

자율운전 SMR을 위한 요소기술 개발

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3. 자율운전 SMR 관련 현안
4. 혁신형 SMR 자율운전

1. Introduction

❖ 자율 (Autonomy)

- The quality or state of being self-governing
- Self-directing freedom and especially moral independence

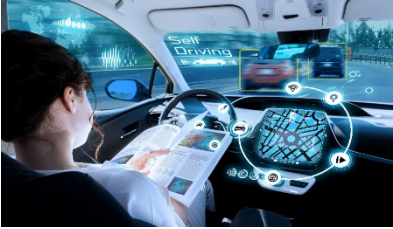
❖ 자동 (Automation)

- Automatically controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor

* Merriam-Webster Dictionary

1. Introduction

❖ 자율운전 자동차 수준: Levels of driving automation



SAE J3016™ LEVELS OF DRIVING AUTOMATION™

Learn more here: [sae.org/standards/content/j3016_202104](https://www.sae.org/standards/content/j3016_202104)

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What does the human in the driver's seat have to do?

SAE LEVEL 0™	SAE LEVEL 1™	SAE LEVEL 2™	SAE LEVEL 3™	SAE LEVEL 4™	SAE LEVEL 5™
You <u>are</u> driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			You <u>are not</u> driving when these automated driving features are engaged – even if you are seated in “the driver’s seat”		
You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	

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What do these features do?

These are driver support features

These are automated driving features

Example Features

These are driver support features			These are automated driving features		
These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/acceleration support to the driver	These features provide steering AND brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met	This feature can drive the vehicle under all conditions	
<ul style="list-style-type: none"> • automatic emergency braking • blind spot warning • lane departure warning 	<ul style="list-style-type: none"> • lane centering OR • adaptive cruise control 	<ul style="list-style-type: none"> • lane centering AND • adaptive cruise control at the same time 	<ul style="list-style-type: none"> • traffic jam chauffeur 	<ul style="list-style-type: none"> • local driverless taxi • pedals/steering wheel may or may not be installed 	<ul style="list-style-type: none"> • same as level 4, but feature can drive everywhere in all conditions

*[sae.org/standards/content/j3016_202104](https://www.sae.org/standards/content/j3016_202104)

1. Introduction

❖ 원자력발전소 Levels of Automation

Automation Level	Description
1 (no automation)	The computer offers no assistance; the human must do it all
2	The computer suggests alternative ways to do the task
3	The computer selects one way to do the task and (see 4)
4	executes that suggestion if the human approves, or (see 5)
5	allows the humans a restricted time to veto before automatic execution, or (see 6)
6	executes automatically, then necessarily informs the human, or (see 7)
7	executes automatically, then informs the human only if asked.
8 (full automation)	The computer selects the method, executes the task, and ignores the human.

< Sheridan's LOA >

	Automation Level	Automatic Functions	Human Functions
6	Autonomous operations	Fully <u>autonomous</u> operation. Human not usually informed. System may or be capable of being disabled.	Human generally has no role in operation and monitoring is limited.
5	Operation by exception	Essentially <u>autonomous</u> operation unless specific situation or circumstances are encountered.	Human must approve of critical decisions and may intervene.
4	Operation by consent	Full automatic control under close monitoring and supervision.	Human monitors closely, approves actions, and may intervene.
3	Operation by delegation	Automatic control when directed by human to do so.	Human provides supervisory commands that automation follows.
2	Shared control	Automatic control of some functions task.	Manual control of some functions/tasks
1	Assisted manual control	Primarily manual control with some automation support.	Human manually controls with assistance from partial automation.
0	Direct manual control	No automation.	Human manually controls all functions and tasks.

< Billings' LOA >

* EPRI TR Guidance for the design and use of automation in nuclear power plants

1. Introduction

❖ 자동과 자율은 같은 Dimension에서 정의됨.

- 자동차 산업에서는 자율이라는 용어를 사용
- 원자력 산업에서는 자동이라는 용어를 사용

❖ 자율운전 SMR은 기존의 대형원전 대비 LOA를 향상시키는 것을 목표로 함.

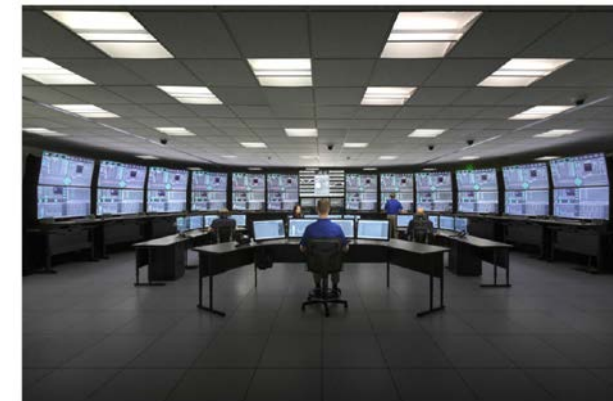
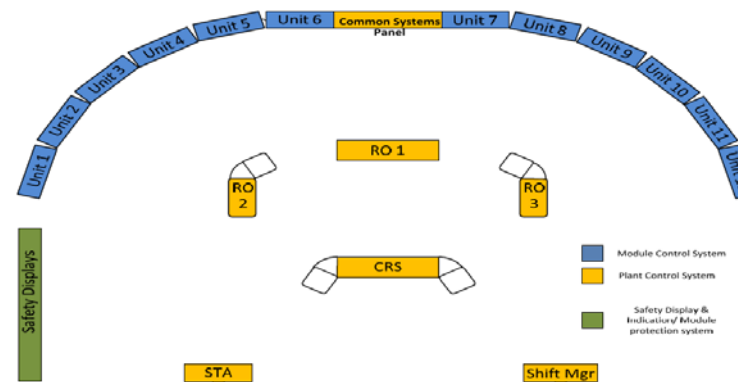
- Shared Control => Operation by Delegation 이상
- Passive System 및 Decision Support 등도 자동화와 동일한 효과가 있음.

1. Introduction

❖ NuScale Features

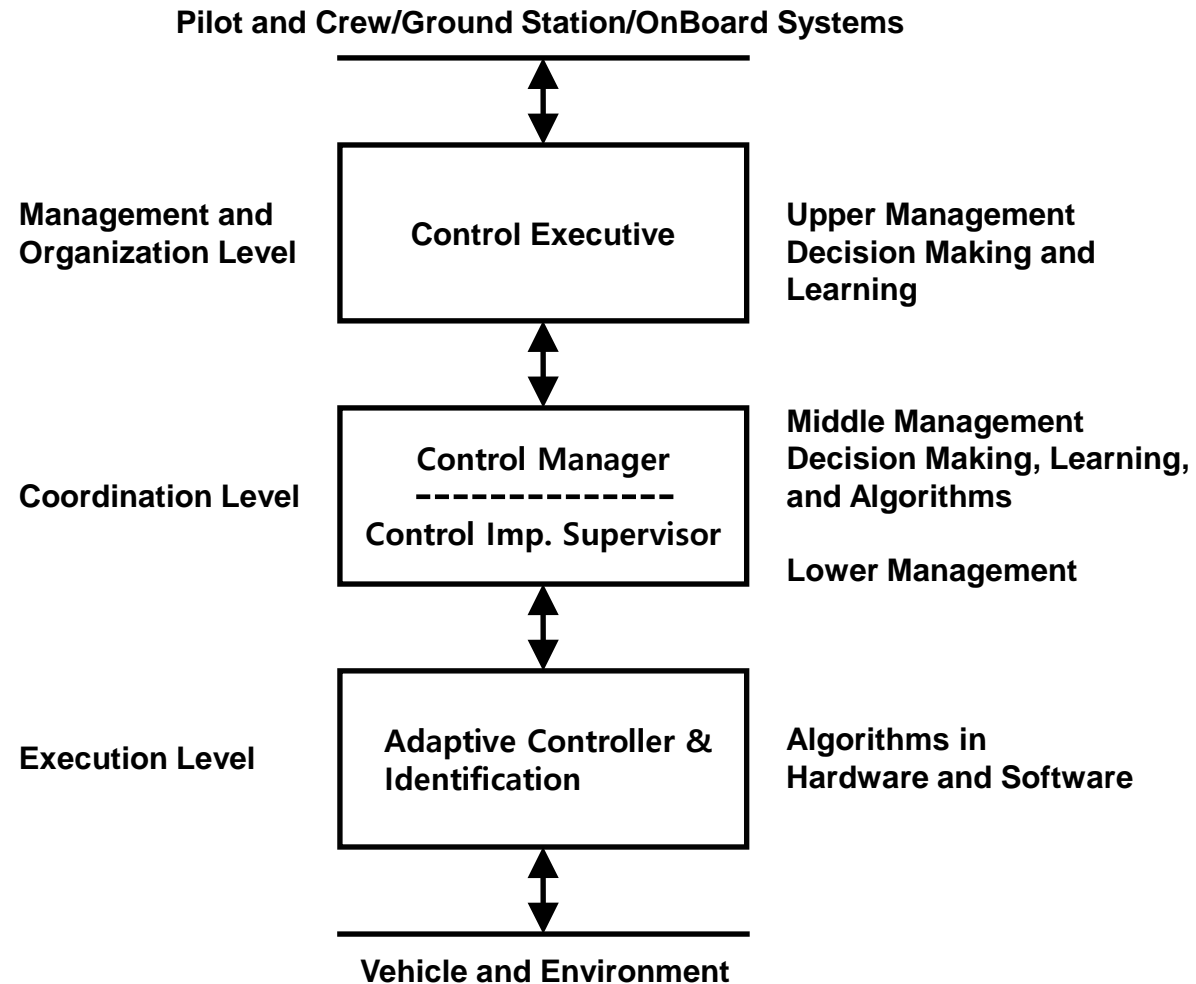
- High levels of automation
 - Automation of necessary **reactivity changes**
 - **Automated startup** to maneuver the unit undergoing startup from shutdown to power operations
 - **Automated shutdown** of one unit of multiple units simultaneously
 - **Automated maintenance** of electric power production or return to capacity after grid fluctuations
- **Monitoring and control** multiple units in one MCR with **acceptable workload levels**
- Integrated HSI
- Optimized MCR staff size
 - **6 operators – 12 units**

Stevens et al., 2019



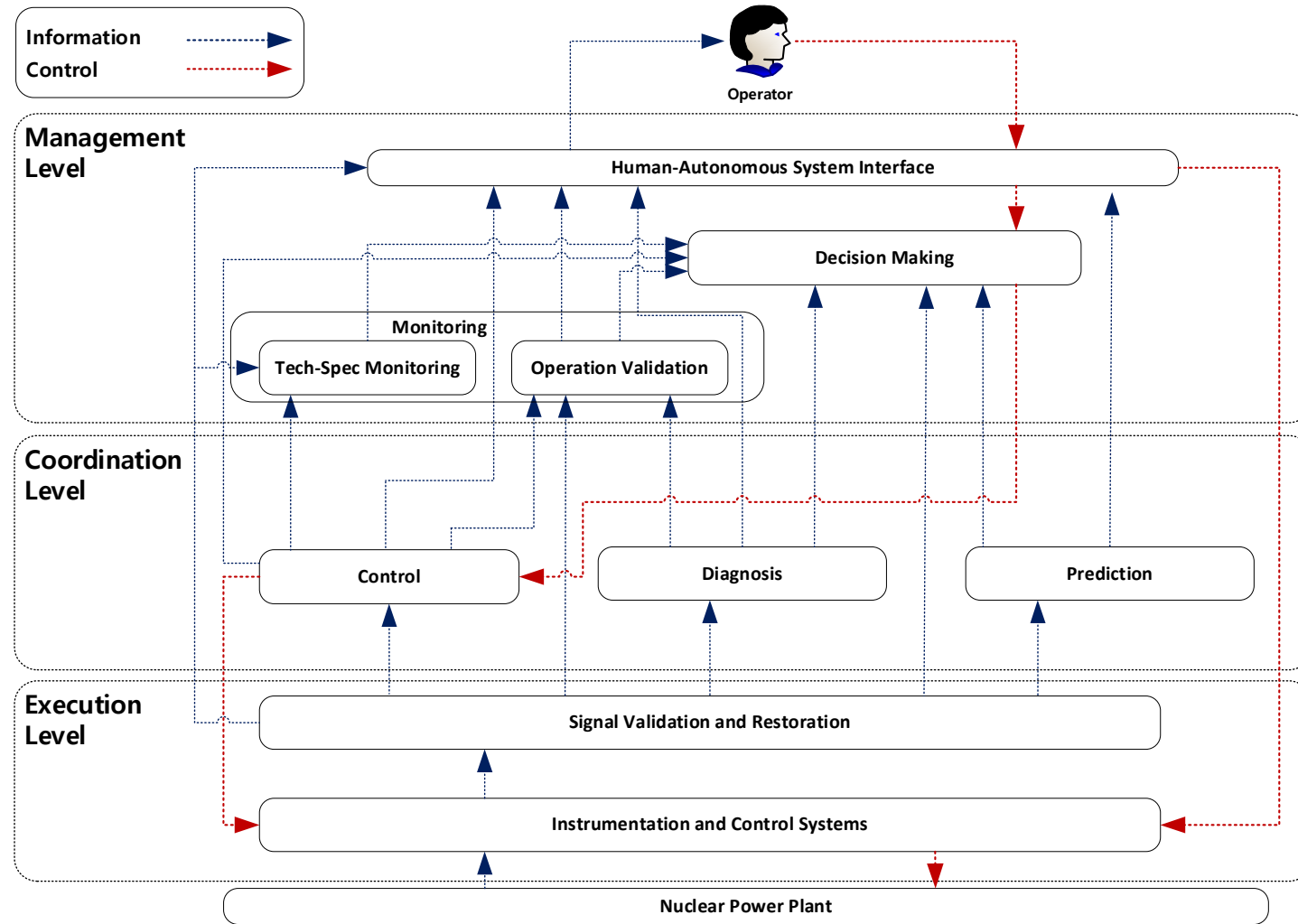
1. Introduction

❖ Antsaklis: Autonomous controller functional architecture (1991)



1. Introduction

❖ 원자력발전소 자율운전을 위한 요소기술 제안



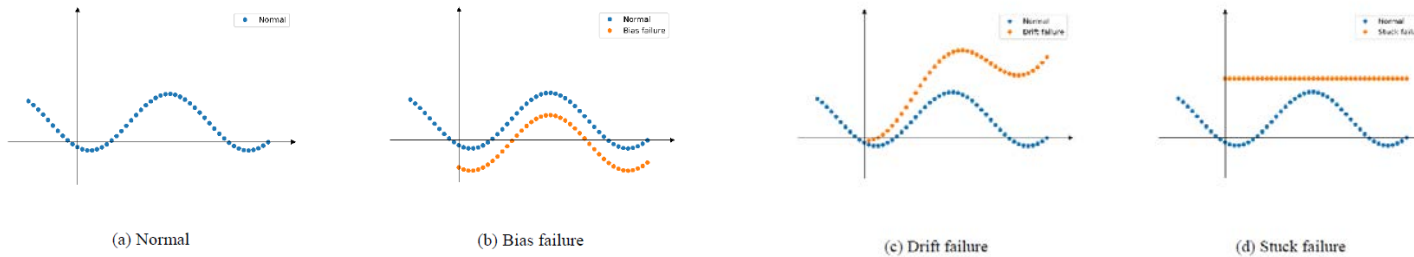
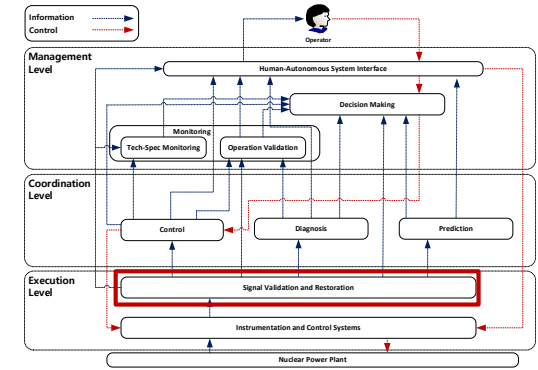
2. 원자력발전소 자율운전 요소기술

1. Signal Validation and Restoration
2. Prediction
3. Diagnosis
4. Control
5. Monitoring
6. Decision Making
7. Human-System Interface

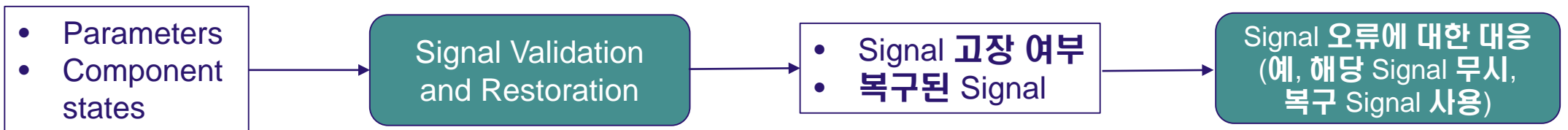
2.1 Signal Validation and Restoration

❖ 목적

- Validation: Sensor **고장**, Signal **오류**를 탐지
- Restoration: 문제가 있는 신호를 정상 값으로 복구
- 자율운전 전체 성능이 신호의 건전성에 영향을 받게 됨

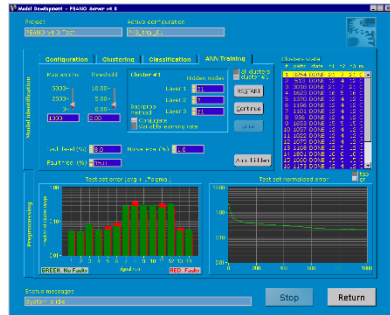


❖ 기능

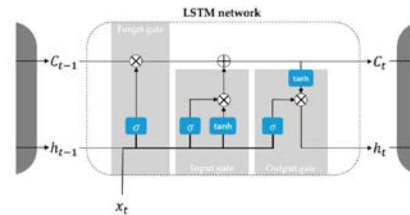


2.1 Signal Validation and Restoration

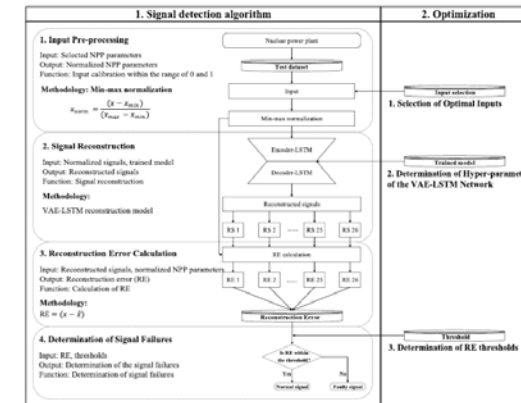
❖ 연구사례



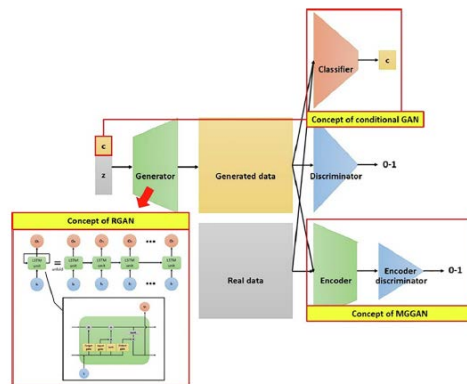
- HRP, PEANO
- Signal validation and calibration monitoring
- AANN



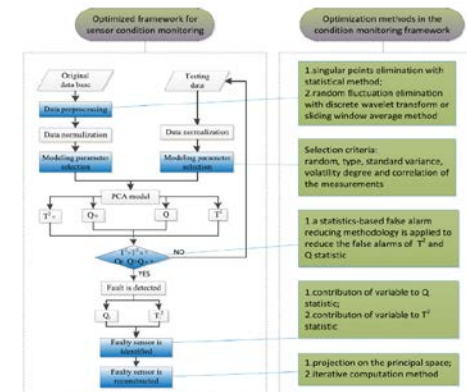
- J. Choi, S. Lee (2020)
- Sensor fault detection in the emergency
- LSTM



- Y. Choi, J. Kim (2022)
- Signal validation in the emergency
- VAE+LSTM



- S. Kim, et al. (2020)
- Signal Reconstruction
- GAN



- Li, et al. (2018)
- Sensor failure detection + reconstruction
- PCA

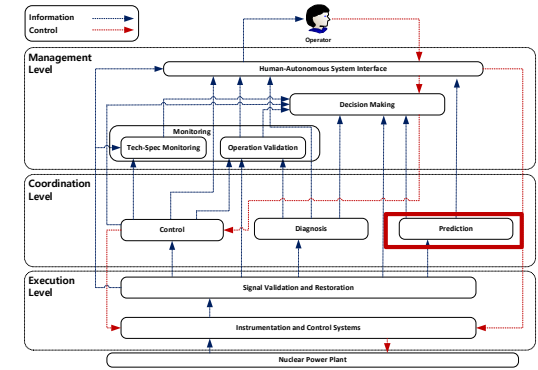
2.2 Prediction

❖ 목적

- 발전소 공정 변수 및 발전소 거동 예측 (Prediction)
- 기기의 Remaining Useful Time (RUL) 예측

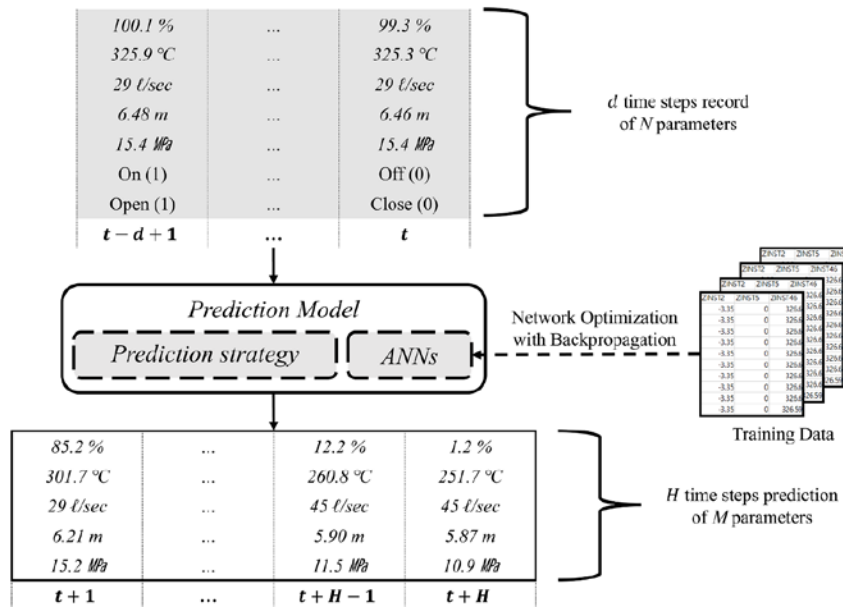
❖ 기능

- 발전소 공정변수 및 거동 예측
- 기기의 고장 예측
- 원자로 정지 예측
- 경보 및 비정상 발생 사전 예측
- 운전원 개입 요청에 활용
- 제어 수단 선택을 위한 의사결정 지원
- 제어 수행 후 발전소 거동 예측

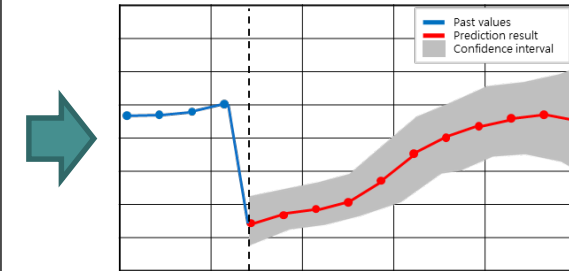
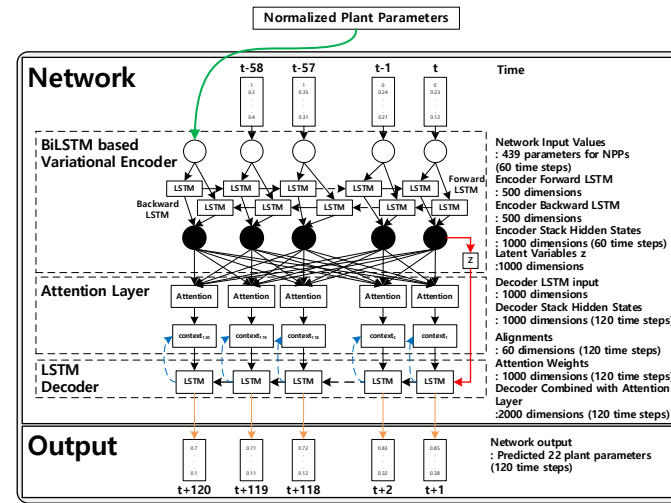


2.2 Prediction

❖ 연구사례



- J. Bae, G. Kim, S. Lee (2021)
- Real-time prediction of plant parameters following operator actions
- 20 steps
- LSTM, MIMO



- H. Kim, J. Kim (2021)
- Long-term prediction with uncertainty
- 120 steps, single network
- BiLSTM, AM, CVAE

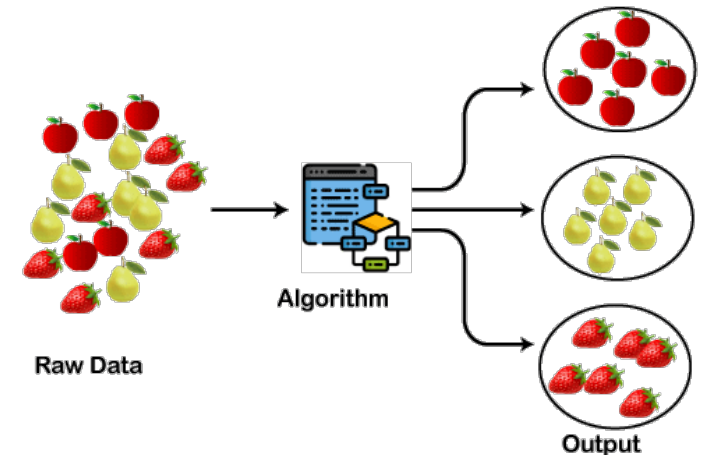
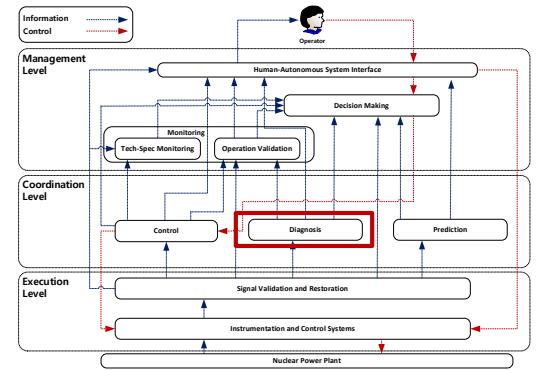
2.3 Diagnosis

❖ 목적

- 비정상상태 발생 감지
- 비정상상태 진단 및 절차서 선택
- 비상상태 진단 및 절차서 선택

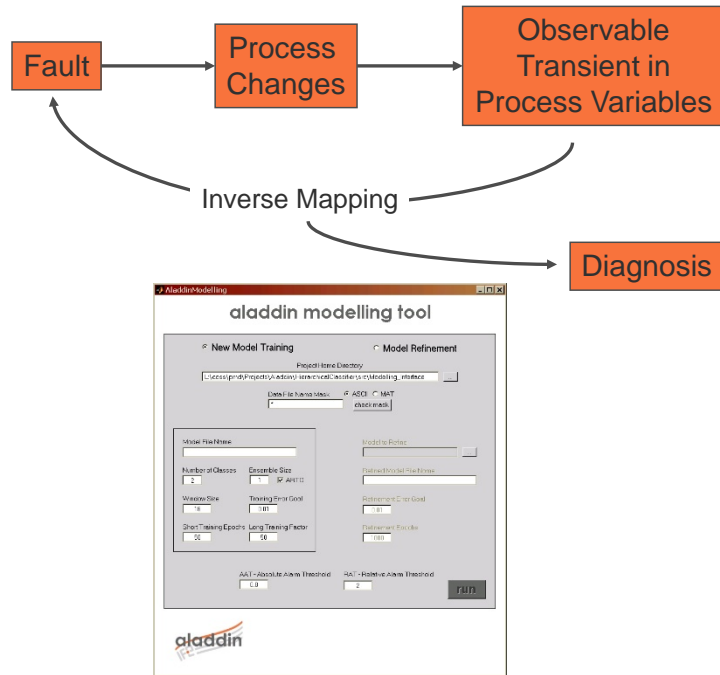
❖ 기능

- 발전소 운전 모드 및 상태에 따른 사고/고장 원인 진단
- Unknown or Untrained Event 감지
- 진단결과의 Confirmation
- 운전상태에 적합한 절차 또는 제어 알고리즘 선택 지원
- 제어 또는 감시 모드를 현재 상태에 적절하게 전환할 수 있도록 지원 (예, SFSC, Tech Spec)

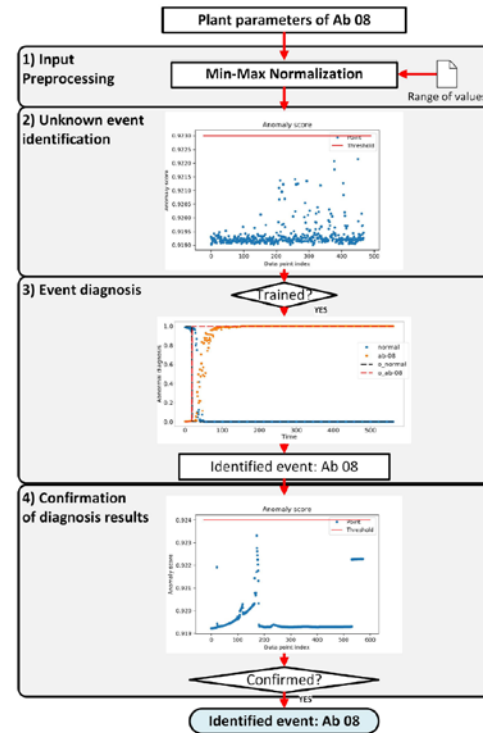


2.3 Diagnosis

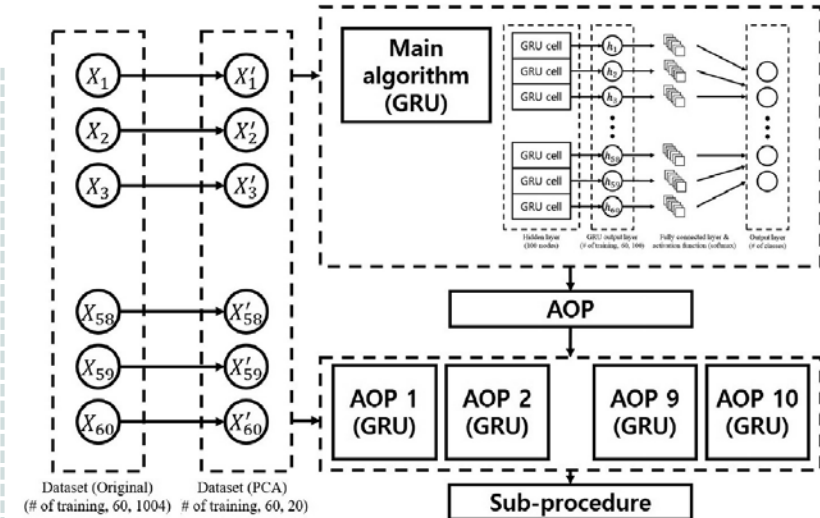
❖ 연구사례



- HRP, Aladdin
- Early detection and diagnosis of faults and anomalies
- Elman Recurrent Neural Network
- Modeling and testing tools



- H. Kim, J. Kim (2021)
- Diagnosis of abnormal events
- Unknown event identification, confirmation
- LSTM-VAE



- J. Kim, S. Lee (2020)
- Diagnosis of abnormal events
- Principal component analysis (PCA), gated recurrent unit (GRU)

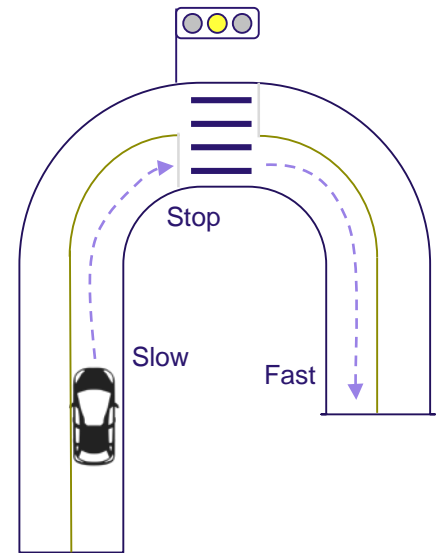
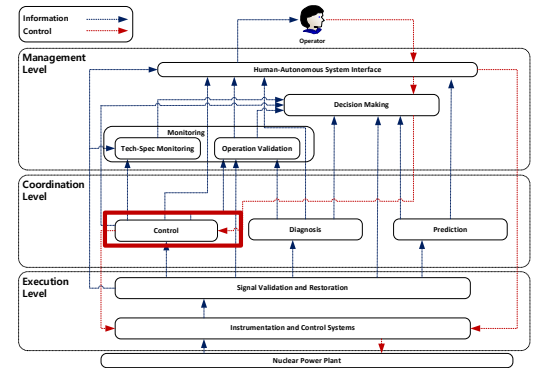
2.4 Control

❖ 목적

- 상황에 적합한 발전소 제어 수행

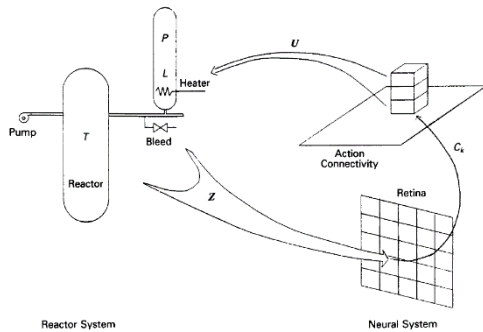
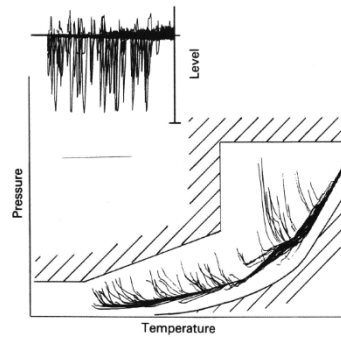
❖ 기능

- 출력증감발, Load Following, 비정상운전, 비상운전
- 운전절차서에 따른 운전
- 절차서에 없는 상황의 경우 발전소 안정화
- 운전원 개입 시간까지 발전소 안정 상태 유지
- Tech Spec 적용: 운전제한조건 준수 및 위반시 대응
- 정주기 시험 자동화

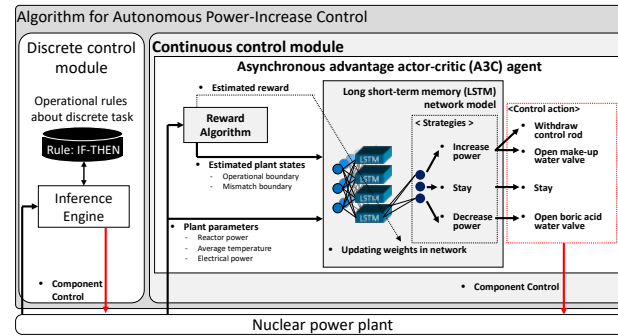
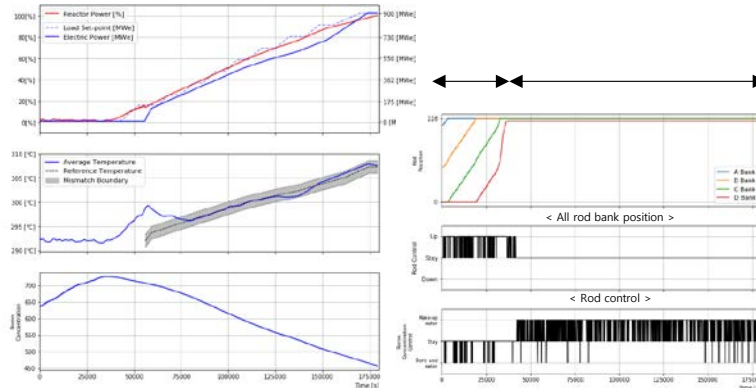


2.4 Control

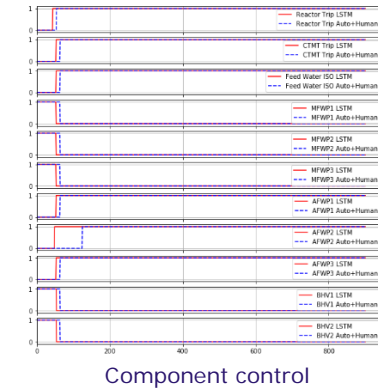
❖ 연구 사례



- W. Jouse, J. Williams (1993)
- Manage system within Limiting Conditions for Operations (LCO)
- Neural network



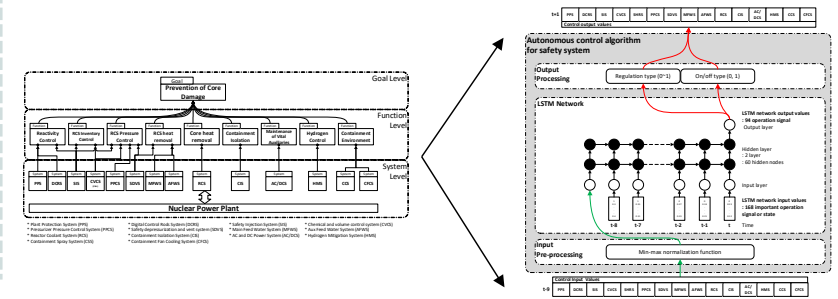
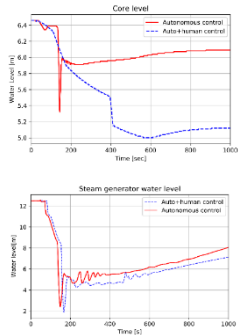
- D. Lee, J. Kim (2021)
- Power increase operation from 2% to 100%
- Rule based system + Asynchronous advantage actor-critic (A3C) agent



Component control

RCS inventory control function

RCS heat removal



- D. Lee, J. Kim (2018)
- Control autonomously systems and components in the emergency operation
- LSTM

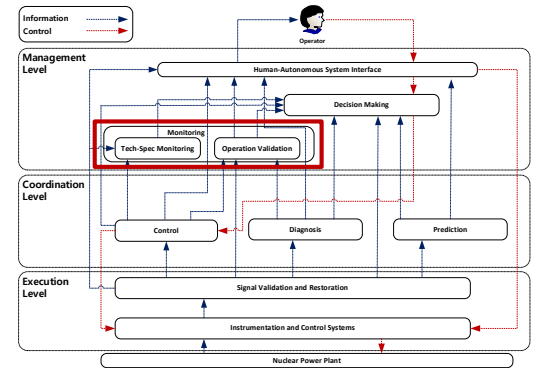
2.5 Monitoring

❖ 목적

- 자율운전에 의해 발전소가 적절히 관리되고 있음을 감시
- 자율운전이 적절하게 동작하고 있음을 감시

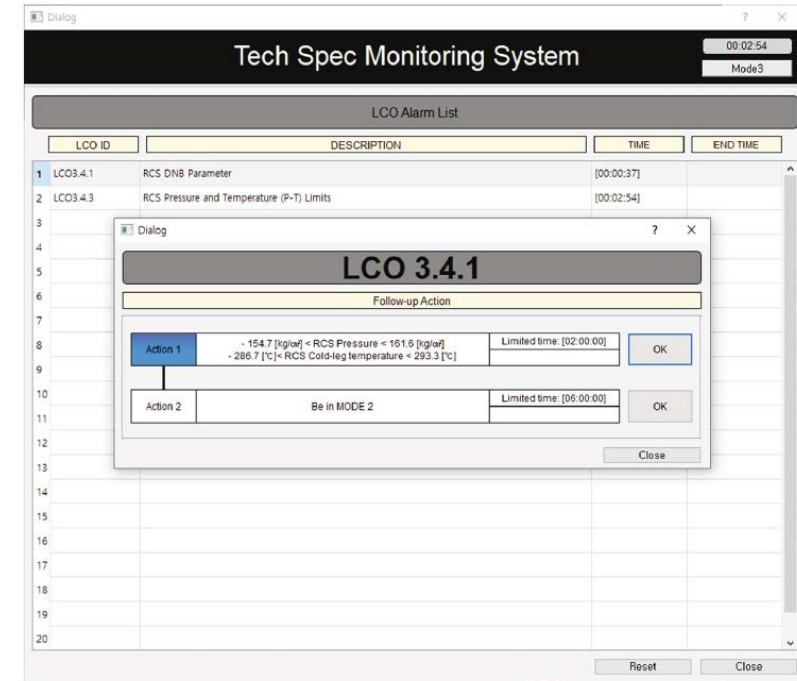
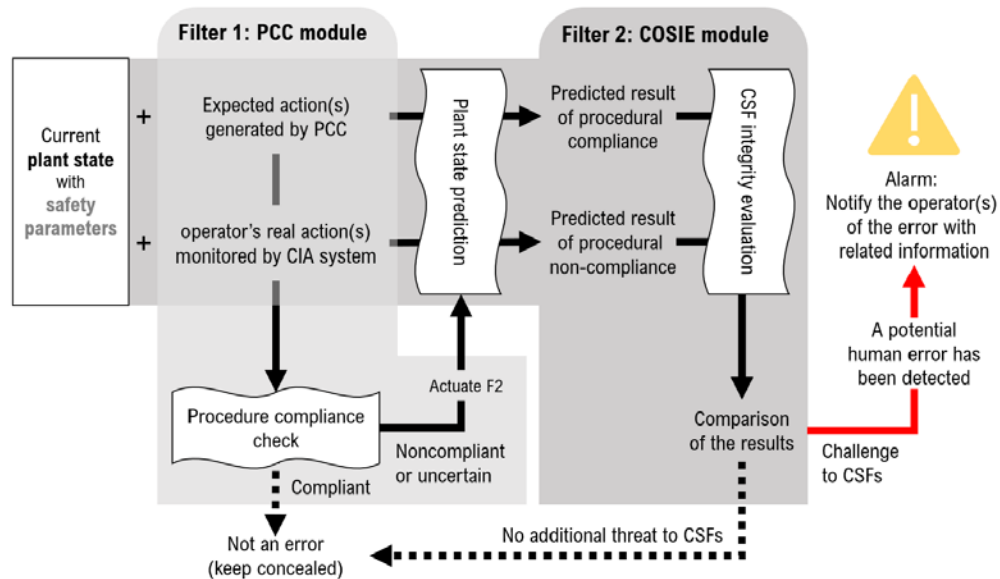
❖ 기능

- 경보 및 비정상 상태 발생 감지
- 자율운전에 의한 제어 적절성 평가
 - 사고 상태에 따른 비상운전 안전기능 감시
 - 운전제한조건 및 Tech Spec 사항 감시
 - 비정상/비상 상황 완화 정도 평가
 - 불만족 시 Decision Making을 위해 신호 발생



2.5 Monitoring

❖ 연구사례



- J. Ahn, et al. (2022)
- Operation validation system (CIA)
- 운전원 비상 조치의 적절성을 절차서 기반으로 평가
- Critical Safety Function 만족 여부 고려
- 발전소 상태 예측 결과를 반영

- S. Lee, J. Kim (2021)
- Tech Spec Monitoring System
- LCO 감시 (SVM, VAE, LSTM 등 적용)
- LCO 위반에 따른 Tech Spec 수행 제안
- 후속조치 적절성 평가
- 정지여유도, 예상임계 제어봉 위치, 붕소주입량, RCS 누설량 계산

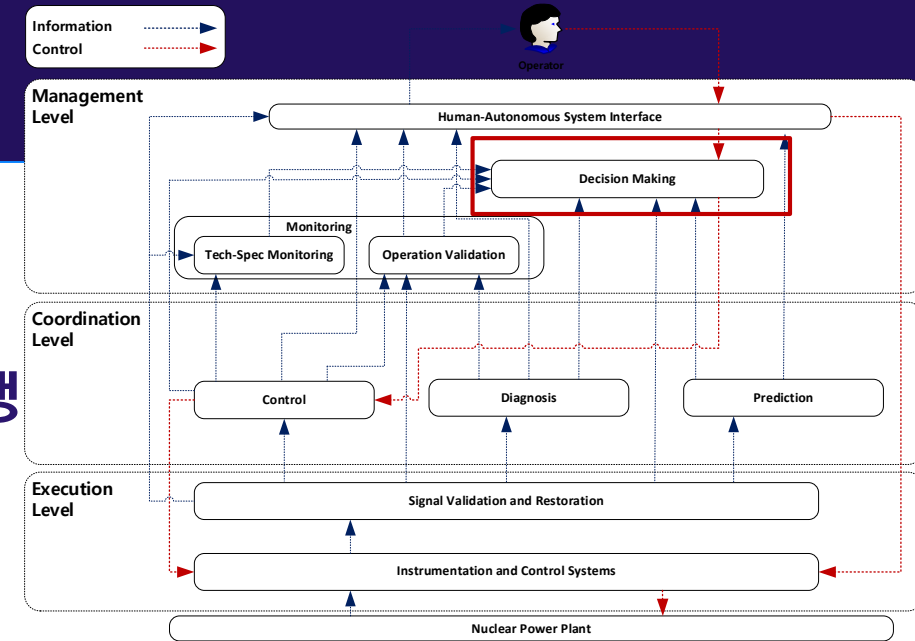
2.6 Decision Making

❖ 목적

- 하위 기능 간의 Interaction 총괄
- 발전소의 상태를 안정적으로 유지하기 위한 의사결정 수행
- 자율운전의 Brain 역할

❖ 기능

- 발전소 운전모드, 발전소 상태 평가
- 발전소 모드 및 상태에 맞는 제어 선택
 - 출력증감발, Load Following, 비정상운전, 비상운전, 진단결과 반영
- 감시 결과 발전소가 자율운전에 의해 적절히 제어되고 있지 않다고 판단될 경우, 현재 운전을 종료하고 적합한 운전 선택
 - Tech Spec 불만족, 안전기능 불만족 시 대응
 - 자율운전에 의해 발전소 운전이 가능한지 여부 판단 => 불가능할 경우 운전원 개입 요청
 - Monitoring 및 Prediction 결과 활용



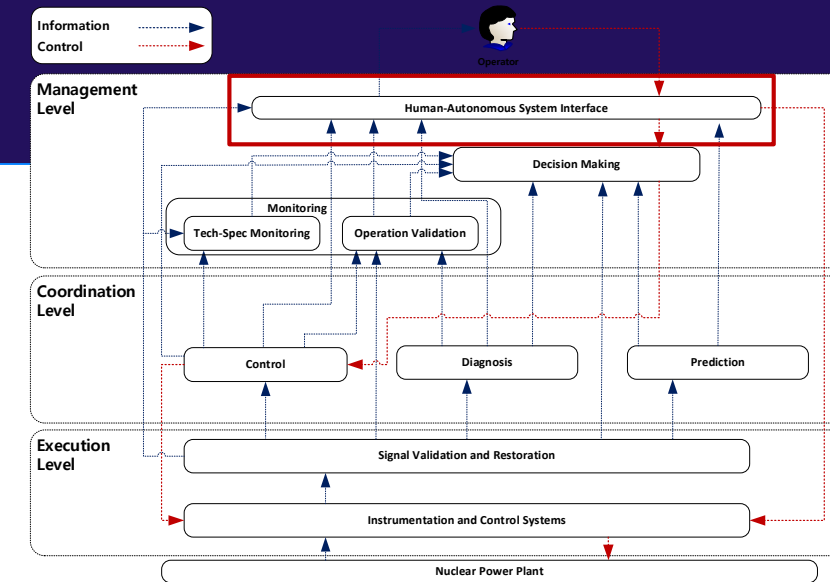
2.7 Human-System Interface

❖ 목적

- 운전원 개입이 필요할 경우 감시 및 제어 수단 제공
- 운전원 상황인식을 위한 정보 제공
 - 발전소 상태 상황인식
 - 자율운전 상태 상황인식

❖ 기능

- 발전소 정보 및 제어 수단 제공
 - 운전모드, 운전상황 등
- 자율 운전 상태에 대한 정보
 - 자율제어 동작 이력 및 근거
 - 진단, 예측, 감시 결과 및 근거
 - Decision Making 이력 및 근거
- 운전원 개입 요청 알림
- 운전 권한 (Authority) 전환 기능

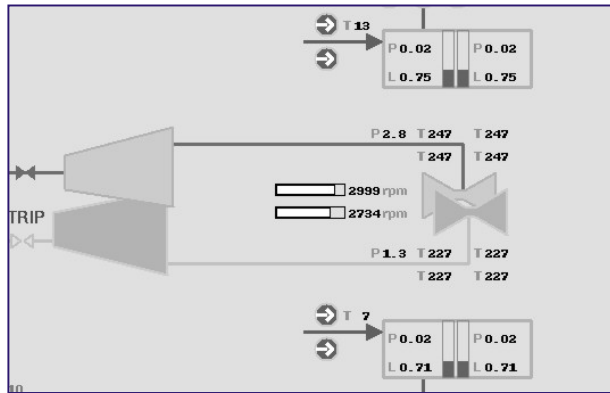


• 자동화 관련 인간공학 현안

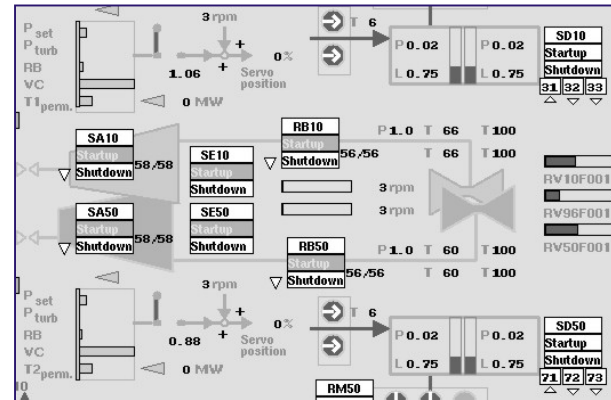
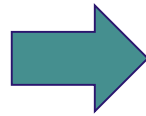
1. Automation complexity
2. Feedback on automation states and behaviors
3. Out-of-the-Loop Unfamiliarity
4. Clumsy Automation
5. Automation induced errors
6. Inappropriate trust: misuse, disuse, and complacency
7. Behavioral adaptation
8. Inadequate training and skill loss
9. Job satisfaction and health

2.7 Human-System Interface

❖ 연구사례

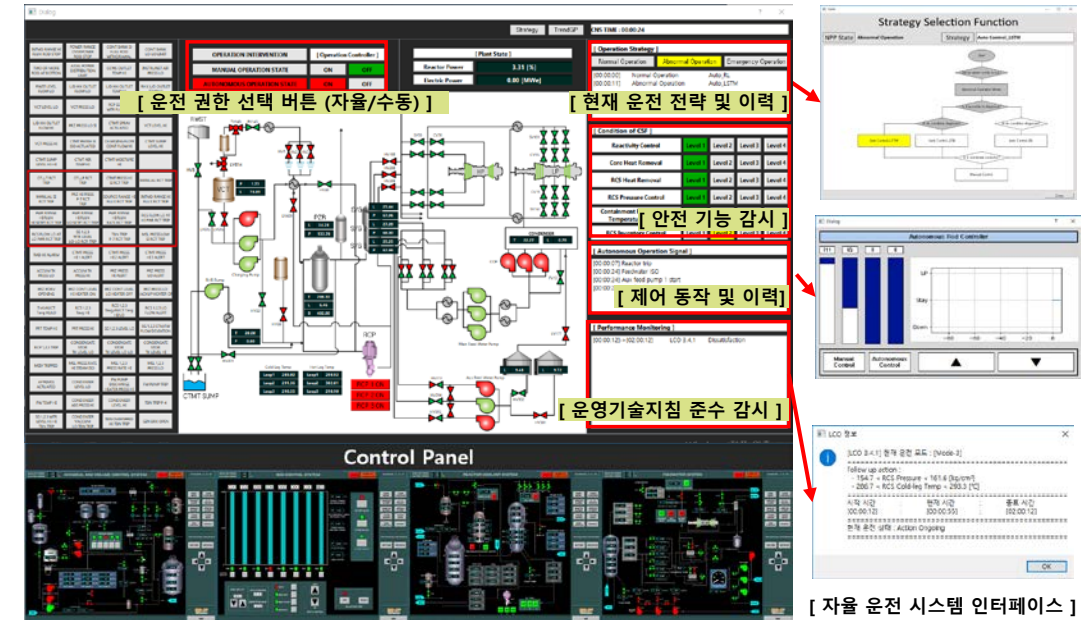


Conventional Interface



HCA Interface

- Information about the activities of the automatic system 추가



[자율 운전 시스템 인터페이스]

<HRP Human-centered Automation Interface>

<ATOM GAIA Interface>

3. 자율운전 SMR 관련 현안

❖ Licensing

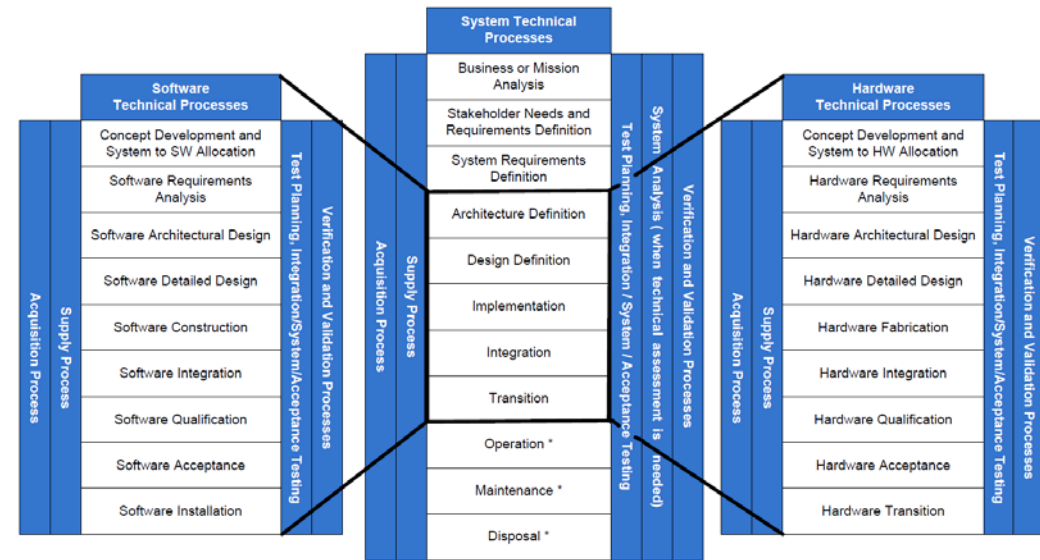
- Blackbox Issue
 - eXplainable AI (XAI)
- Validation Issue
 - Software Development Process를 적용하여 개발

❖ Data

- Lack of actual plant data for training
 - Robust AI (2022년 5월 19일(목) 09:00 이대일 발표)

❖ Continual Lifelong Learning

- The ability to continually learn over time by accommodating new knowledge while retaining previously learned experiences



<IEEE Std 1012>

4. 혁신형 SMR 자율운전

❖ 에타 혁신형 SMR 자율운전기술 개발 (RFP 제출안)

구분	내용	목표
혁신형 SMR 자율 운전 개념 정립	<ul style="list-style-type: none"> 운전상황별 자율운전 개념 및 자동화 수준 정의 자율운전 기능분석 및 기능할당 	Billings 자동화수준 Level 4 (Operation by Delegation) 이상 3 operators – 4 units
정상 및 출력제어 자율운전 기술 개발	<ul style="list-style-type: none"> 출력 증감발 자율운전 기술 개발 출력제어 운전 기술 개발 	
비정상 자율운전 기술 개발	<ul style="list-style-type: none"> 비정상 상황 자율운전을 위한 알고리즘 개발 비정상 상황 자율운전 알고리즘 구현 비정상 상황 자율운전 검증 비정상 상황 자율운전을 위한 인간기계연계(MMI) 개발 	
비상 자율운전 기술 개발	<ul style="list-style-type: none"> 비상 상황 자동(자율)운전을 위한 알고리즘 개발 비상 상황 자동(자율)운전 알고리즘 구현 비상 상황 자동(자율)운전 검증 비상 상황 자동(자율)운전을 위한 인간기계연계(MMI) 개발 	

감사합니다!!!

