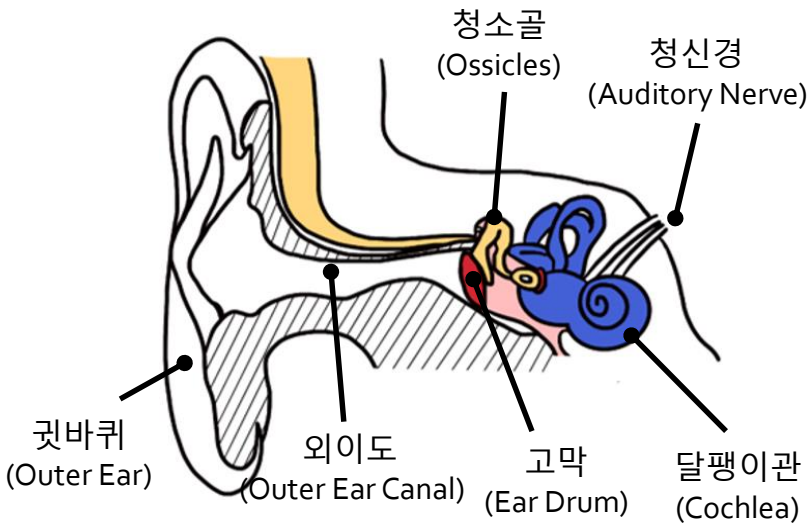


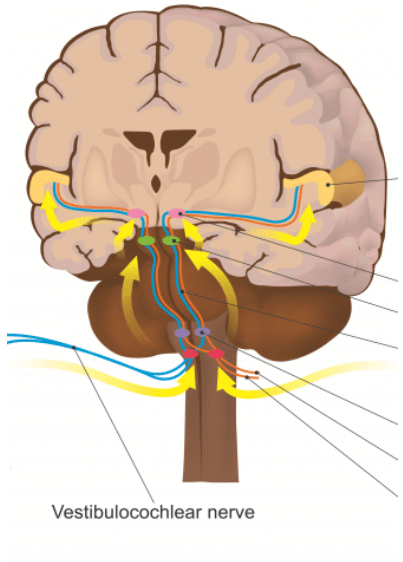
A typical cocktail party scene (image from Daniel Handerman: **High Society Cocktail Party – End of Prohibition 1933**)
from Cherry EC, 1953. Some experiments on the recognition of speech, with one and with two ears. J Acoust Soc Am, 25(5):975-979.

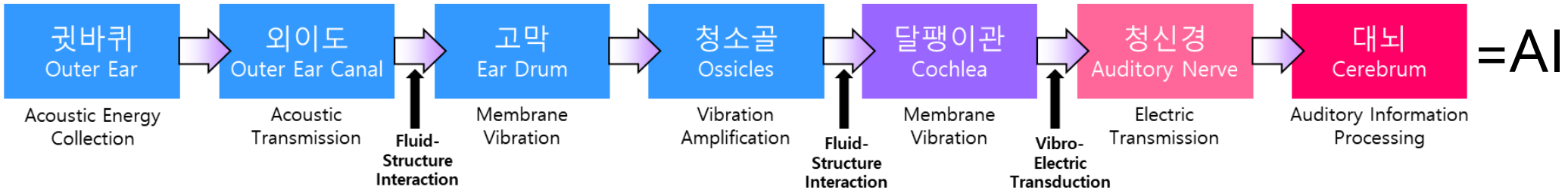
청각지능의 연구주제:

공간 음향 + 청각계 + 대뇌 인지 (AI)

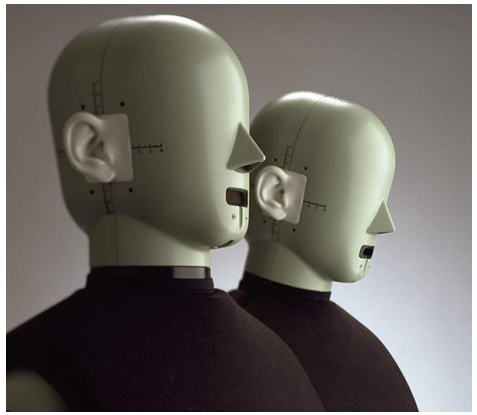


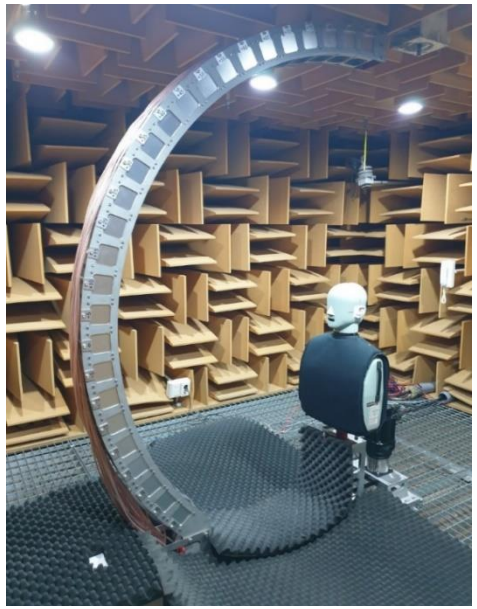




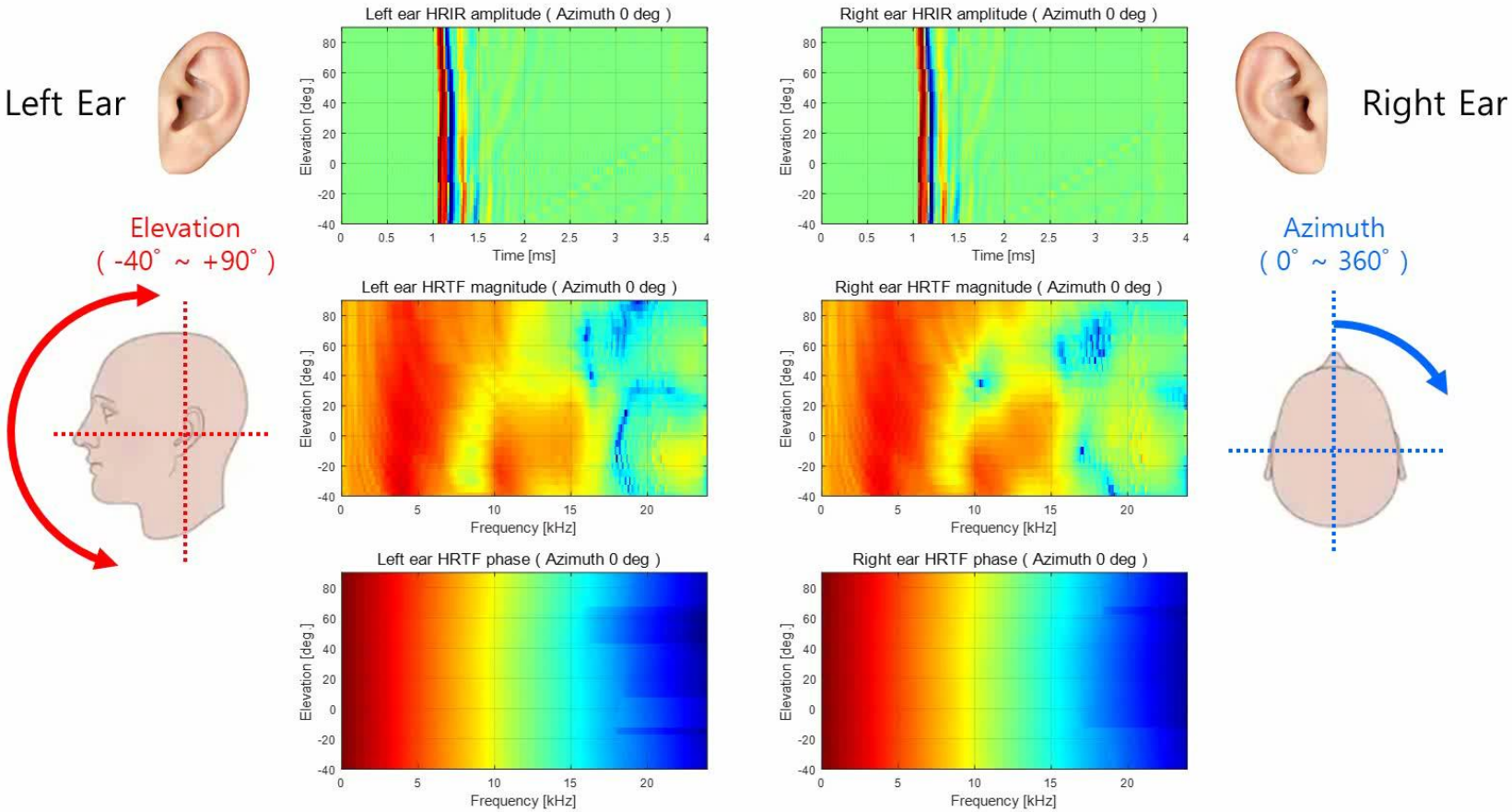


소리를 인지하는 머리전달 함수 - Head Related Transfer Function (실험실 측정)

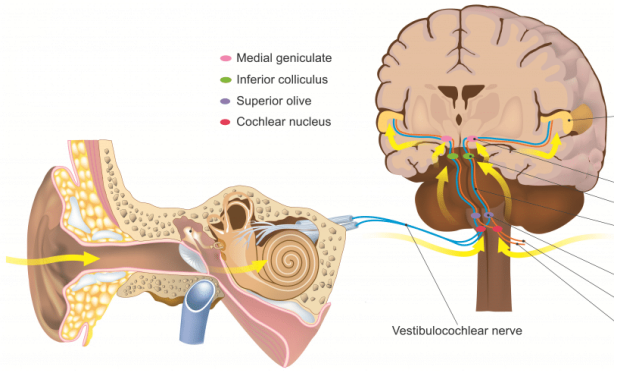




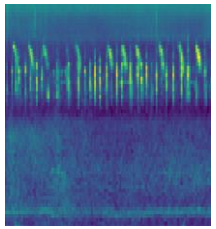
NOVIC+, Human Lab 무향실

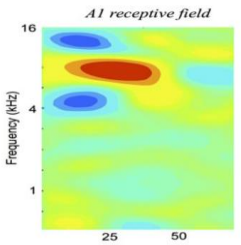


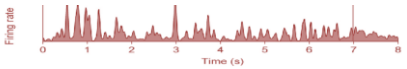
동물의 청각신경을 모사한 음향인식 기술 (STRF: Spectro-Temporal Receptive Field)



Input sound stimulus spectrogram $x(t,f)$ → STRF $h(t,f)$ → A1 neural response $y(t)$

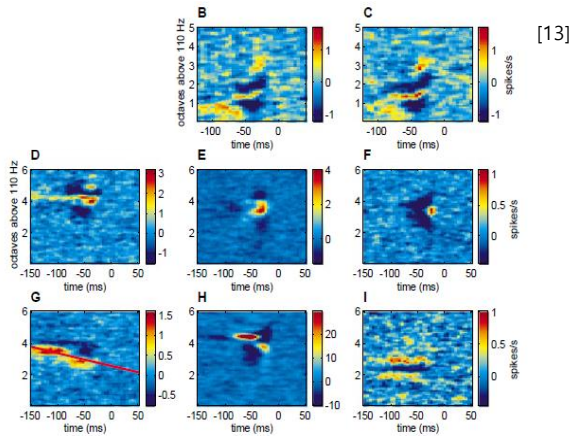




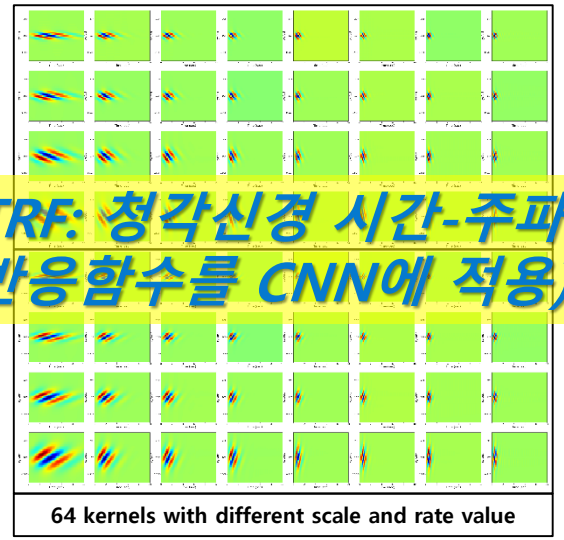


$$x(t,f) * h(t,f) = y(t)$$

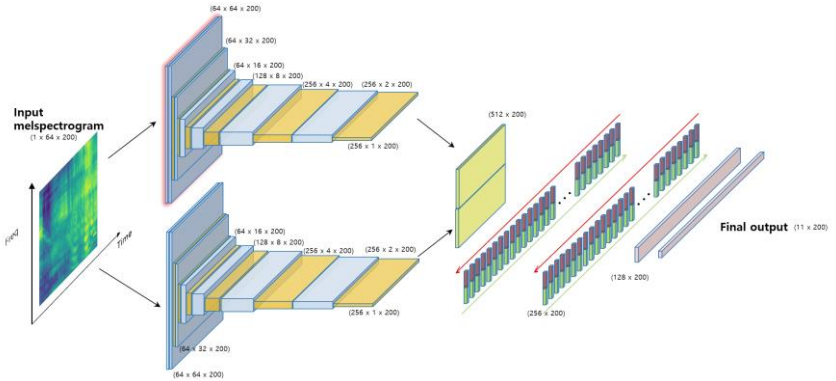
1. Estimated A1 STRF Analysis → Bio-mimic → 2. A1 STRF construction → Apply → 3. SED Deep learning model



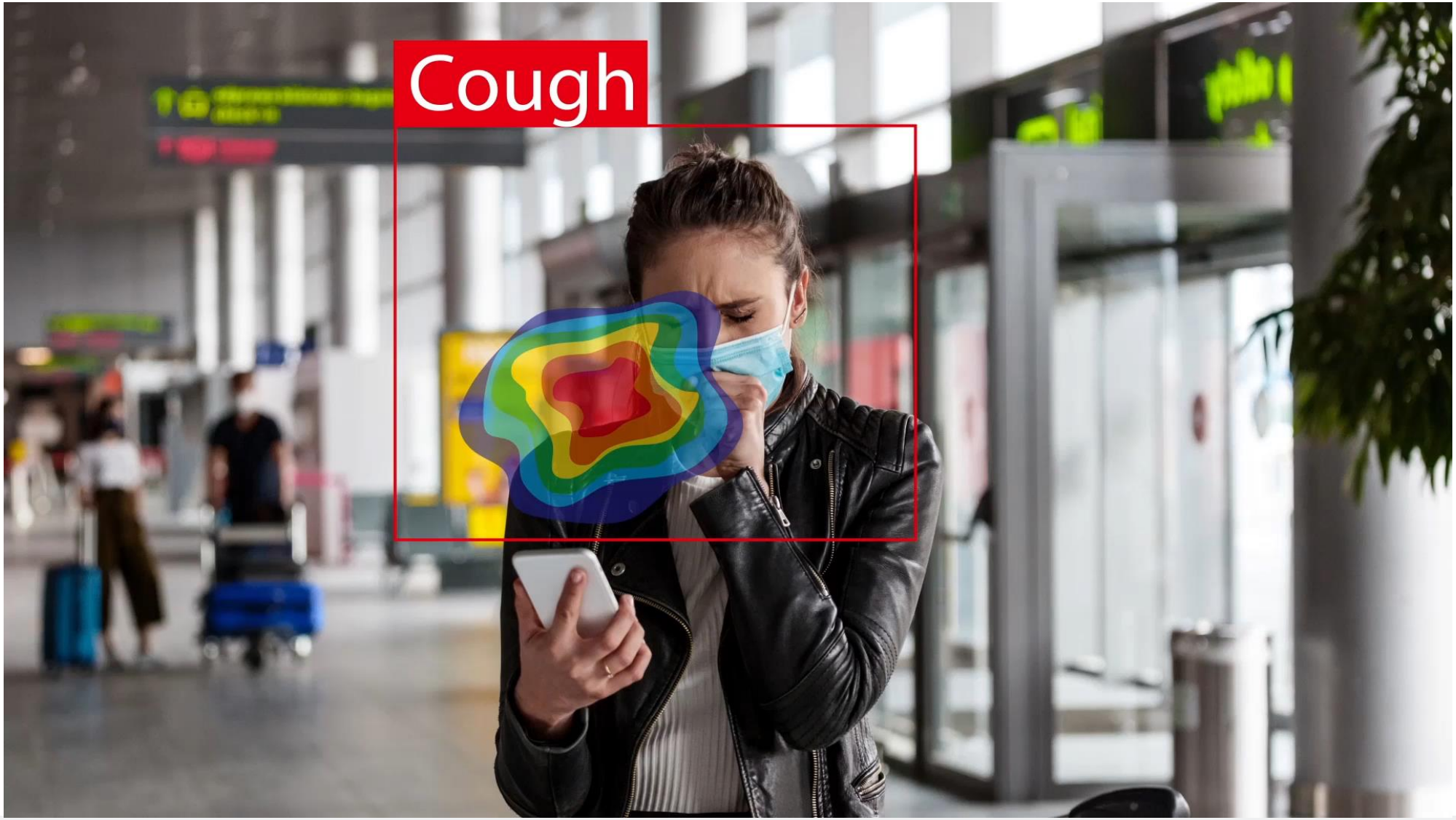
[13]



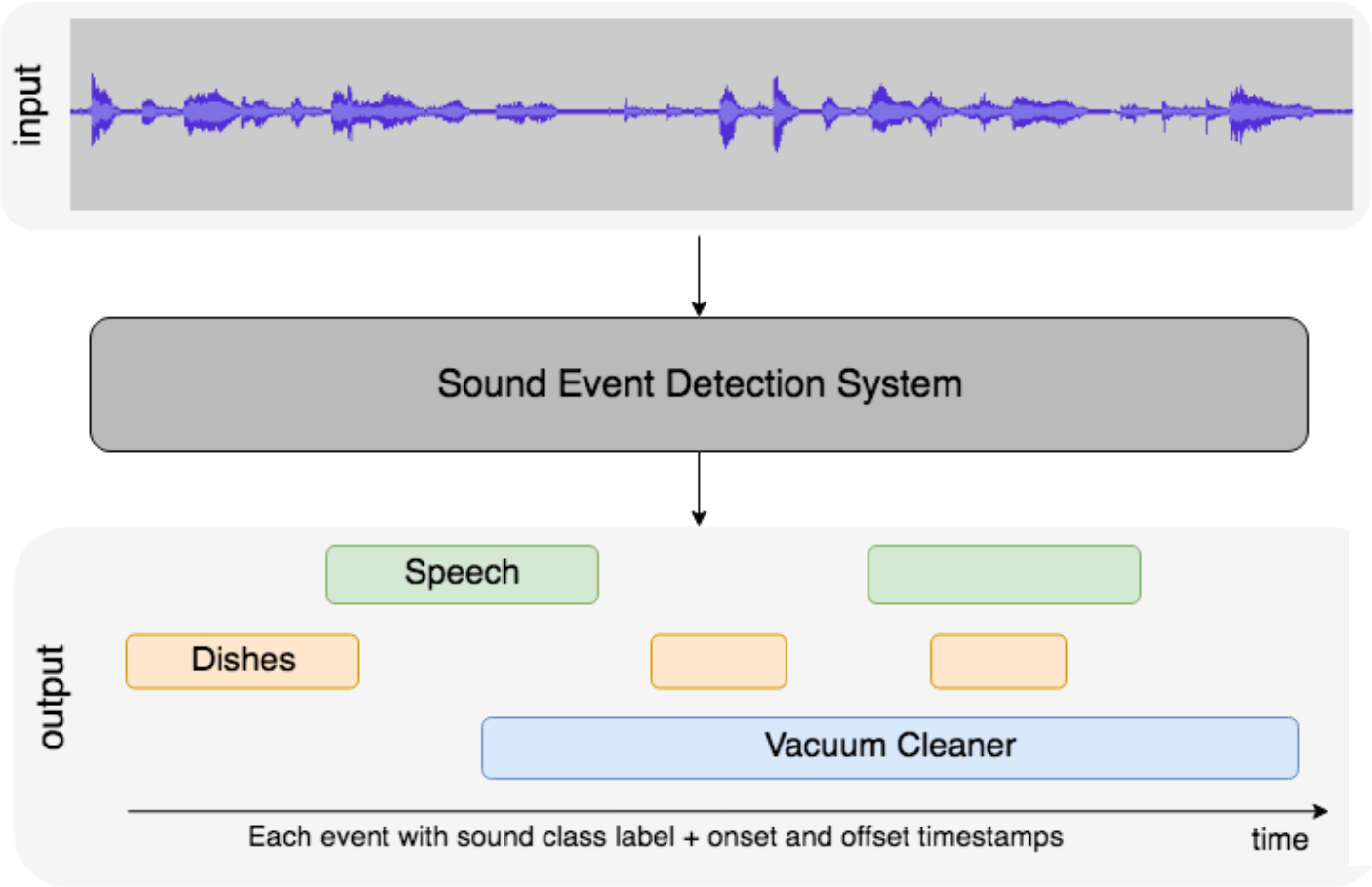
(STRF: 청각신경 시간-주파수 반응함수를 CNN에 적용)



KAIST 기침인식 카메라 (KBS, MBC, YTN 방영)

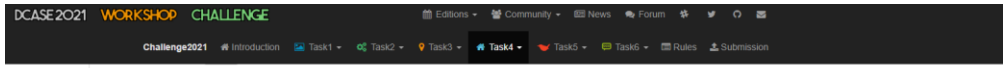


음향 이벤트 인식(Sound Event Detection)



IEEE DCASE 2021 Challenge Task4

- AI를 활용하여 특정 오디오파일 내에 몇 초부터 몇 초 사이에 어떤 음향이벤트가 존재하는지를 인식
- 총 28개의 팀 중 3위
- 해외 TOP 음성학회 논문 게재 (2편)
- Github 코드 공개





Hyeonuk Nam

FOLLOW

Korea Advanced Institute of Science and Technology
Verified email at kaist.ac.kr - Homepage
Sound Event Detection (SED) Sound Event Localization a… Auditory Intelligence

TITLE	CITED BY	YEAR
Filteraugment: An acoustic environmental data augmentation method H Nam, SH Kim, YH Park ICASSP 2022-2022 IEEE International Conference on Acoustics, Speech and …	36	2022
Frequency dynamic convolution: Frequency-adaptive pattern recognition for sound event detection H Nam, SH Kim, BY Ko, YH Park arXiv preprint arXiv:2203.15296	36	2022
Heavily augmented sound event detection utilizing weak predictions H Nam, BY Ko, GT Lee, SH Kim, WH Jung, SM Choi, YH Park arXiv preprint arXiv:2107.03649	28	2021

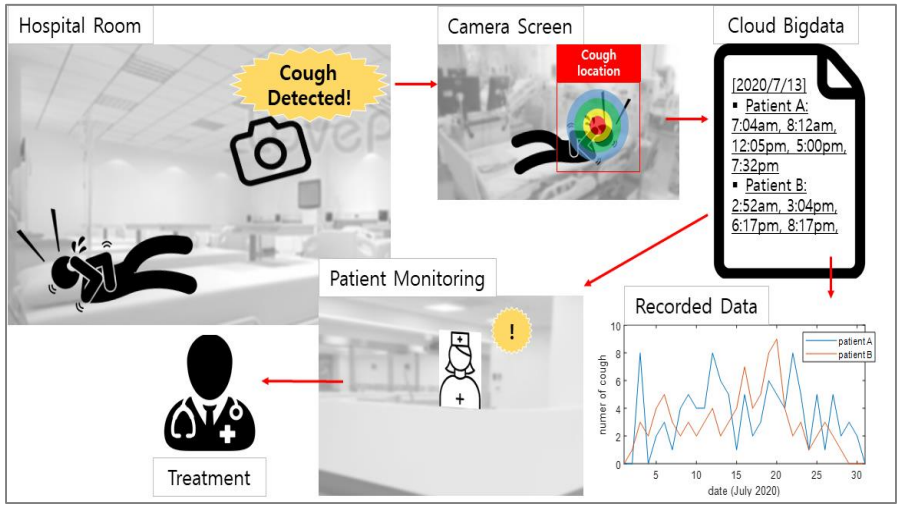
No.1 State-of-the-art Algorithm by Mr. Hyeonuk Nam from Human LAB!

한국형 휴먼케어 로봇 개발 (음향상황인식 AI 개발)

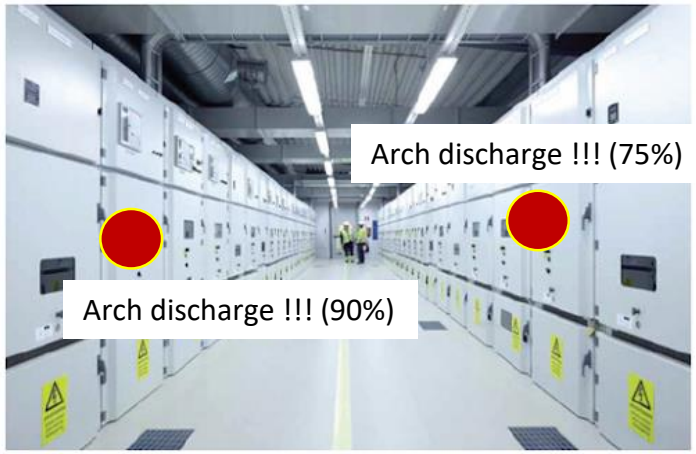


Cough Detection Camera





Condition Monitoring based on Sound (아크방전진단)



휴먼 케어 로봇 - 환경음향인식

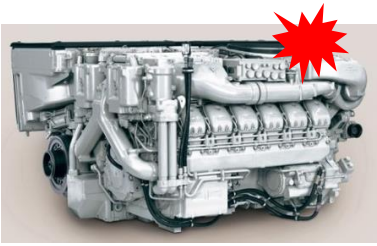


기침
코골이
낙상
깨지는 소리
화재경보
침입
초인종
핸드폰 알람

진동음향 기반 무기체계 고장 진단 (전차 엔진/변속기/체인 등 각종 고장진단)

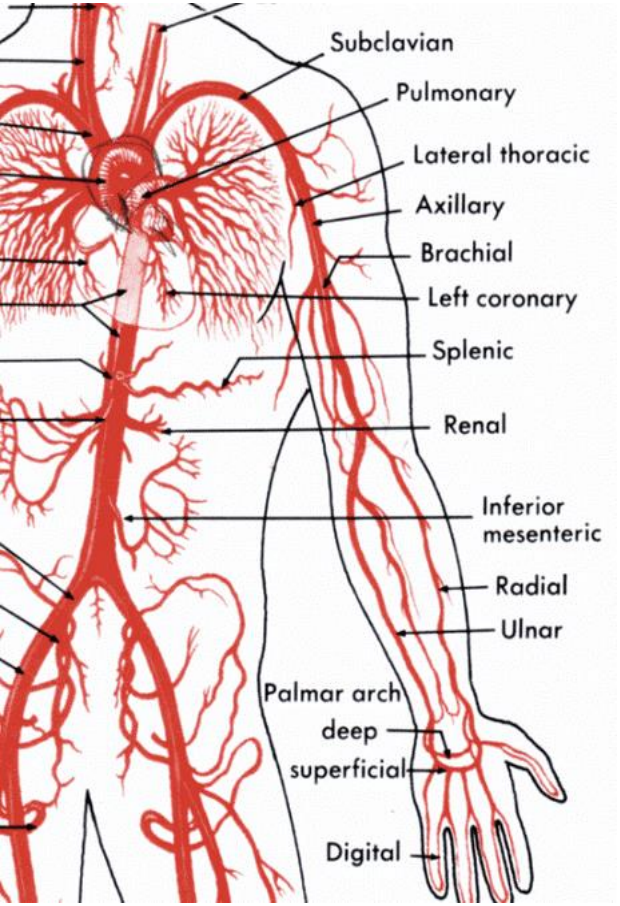


▲ 방위사업청이 지난 2월 K2 전차 2차 양산분에 국산 엔진과 독일산 변속기를 결합한 '혼합 파워팩'을 탑재하고 저온시험 뒤 3200km 주행시험을 시행하는 모습. 방위사업청 제공



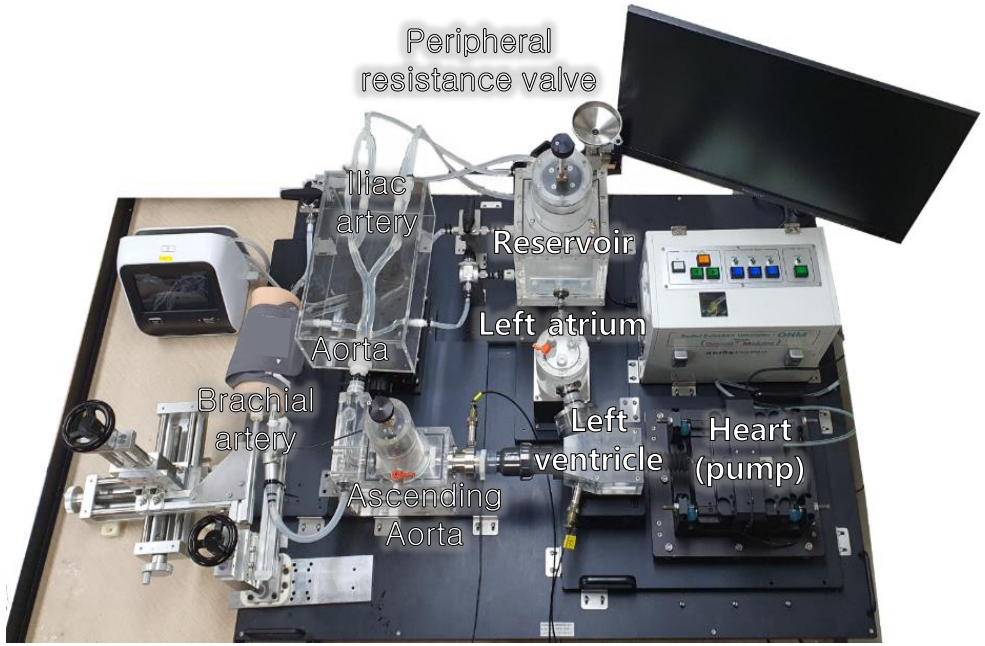
K2 전차엔진 - 두산인프라코어

Virtual Patient - 심혈관계 질환 가상환자

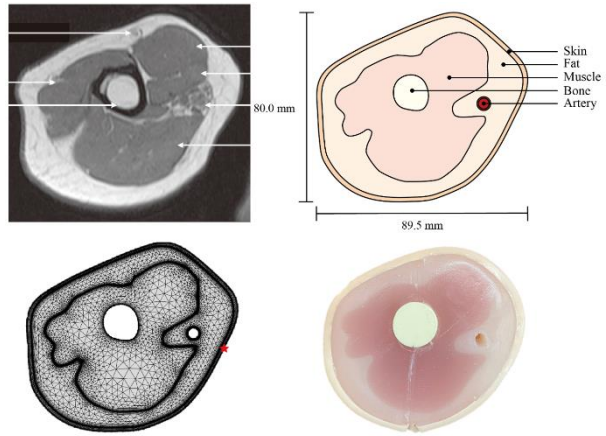


Virtual Patient for Cardiovascular Studies

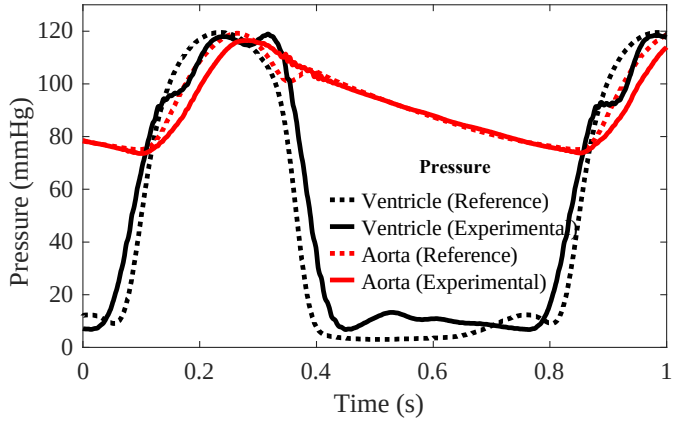
- Artificial cardiovascular system mimicking human body for study of cardiovascular disease (virtual patient)
- In depth study on the correlation between CVD and human organ and tissues in virtual setup



Artificial Cardiovascular System in Lab

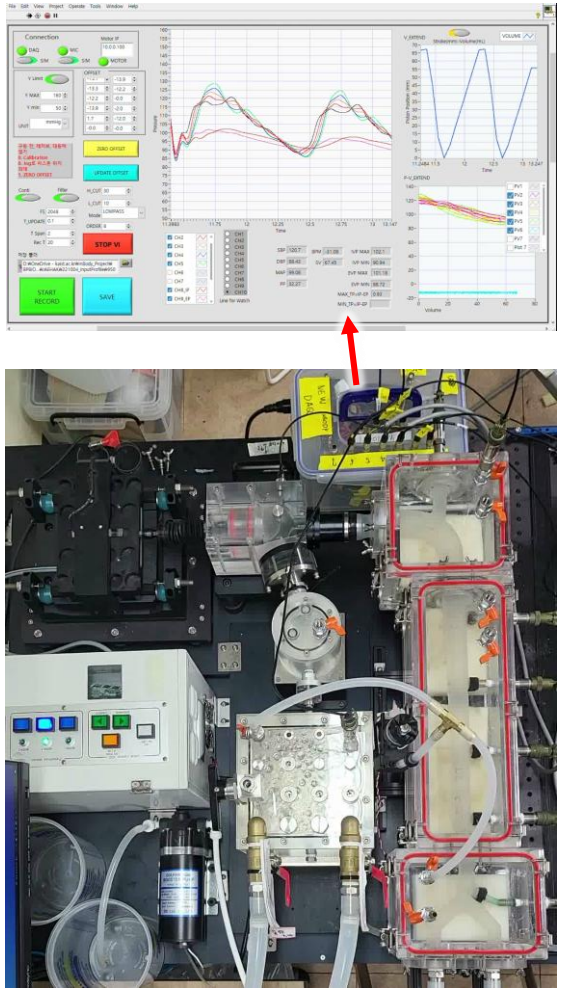


Reconstruction of blood pressure transmission mechanism in upper arm
: MRI image based numerical model and phantom for blood pressure analysis

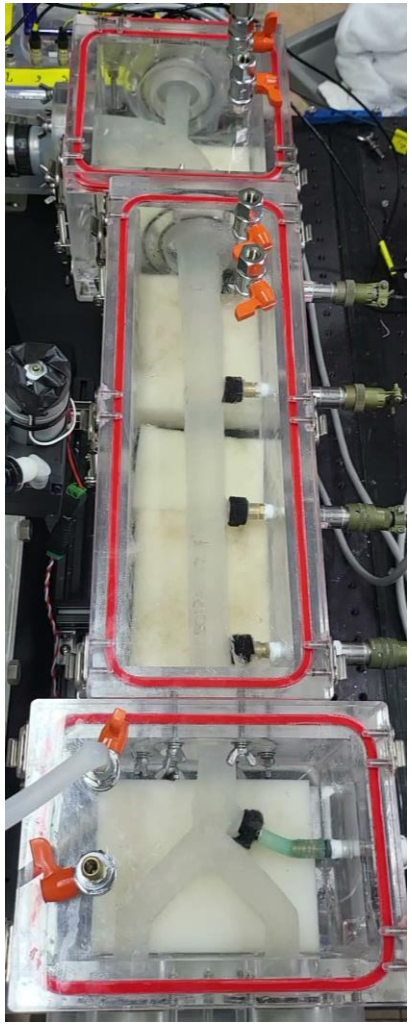


Reproduction of human blood pressure
: Ventricular and aorta pressure compared with Wigger's diagram (reference)

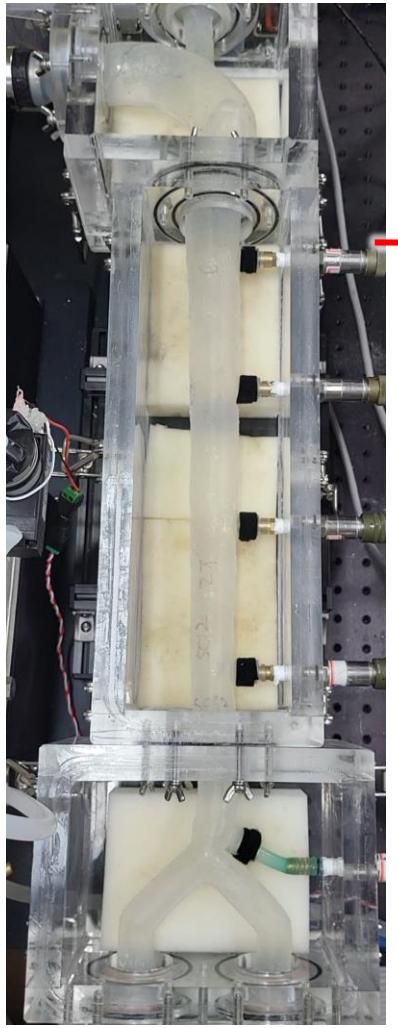
가상환자 시스템을 이용한 인체의 혈압 파형 생성 실험



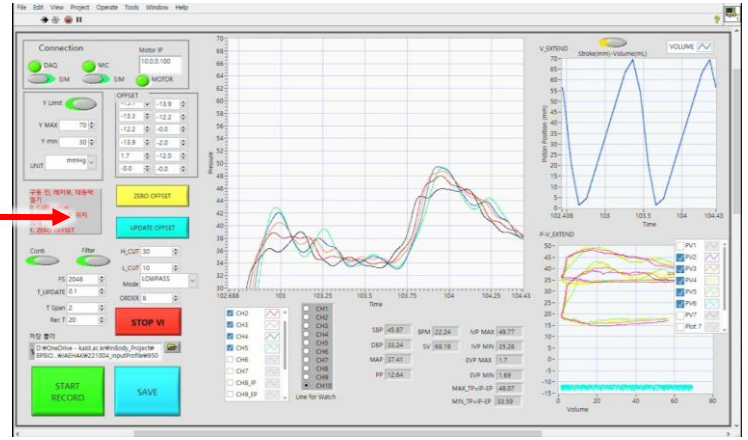
Reproduction of human BP wave using cardiovascular simulator



1/4x Speed Play



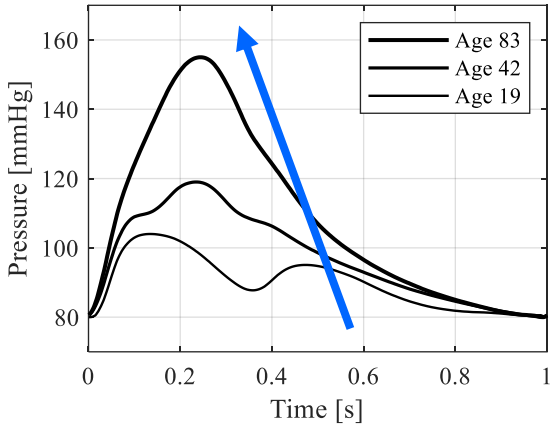
Without Compliance Chamber



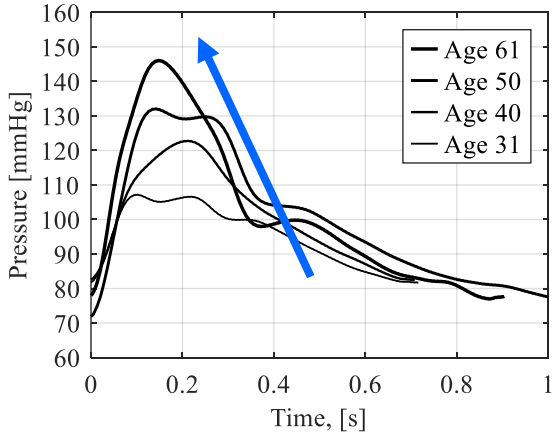
Waveform distorted and cannot reach human BP level

- Ventricular pump generates pulse
- Pulse propagation in artificial aorta
- Compliance chamber mimics intrathoracic pressure to prevents waveform distortion from strain-softening
- Without compliance chamber, waveform distorted

Human Central Blood Pressure Wave According to Age



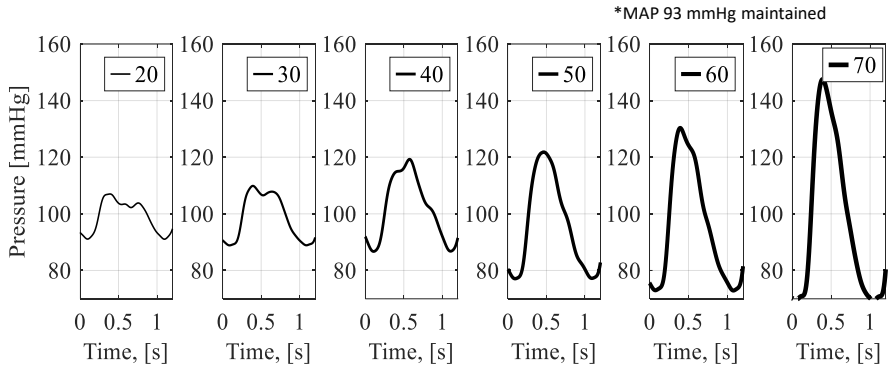
From literature

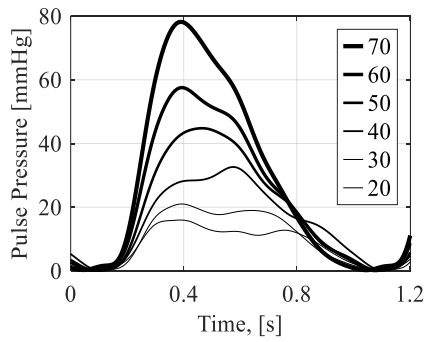


From non-invasive data

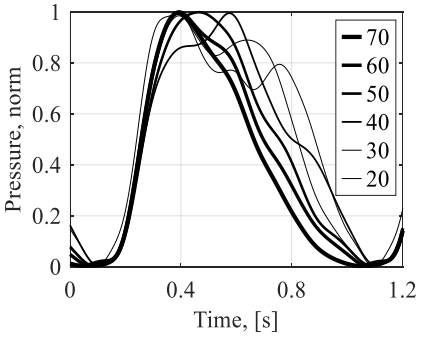
연령별 동맥을 이용한 혈압파형 구현 및 준 임상데이터 확보!







Pulse pressure

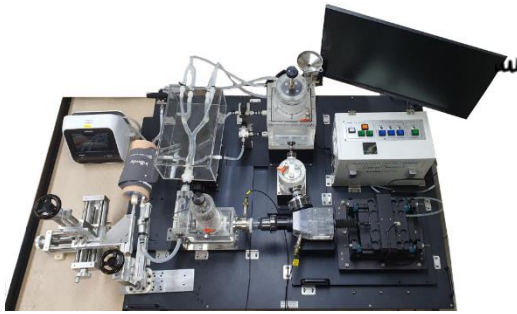


Normalized pressure pulse

Waveform Changes According to Aging!

혈압계를 이용한 심혈관계 상태 진단 (심장, 대동맥, 혈관벽 등)

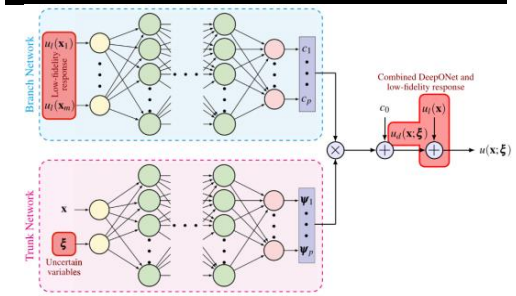
Virtual Patient
(Source Domain)



Oscillometric waveform (OMW)

다양한 심혈관계 상태 모사 후 혈압 신호 측정

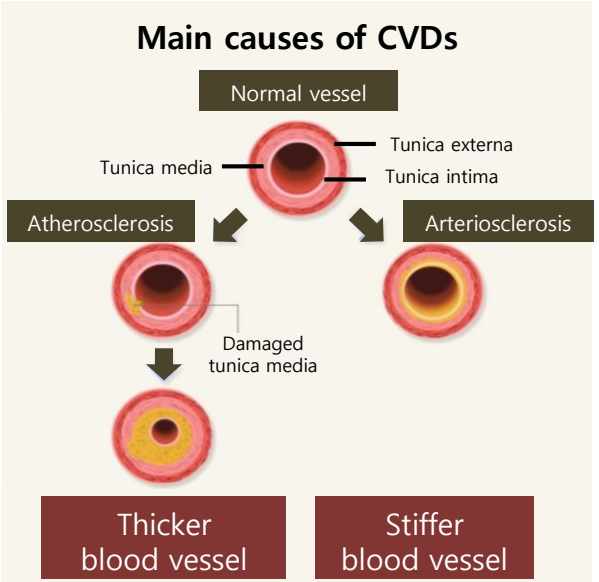
Cardiovascular Digital Twin by DeepOnet



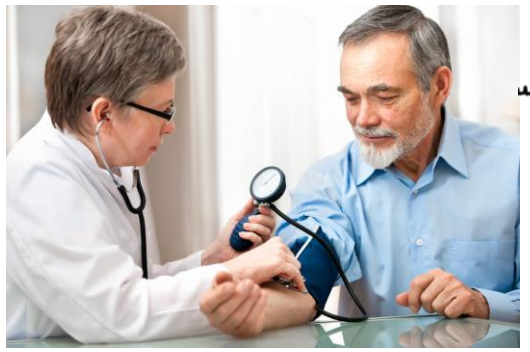
Deep Operational Source Network

심혈관계 상태재현

혈관나이
동맥경화
심박출량
대동맥류

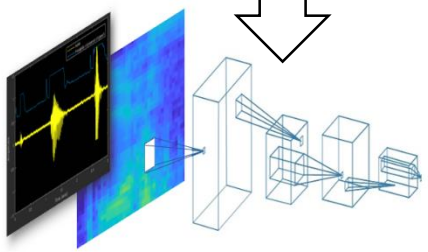


Human
(Target Domain)



Oscillometric waveform (OMW)

"Transfer Learning"



$+\alpha$

Fine tuning

Target Network

심혈관계 상태진단

심혈관계 상태 모니터링이 가능한 혈압계



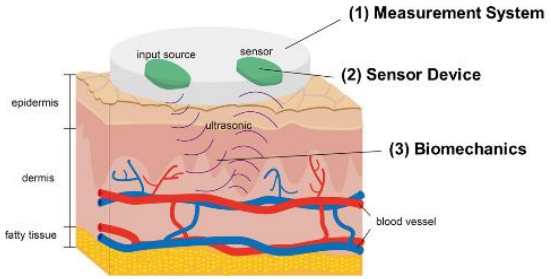
비침습 혈당센서 – Non-invasive Glucose Sensor by Human Body Vibration

Non-invasive glucose measurement sensing architecture (patented)

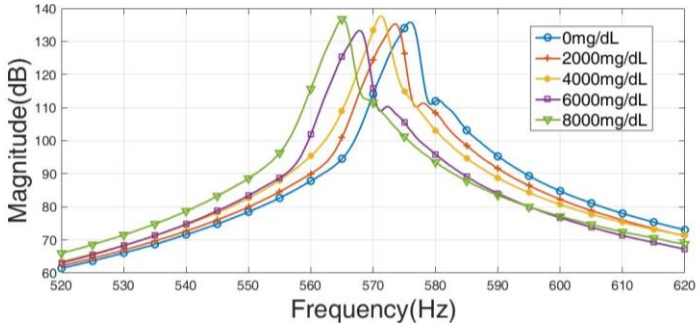




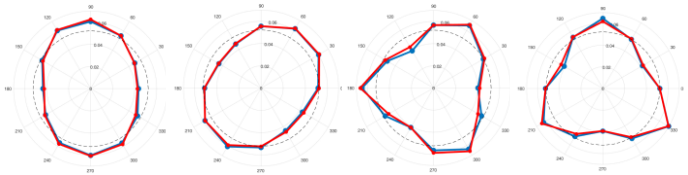




Frequency response function(2nd mode) and Glucose Concentration



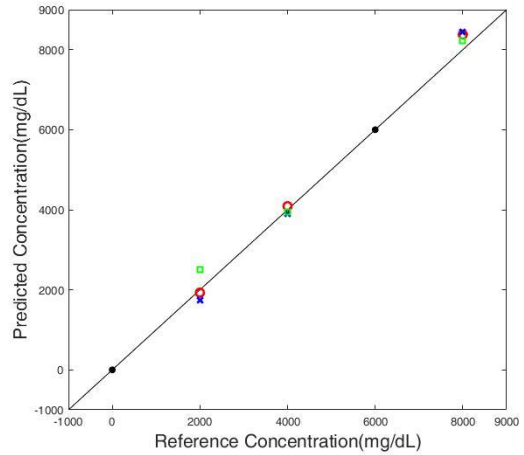
Mode shape analysis of sensor



Mode	1st	1st(2)	2nd(1)	2nd(2)
MAC	0.99	0.99	0.94	0.96

US/KP Patent

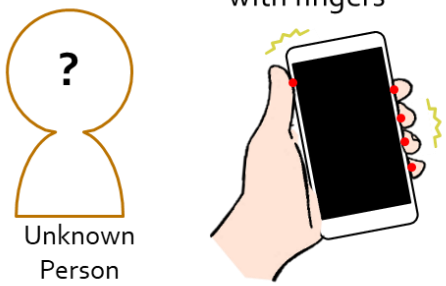
Glucose concentration extraction result



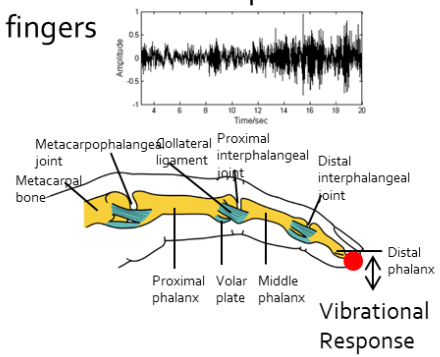
생체인증 - Biometric Authentication using Human Finger Vibration

인체 손가락 진동과 머신러닝을 이용한 모바일 기기 생체인증 시나리오

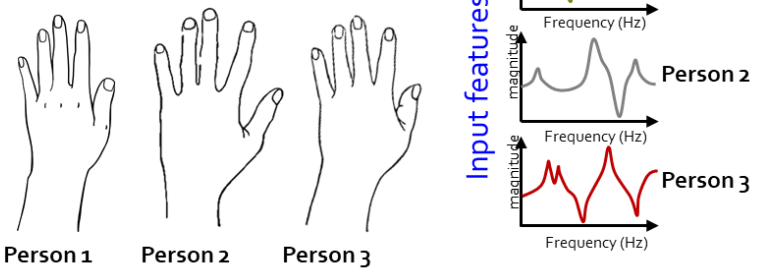
① Contact the device with fingers



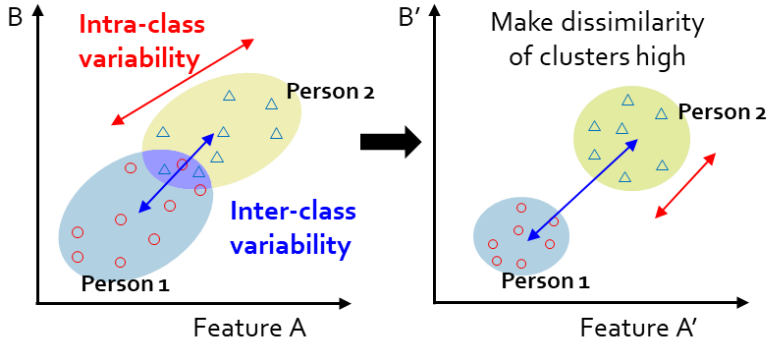
② Vibration transducer measures the vibrational response of fingers



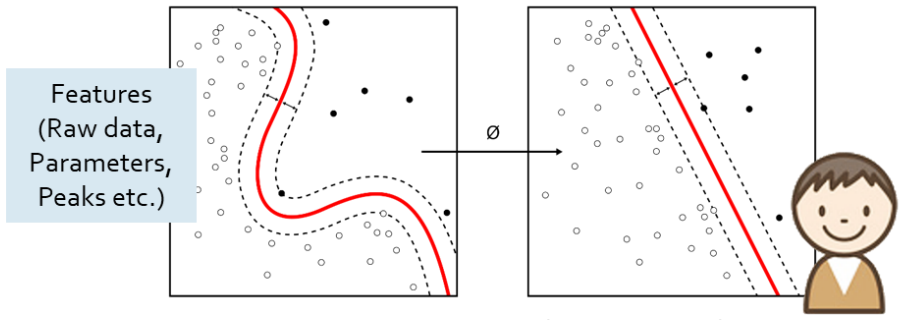
③ Calculate the frequency responses of fingers or different person



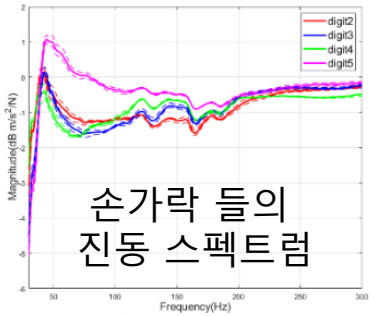
④ Optimize features which maximize the inter-class variability and minimize the intra-class variability

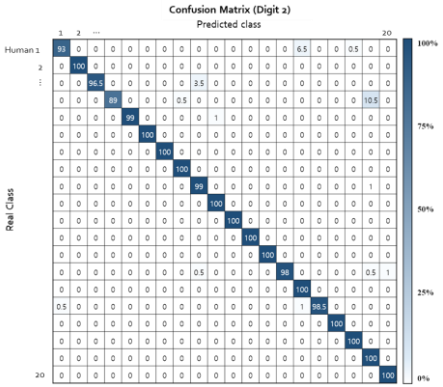


⑤ Apply the classification algorithms (SVM)





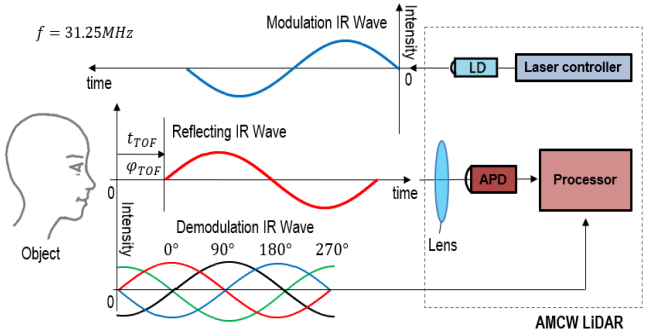


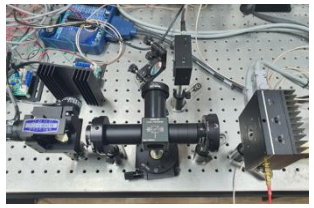


개인구분 정확도 99%

초소형 고정밀 Full HD 급 3D Lidar 독자 개발

3D Lidar 독자 구조 (광 상관함수 이용)



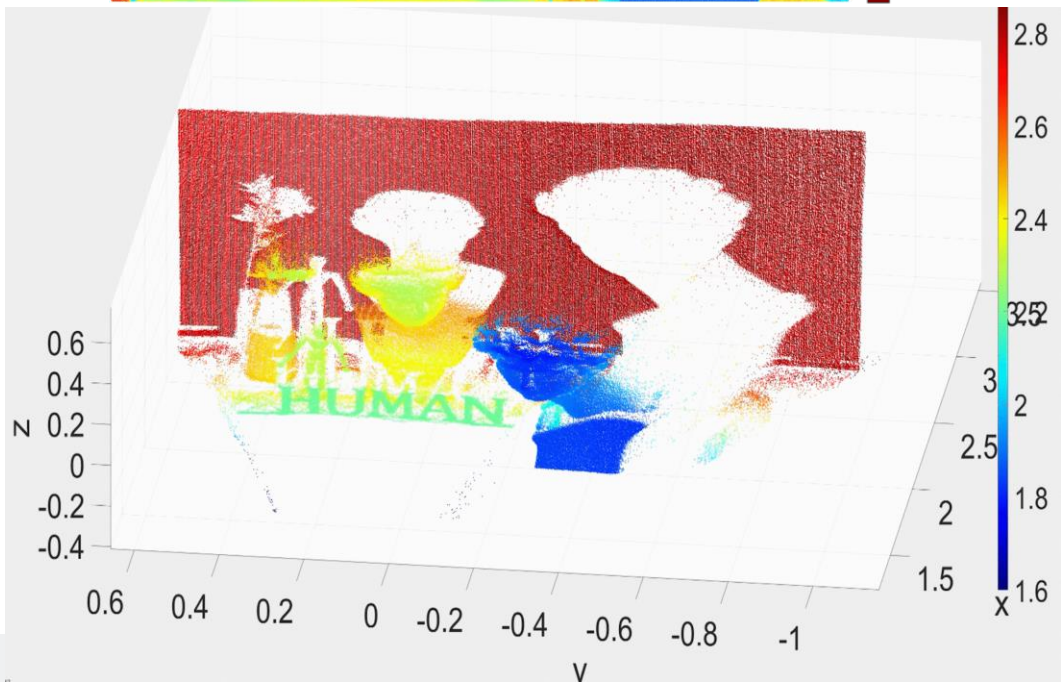


Continuous Wave
Parallel Demodulation
3D Scanning Lidar

Real Scene



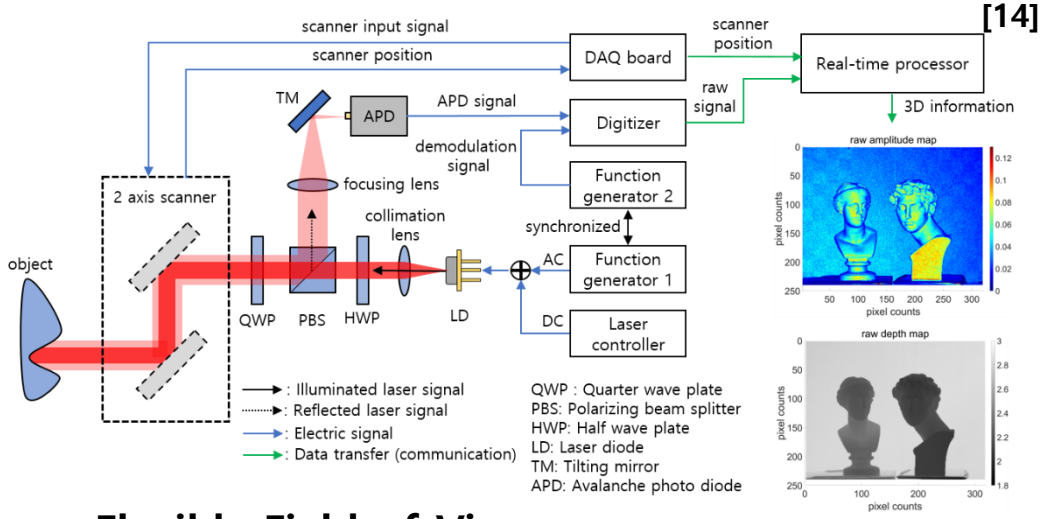


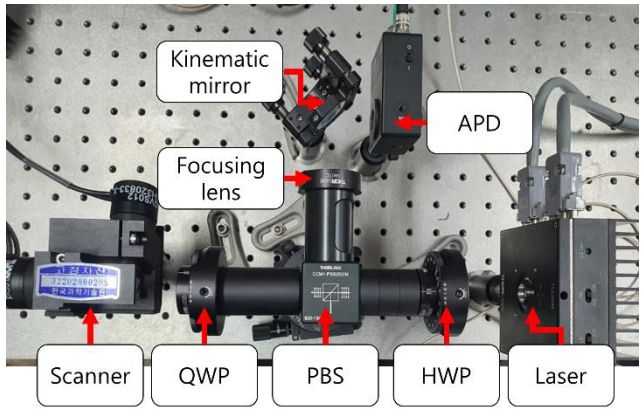


원거리 얼굴인식 시스템 (초소형 라이다 적용)

- **Sensor framework**

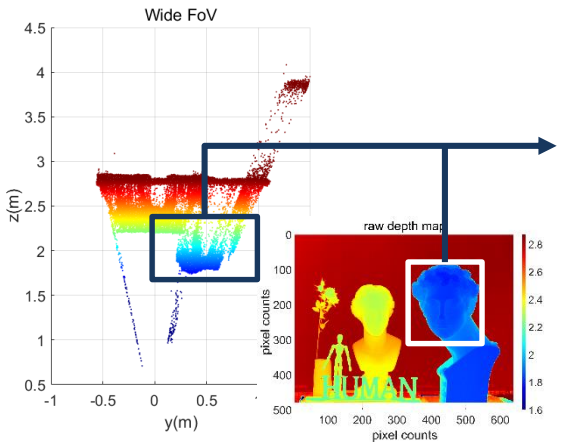
[14]



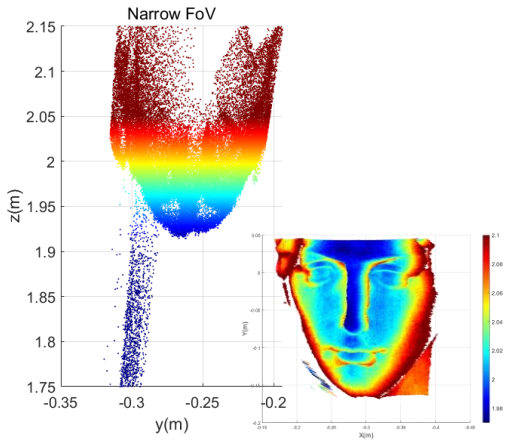


	Conventional ToF sensors	Proposed sensor
Laser power	1 – 2 W	20 mW
Number of pixel	0.3Mpx	No limit
Frame rate	15 - 30 FPS	15 FPS (QVGA) w/o scanner limitation
Precision (@3m)	< 1%	< 0.1%

- **Flexible Field-of-View**

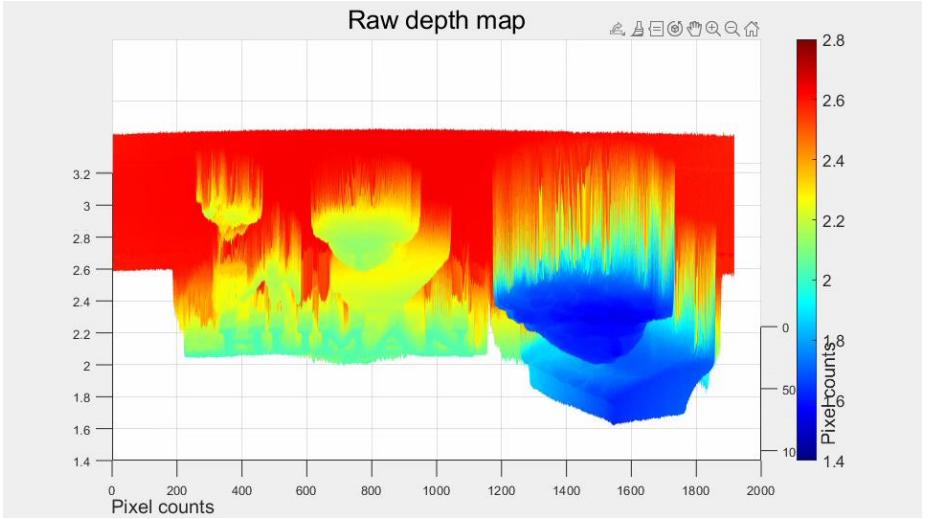


Wide field-of-view image



Narrow field-of-view image

High-resolution Depth image (FHD)



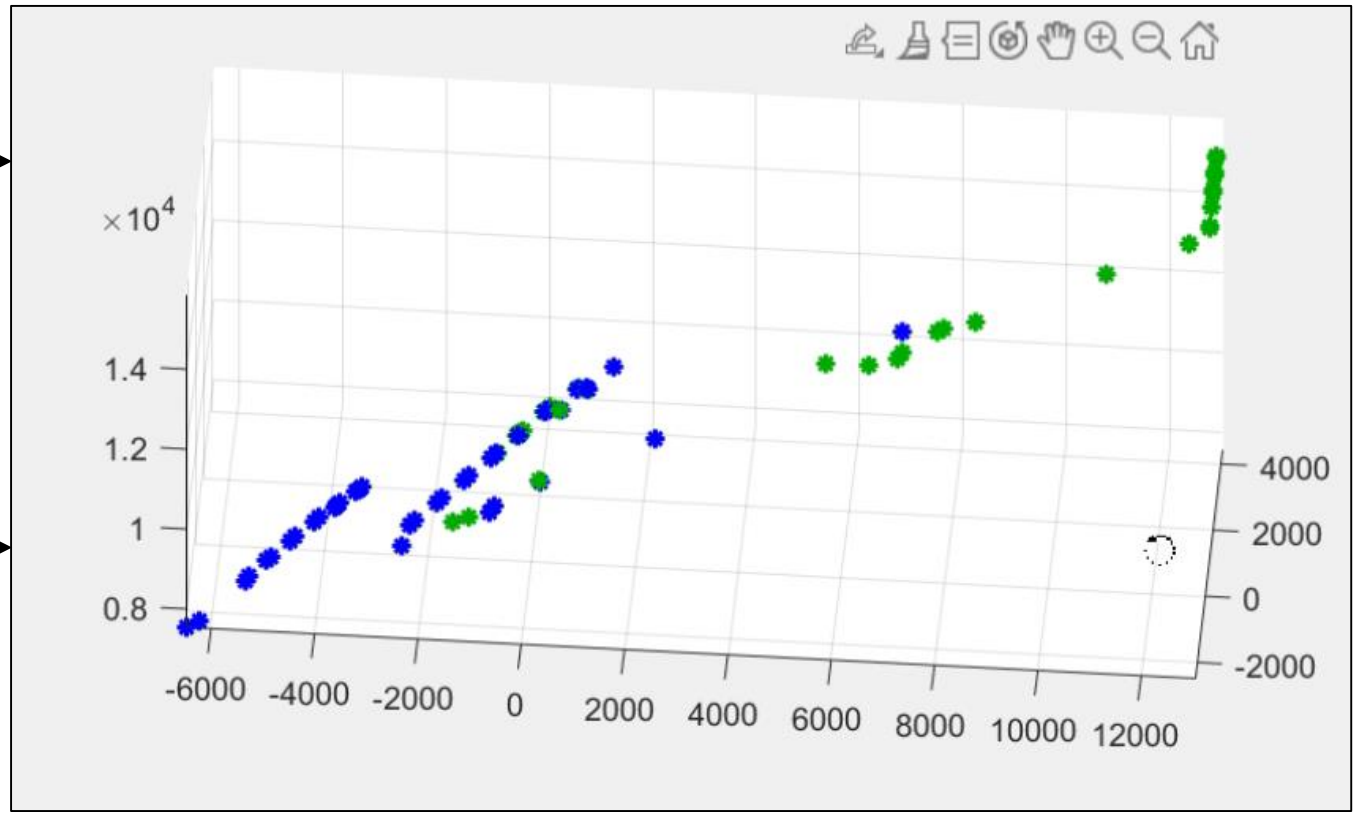
3D Lidar와 CNN을 이용한 원거리 얼굴인식 시스템 (초소형 라이다 적용)

원거리에서도 선명한 얼굴 인식 가능!!

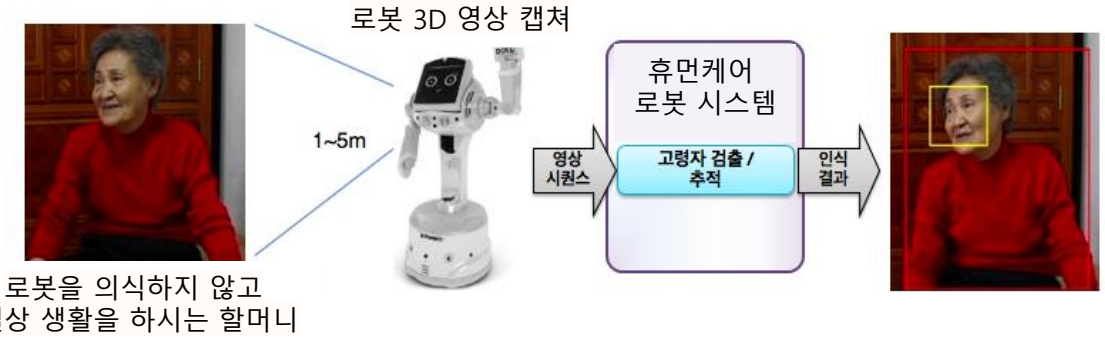
		Proposed ToF sensor	Azure Kinect	Kinect V2
		✓ Maintain quality over long distances ✓ No distortion (pixelation, blurring)	✓ Exponential degradation in quality over long distances ✓ Blurred face due to internal filtering	
Depth image	2m	120x80	40x50	30x40
	3m		25x30	20x25
	4m		20x25	15x20
Amplitude image	2m		40x50	30x40
	3m		25x30	20x25
	4m		20x25	15x20



대규모 선박 제조 공정의 정밀 3D 좌표 인식 (스테레오 기반)

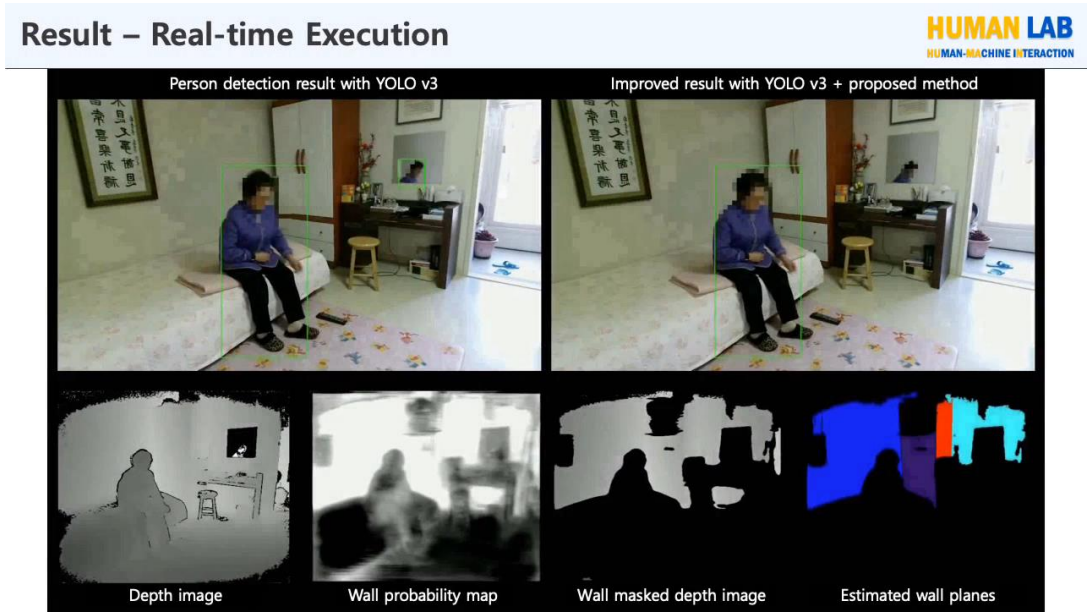


휴머노이드 로봇의 인체 인식에 적용



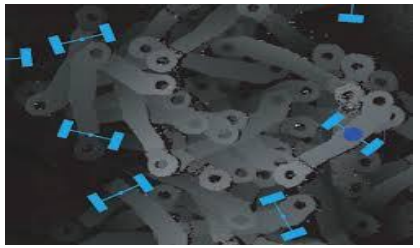
자율 주행 로봇의 3차원 물체인식에 적용





로봇 제조 공정에 적용 (bin picking)

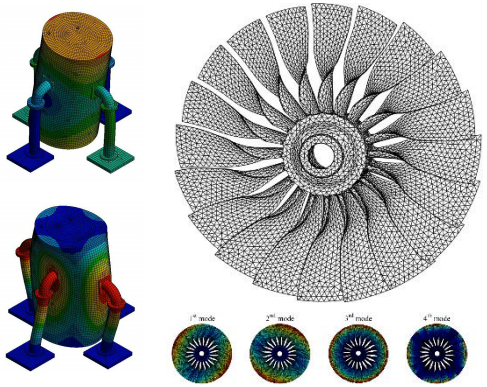






Summary of Human Lab's Research and Developments

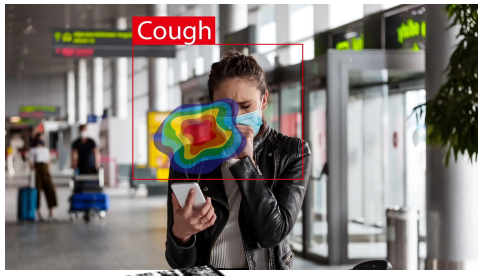
Mechanical Vibration & Condition Monitoring

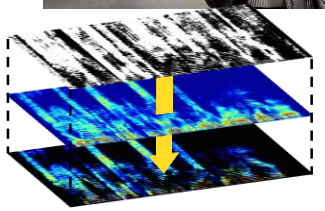


High Fidelity Structural Vibration Modeling and Analysis

- Vibration analysis of linear /nonlinear systems in time, frequency and modal domain
- System identification and inverse problem
- Vibration signature-based condition monitoring
- Deep learning for dynamical system modeling
- Prognostics and Health Monitoring (PHM)
- High-fidelity digital twin
- FEM model updating
- Experimental modal analysis

Auditory Intelligence & Acoustic Recognition





Sound
Classification
Localization
Separation

- Deep Sound Event Detection
- Human auditory system
- Binaural sound event localization and detection for Humanoid Robot
- Acoustic signature-based condition monitoring and fault diagnosis
- Cocktail Party Problem: classification, localization and separation of sound
- Artificial ear for humanoid robots

Human Sound & Vibration (Health Sensors)



Non-invasive
Health Sensor

- Human vibration and sound for health monitoring applications
- Non-invasive, wearable health sensors (blood pressure, diabetes, etc.)
- Coupled-field dynamic modeling and analysis of human body
- Deep operational learning for biodynamic modeling and bio-signal analysis

3D Measurement (LIDAR) & AI-based Recognition



Real Object

Full HD 3D Map
(KAIST Human Lab)



- High-resolution, robust, compact 3D LiDAR for humanoid robots and autonomous vehicles
- Stereo-vision and deep learning based high-precision depth measurement
- Human gesture / human face detection by 3D depth information
- Video motion magnification for non-contact measurements

Human Lab Members (박사 17명, 석사 10명)



Human Lab Members (박사 17명, 석사 10명)



Human Lab Members (박사 17명, 석사 10명)



"Make future together"

KAIST HUMAN LAB

HUMAN-MACHINE INTERACTION

YOU ARE WELCOME!

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