Safe and Efficient Maintenance of Civil Infrastructure Systems through Predictive Control of Human-in-the-Loop Operational Workflows

Health and Hope for Everyone on this Planet

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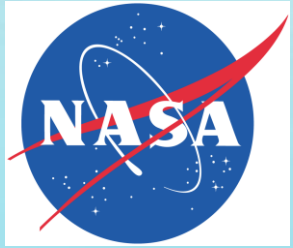
Construction Industry Institute®

Carnegie Mellon University

A Speech for the Construction Industry Institute (CII)

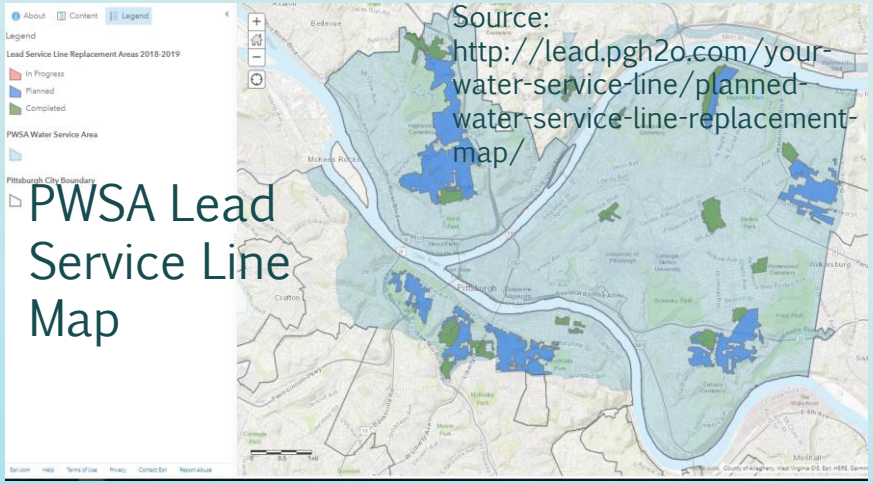
Thank You All First!

- Construction Industry Institute
- My institutions
- Funding agencies
- Collaborators, colleagues, and friends
- My students
- My family



A Decision-Making Scenario …

Cyber-Human Systems



PWSA Lead Service Line Map

Source: http://lead.pgh2o.com/your-water-service-line/planned-water-service-line-replacement-map/

Cyber Infrastructure Operations

Human-Physical Systems

Source: https://imgur.com/gallery/YbPMJ6k

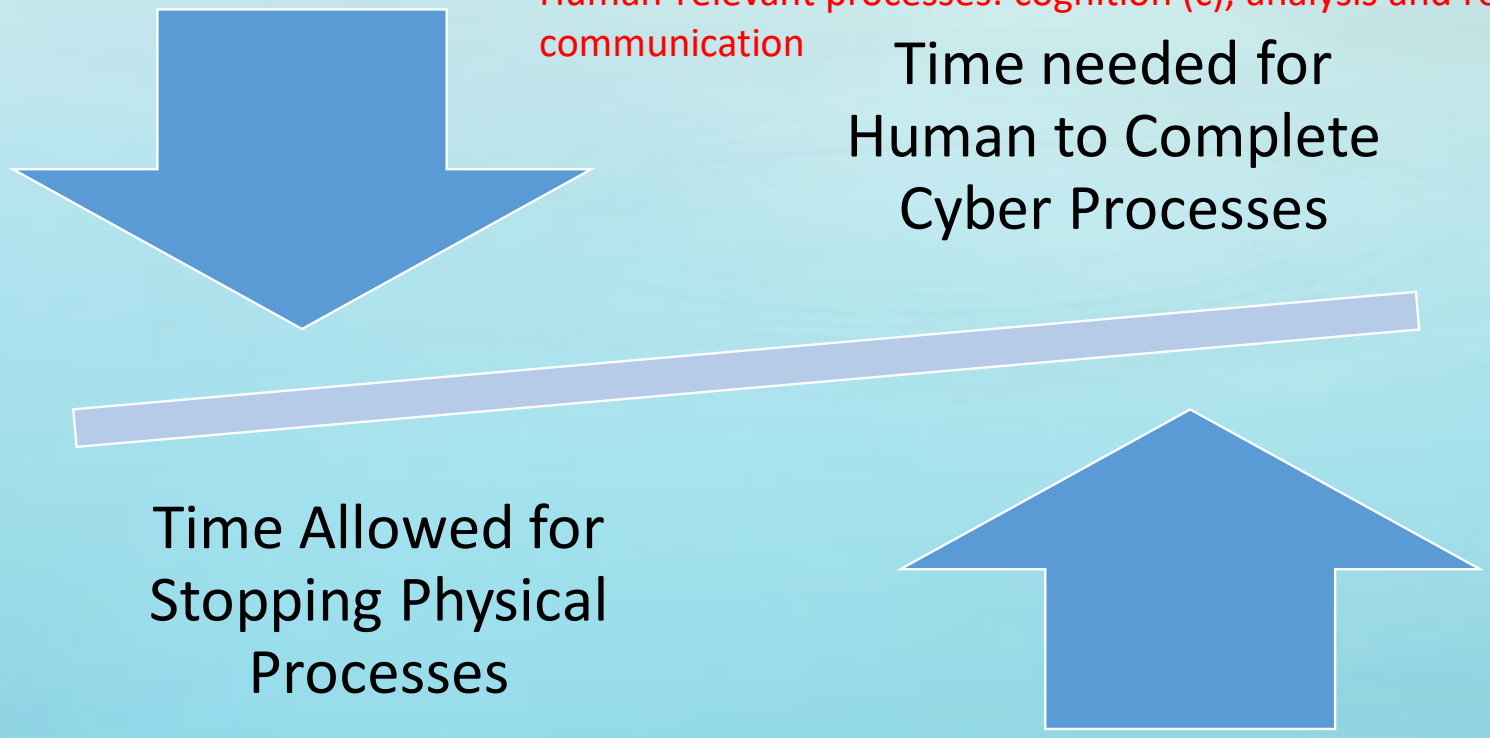
Physical Infrastructure Operations

Human-Cyber-Physical Infrastructure Systems?

Source: vr360app.net

Understanding Human-Cyber Physical Systems (H-CPS) Reliability for Safety and Efficiency

- Human-irrelevant processes: computational, sensing, visualization
- Human-relevant processes: cognition (c), analysis and response (r), communication



A Mathematical Representation for Understanding the H-CPS Safety and Efficiency

- Two levels of human factors that influence the probability of avoiding an event

$$P[\left(T_{c,i}(t) > \boldsymbol{T_{c-human,i}(t)}\right) \quad \cap \quad (T_{r,i}(t) > \boldsymbol{T_{r-human,i}(t)} + \boldsymbol{Communication})]$$

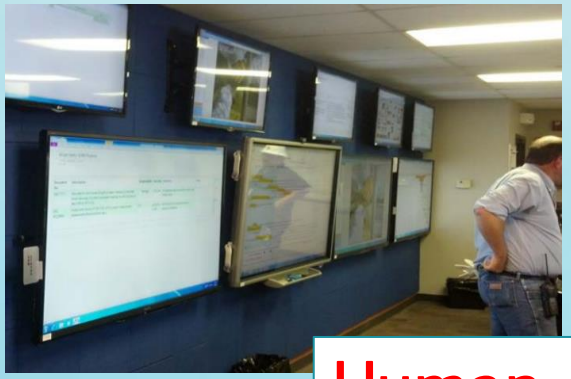
Cognitive capabilities at the individual level

Communication and organization level

- *Symbols:*
  - *c: cognition*
  - *r: response*
  - *i : the number of activities and cognitive tasks,* $i \in (1,2,\dots n)$*, n is the total number of activities and tasks*
  - $\left[T_{c,i}(t), T_{r,i}(t)\right] = F\{G_j(t), \Pr(Event|G_i(t))\}$
    - G: Geometry
    - j: the number of objects in the scene, $i \in (1,2,\dots m)$, m is the total number of objects in the scene

This Fundamental H-CPS Framework Applies to Many Civil Infrastructure Systems O&M Problems

Nuclear Power Plant Outage Control



Cyber

NPP Control Room (INL, 2015)

Human Controllers

Physical

Palo Verde Nuclear Generation Station (Source: Wikipedia)

Air Traffic Control

http://www.scmp.com/news/asia/south-asia/article/20018 controller-shortage-threatens-indian-airline-boom

Cyber

Airport Control Tower (Source: scmp.com)

Human Controllers

Physical

Pudong Airport Runway Incursion (Nov. 13th, 2018)

https://www.facebook.com/Aeronews.ro/posts/serious-incident-runway-incursion-at-shanghai-pudong-intl-airport-when-a-japan-a/1958233614252729/

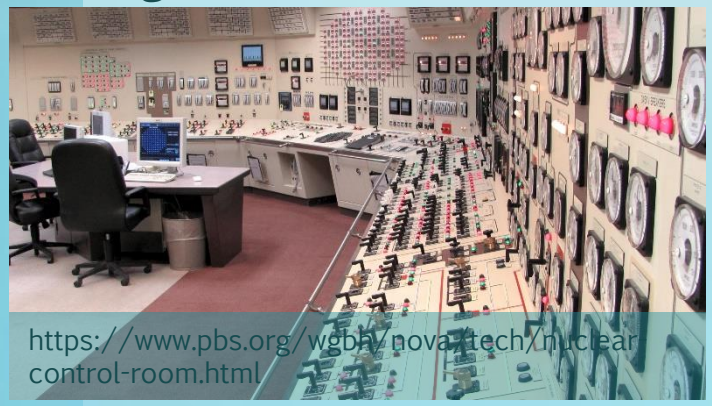
This Fundamental H-CPS Framework has Two Aspects – Humans in the Control Room and Humans in the Field

Cyber

Human

Physical

Analog Control Room



https://www.pbs.org/wgbh/nova/tech/nuclear-control-room.html

Digital Control Room

https://e360.yale.edu/features/when-it-comes-to-nuclear-power-could-smaller-be-better

Operator Control

Field Operator/worker Inspection

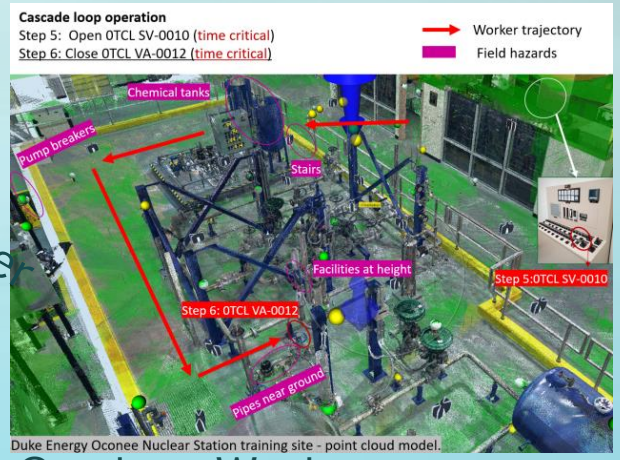
Field Observations

Remote Actions

Nuclear Power Plant Operations – operators and field workers (inspectors) are collaborating to drive dynamic and complex systems, much more complicated than driving a car…

A Speech from the Construction Industry Institute (CII)

Indoor Workspaces

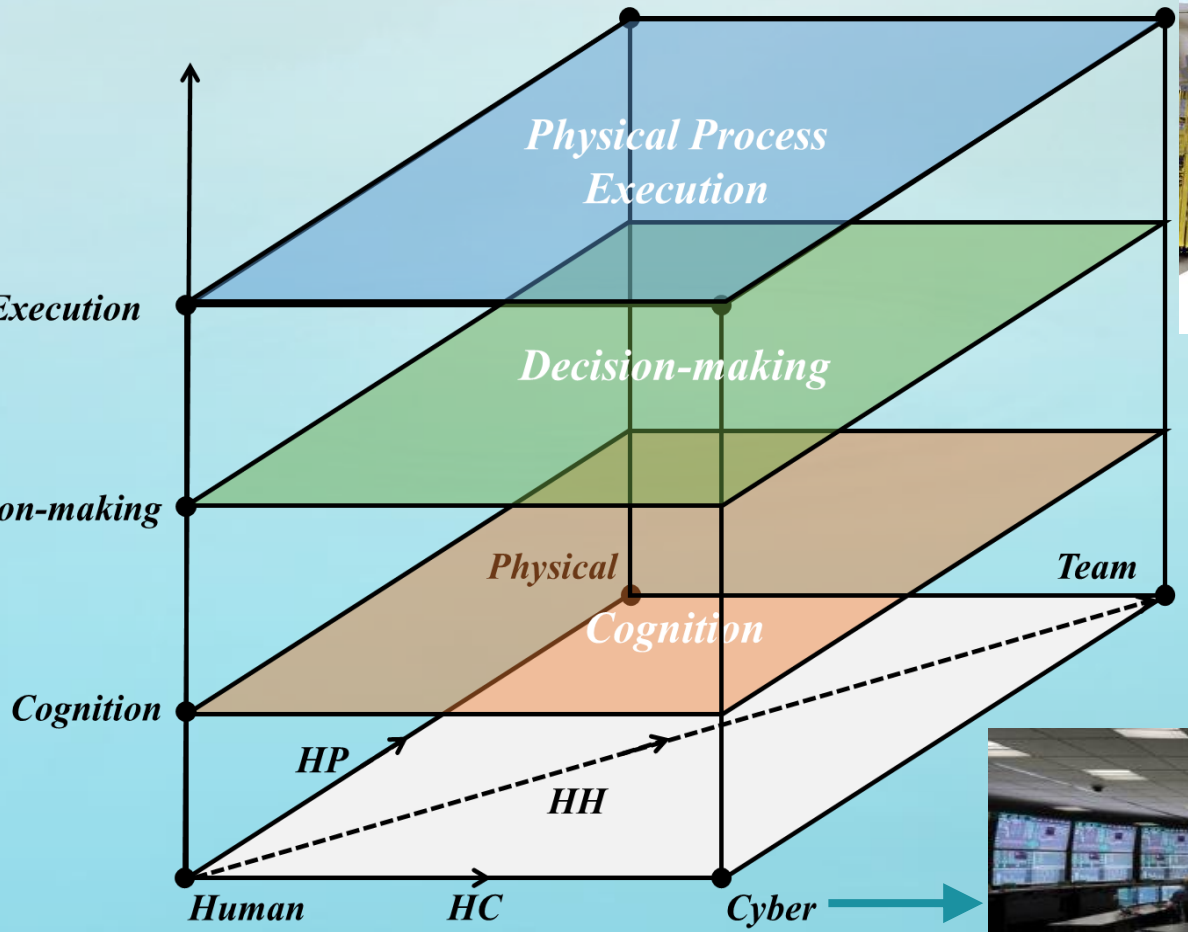


Duke Energy Oconee Nuclear Station training site - point cloud model.

Outdoor Workspaces

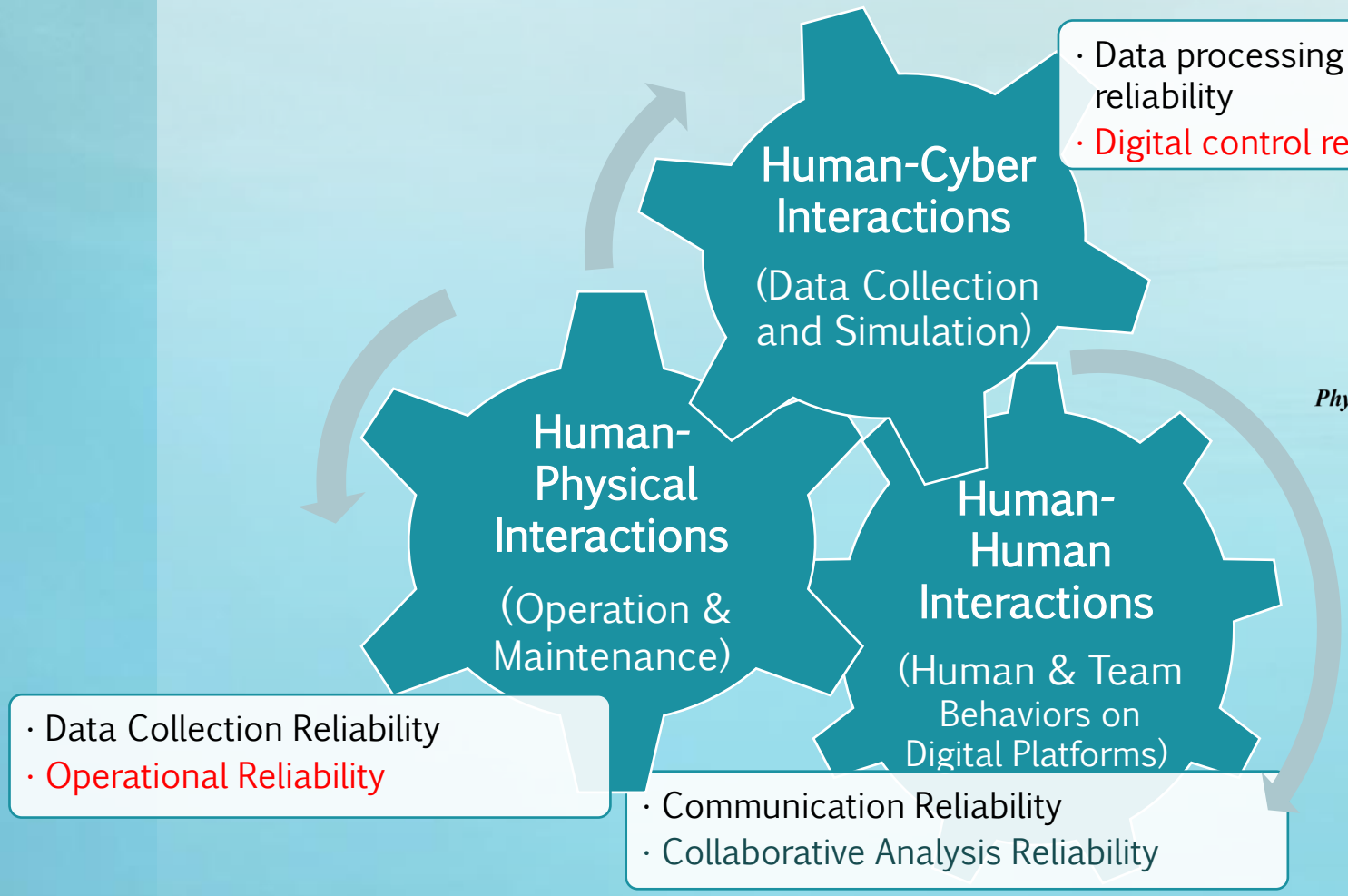
https://www.power-eng.com/nuclear/sandia-labs-working-on-water-reduction-options-at-3-3-gw-palo-verde-nuclear-plant/#

Modeling Human-Cyber-Physical Infrastructure Systems (H-CPS) for Predictive and Secured Control



Virtual information for highlighting target work location

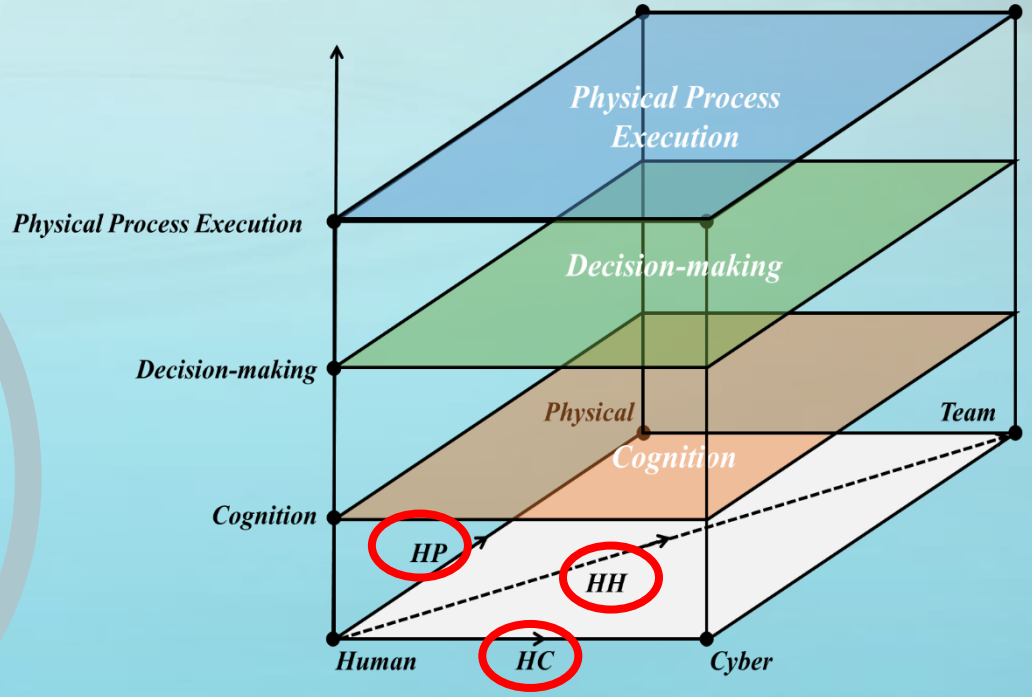
Reliability Analysis of Human-Cyber-Physical Infrastructure Systems (H-CPS) for Predictive Control



· Data processing & interpretation reliability
· Digital control reliability

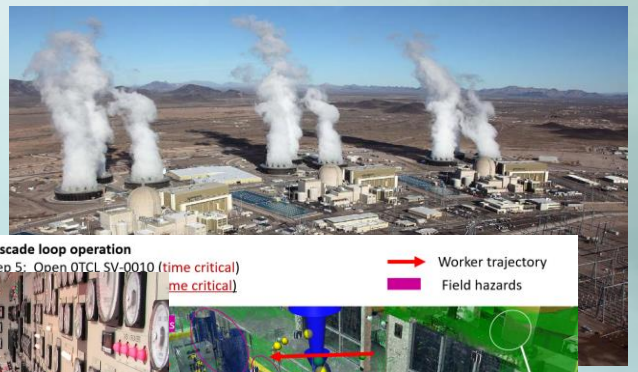
· Data Collection Reliability
· Operational Reliability

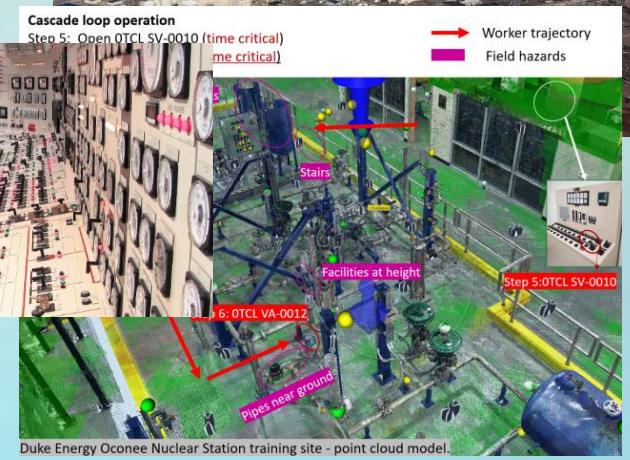
· Communication Reliability
· Collaborative Analysis Reliability



Two Cases for Capturing and Predicting Various Interactions within a H-CPS

- Human-Physical Interactions (Field)
  - Field worker reliability problem
  - Using nuclear power plant operation safety as an example
- Human-Cyber Interactions (Control Room)
  - Digital control reliability problem
  - Human data analytics for identifying anomalous behaviors of air traffic controllers
- Human-Human Interactions (we can talk if we have infinite time for this lecture)
  - Communication reliability problem
  - Using air traffic control involving the communications between a controller and multiple pilots as an example





http://www.scmp.com/news/asia/south-asia/article/2001820/air-traffic-controller-shortage-threatens-indian-airline-boom

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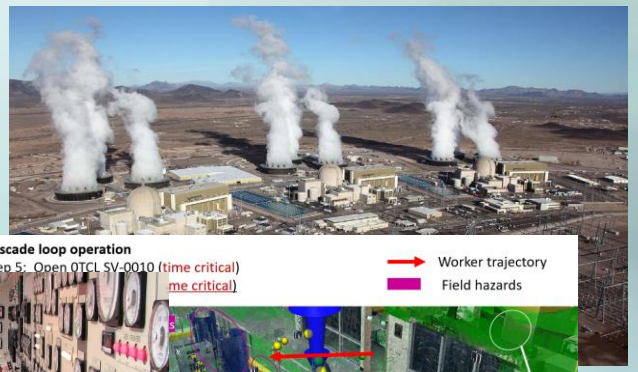

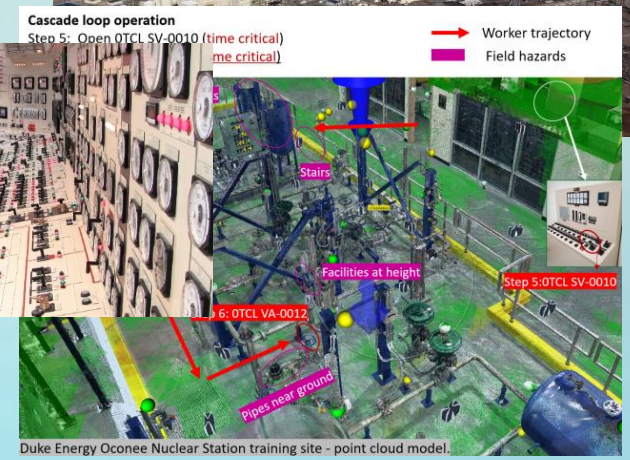

Duke Energy Oconee Nuclear Station training site - point cloud model.

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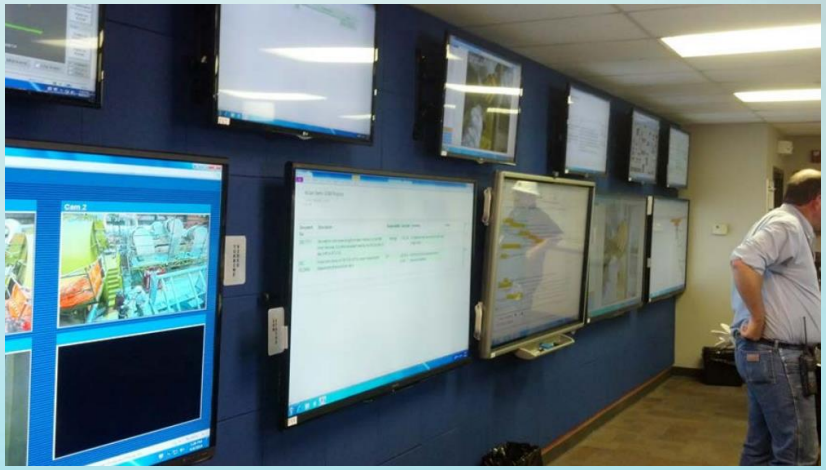
Reliability Problems in Nuclear Power Plant Operations for Safety and Efficiency

- Nuclear Power Plant (NPP) outage control
  - 20-30 days to complete 2,000+ refueling activities
  - 2,000 workers in the field at the same time,
  - Safety: are they following the safe procedures??
  - Productivity: 1 day of delay – a loss of $1.5 million
  - Highly uncertain field findings
  - Nuclear safety
- Challenges
  - Large number of workers collaborating at different locations
  - Could hardly cover all spaces



Cyber

Physical

Field and Remote Operation of Nuclear Power Plants

Field operator

Predefined lists of information that need to be verified or collected

Inaccurate

Communicate/ report the collected information

Control room operator

Human errors, miss critical information or collect wrong information

Operator rounds - Collect information e.g., Component status, Temporary modifications in the field

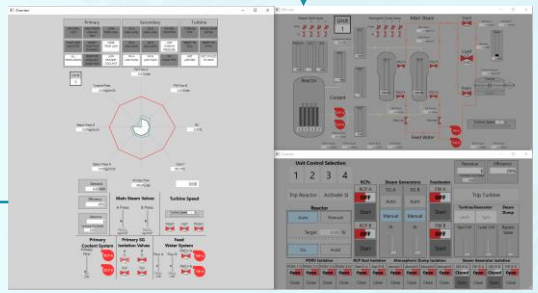
Control decision making and execution

Sensor data are not reliable, some information can't be captured by sensors

Information collected by field sensors

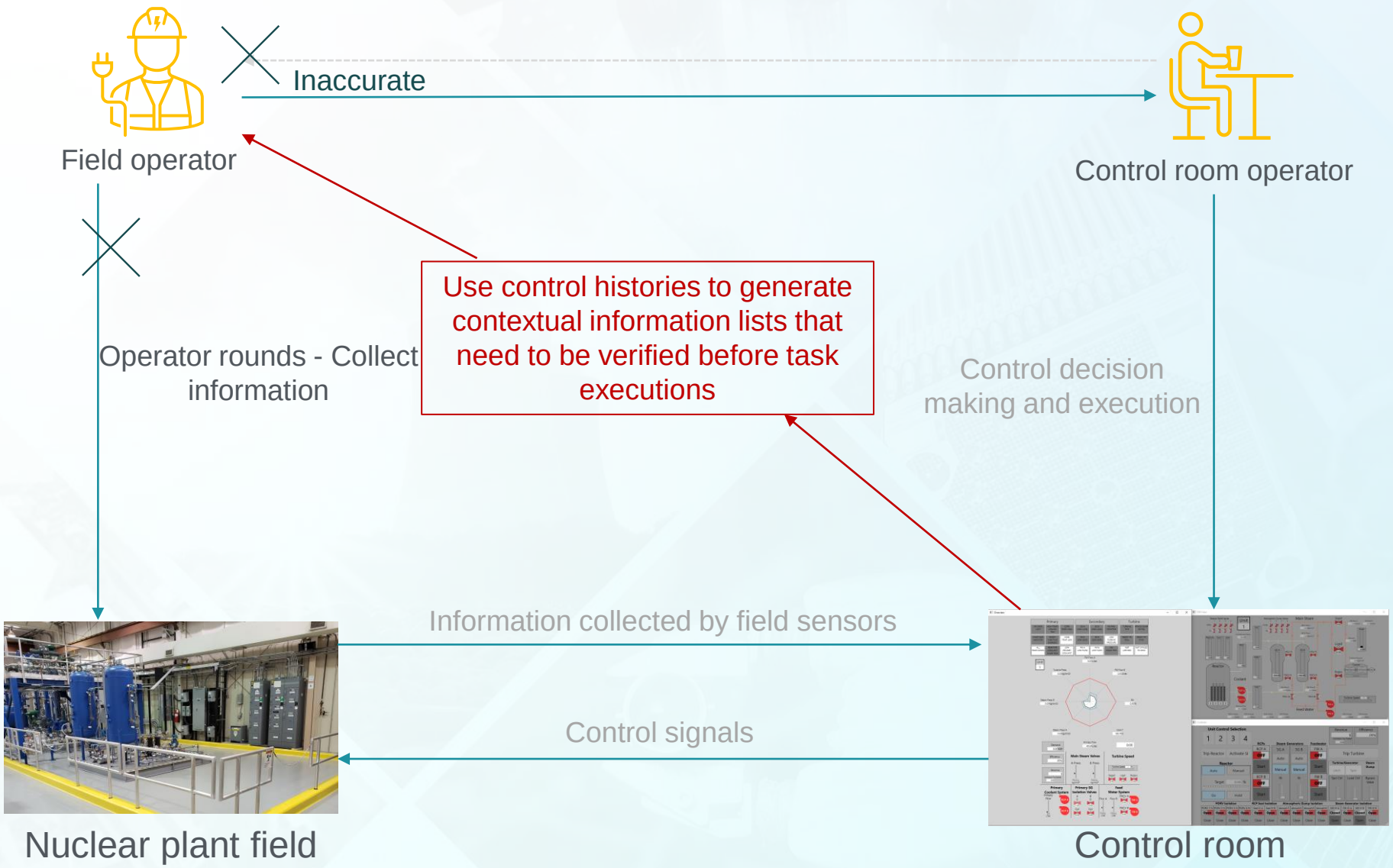
Control signals

Nuclear plant field



Control room

Field and Remote Operation of Nuclear Power Plants



Field and Remote Operation of Nuclear Power Plants

Field operator

Operator rounds - Collect information
e.g., Component status, Temporary modifications in the field

Operator Navigation

- Locate and navigate operators to targeted work locations

Highlight Critical Objects

- Identify critical sensors associated with each steps

Flow Trend Prediction

- Predict the likely condition of a typical flow and detect anomalies

Nuclear plant field

Information matching

Information matching

Computer vision

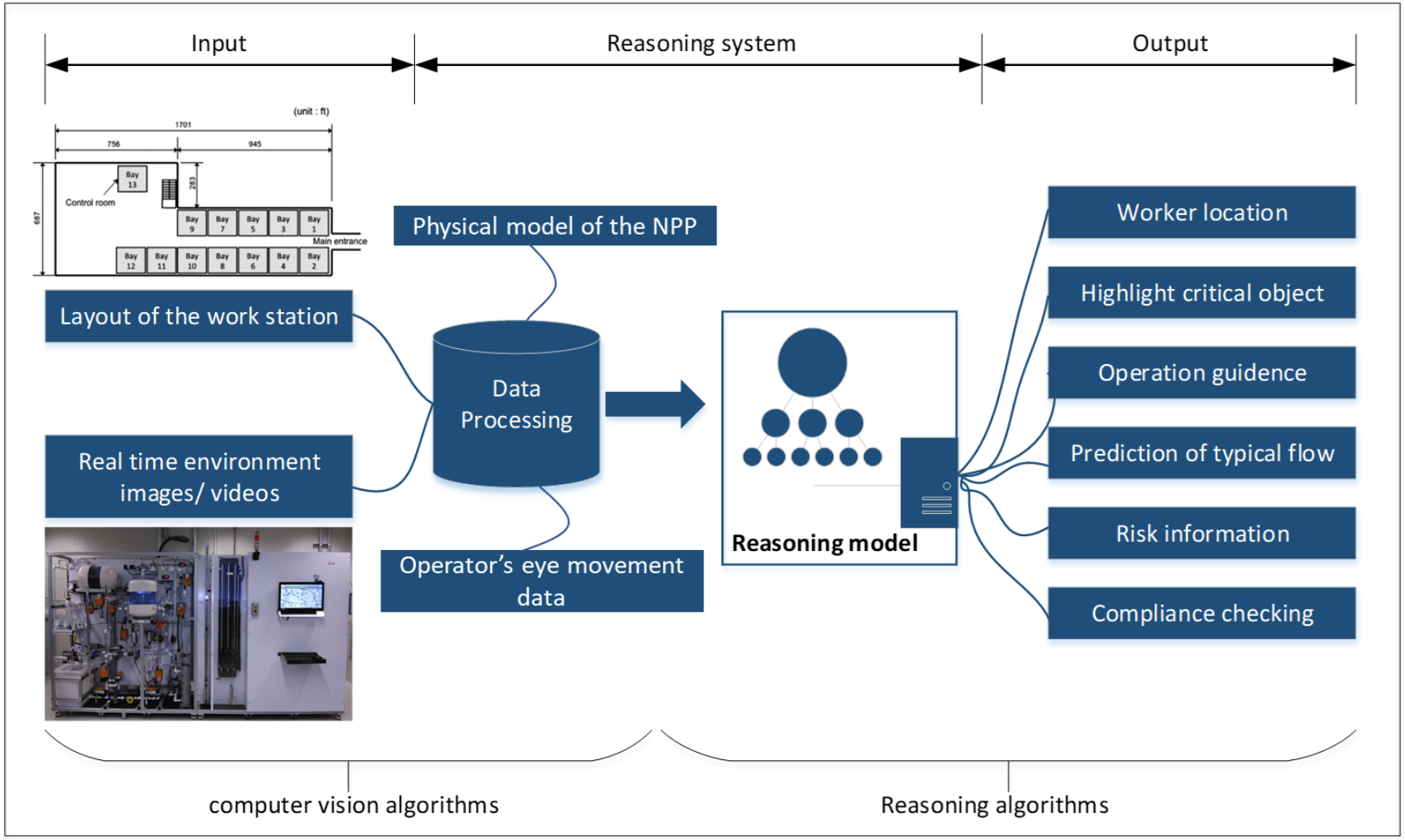
Information display

Augmented Reality Glasses

Context-Aware Safety Information Display for Nuclear Field Workers

- Locate the operation place
- Automatically identifying safety compliance issues and highlighting the correct operation processes
- Real-time AR video views for guiding safe field operations
- Predict the likely conditions of a typical flow and identify operational options along with the impacts of those options on the flow

Intelligent Context-Aware Safety Information Display



A conceptual framework of the "Intelligent Context-Aware Safety Information Display" (ICAD) system

How to Achieve Context-Aware Safety Information Display for Nuclear Field Workers?

Context-Aware Safety Information Display for Nuclear Field Workers

Objectives

- The developed display should integrate the real-time overlay of physical workspaces with maintenance processes and safety information visually displayed through Augmented Reality (AR) glasses.
- The purpose of the display is to assist and guide field workers in assessing workspace risks, locating task-relevant objects, and carrying out the tasks in the correct order in a safe manner.

Research areas

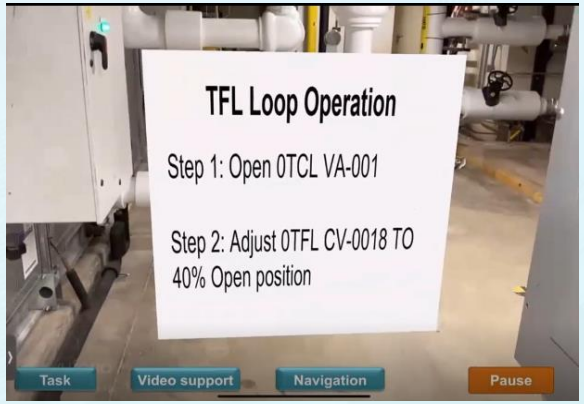
- Human reliability
- Work process modeling
- Operational safety

Major techniques

- Sensor Log Analysis
- Survey and interview
- Natural language processing
- Computer vision
- Augmented Reality

Outcomes

- AR Glasses with context-aware safety information display functions
- Real-time dynamic instructions for safe and efficient NPP field operations



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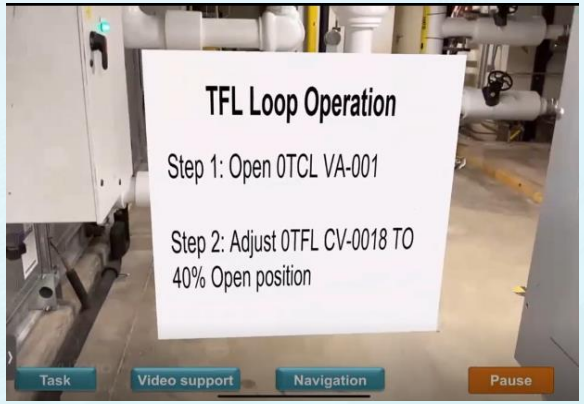
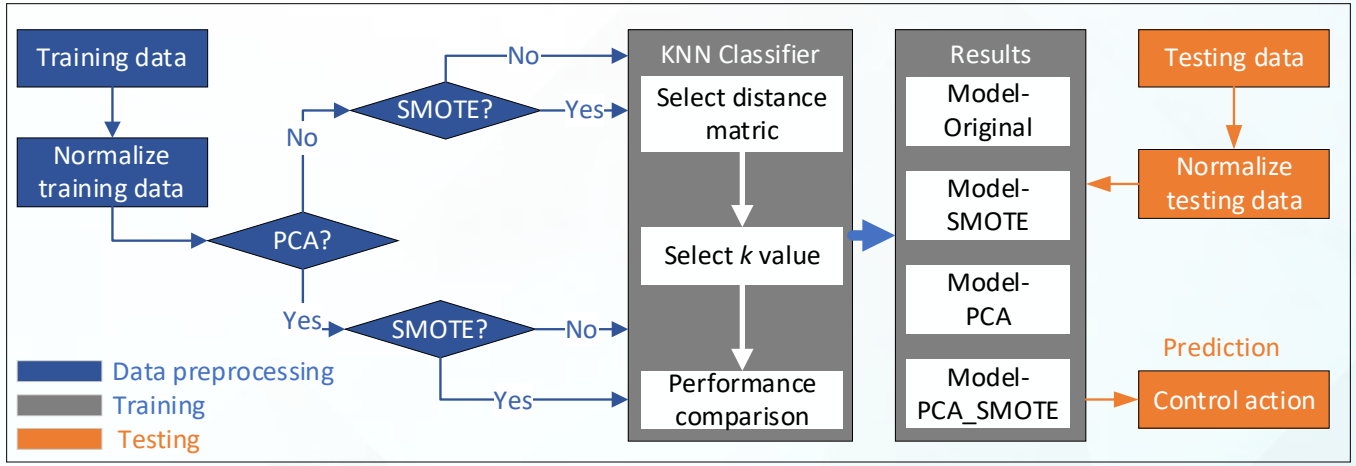


Sensor Log Analysis - Predicting Proper Control Actions

Algorithm for Analyzing Simulated Sensor Logs of Nuclear Power Plants for Safety and Efficiency Diagnosis of Real-Time Operations.



The framework of the proposed method for predicting switch parameters.

The operating state of NPP at a specific time is represented by a set of analog parameters and switch parameters. The changes of switch parameters reflect the operator's control decision.

Time (s)	Work status (control action/wait)	Core temperature (DEG F)	Cooling flow (KPPH)	…
1	Wait	181.16	20.45	
2	Valve A ON	182.50	20.22	
3	Rod 1	184.03	20.12	
4	Wait	185.60	20.11	
5	Valve B ON	187.40	20.09	
6	Rod 1	189.23	20.08	

Model input: Time series of analog parameters in the last three seconds

Model output: Work status at the fourth second

Jinding Xing, Pengkun Liu, Pingbo Tang, Alper Yilmaz, Ronald Laurids Boring, George Edward Gibson Jr, Analyzing Operation Logs of Nuclear Power Plants for Safety and Efficiency Diagnosis of Real-Time Operations. In 29th International Workshop on Intelligent Computing in Engineering, EG-ICE 2022. Aarhus, Denmark.

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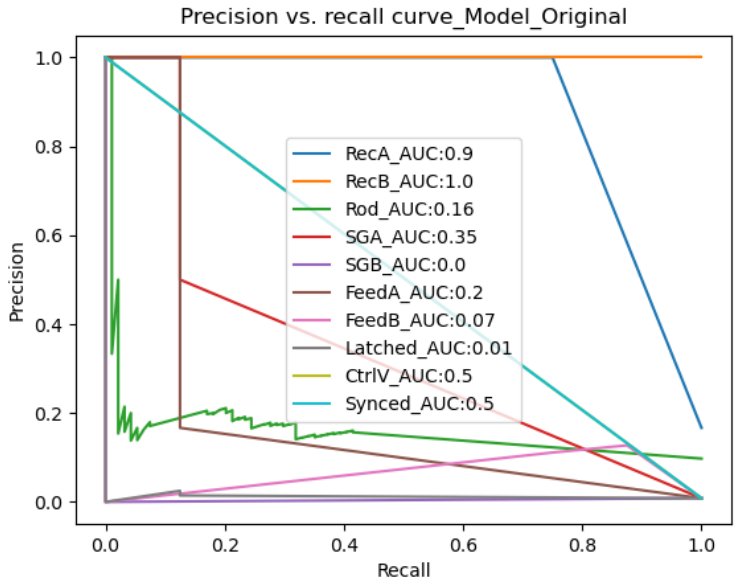

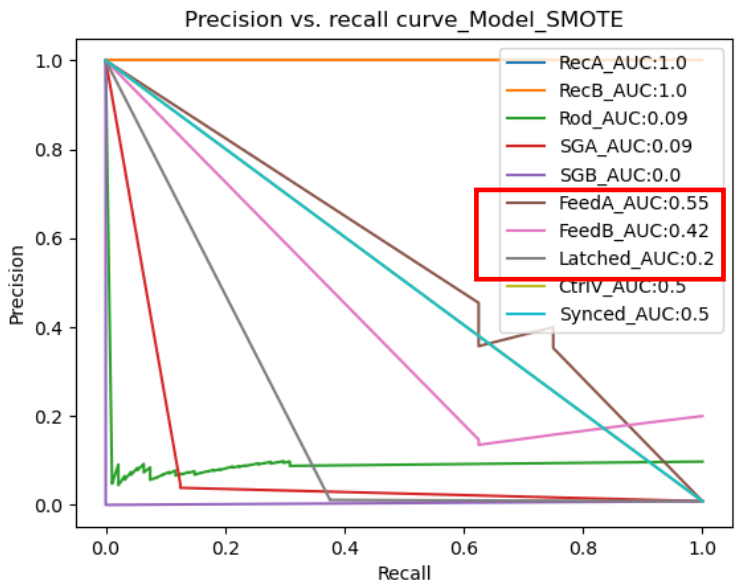

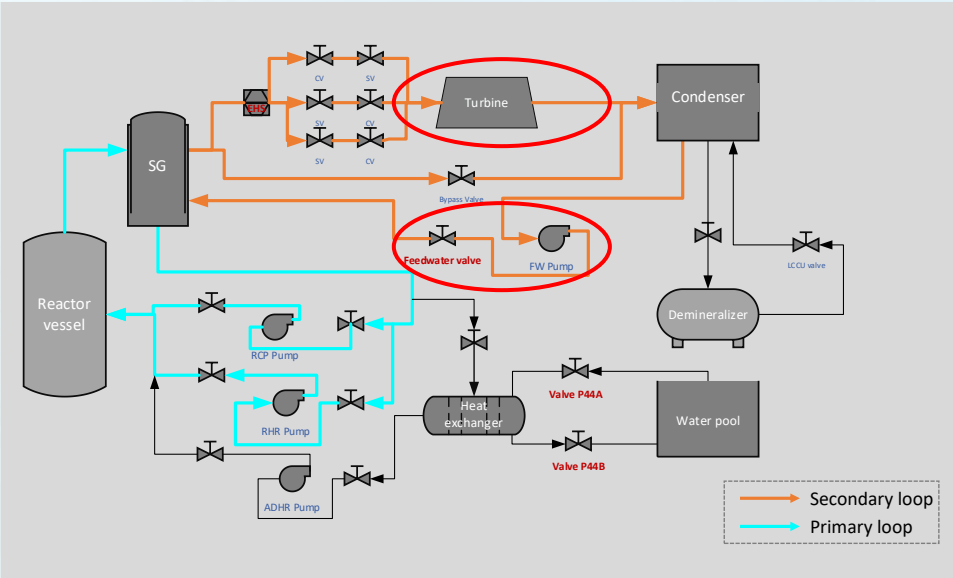

This study proposed a variant of models based on KNN classifiers that uses analog parameters to infer the most suitable control actions.
The testing results indicate that the model with SMOTE data (F1 score 0.323) augmentation has better prediction performance than the models without SMOTE (F1 score 0.263).

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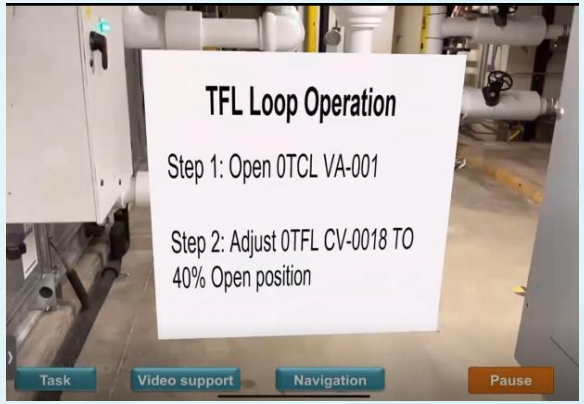
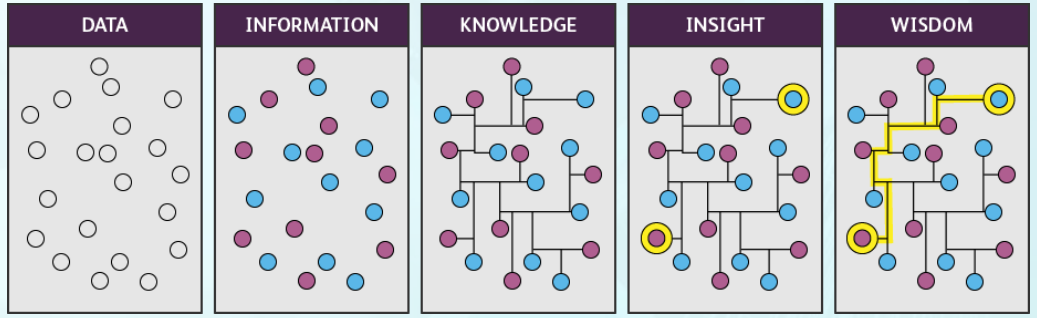


Field Interviews and Survey for Identifying Critical Factors Influencing Safety and Efficiency

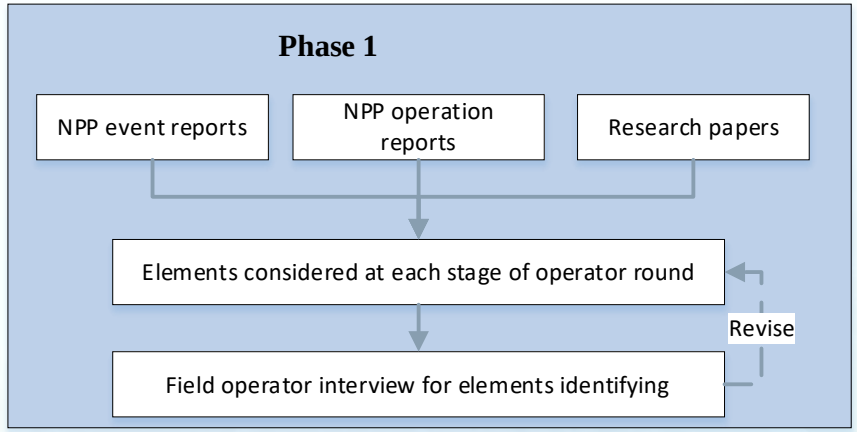
- What are the stages involved in NPP field operations?
- What is the mechanism of human errors?
- What are the factors involved in each stage of operations?
- What's the root cause of human errors?

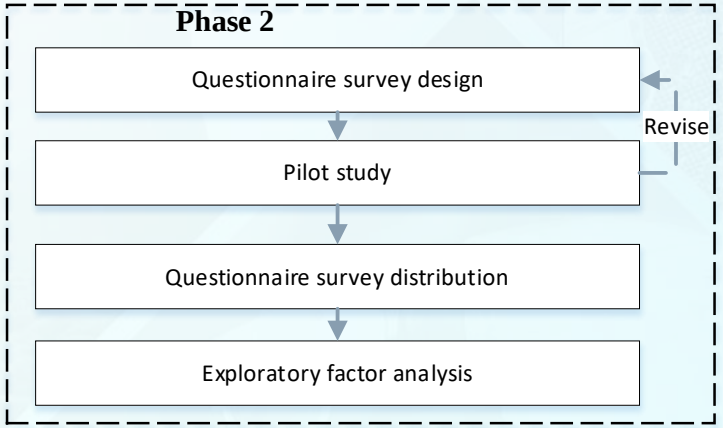


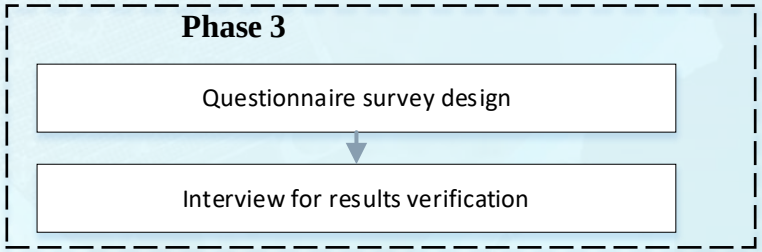
Field Interviews and Survey for Identifying Critical Factors Influencing Safety and Efficiency

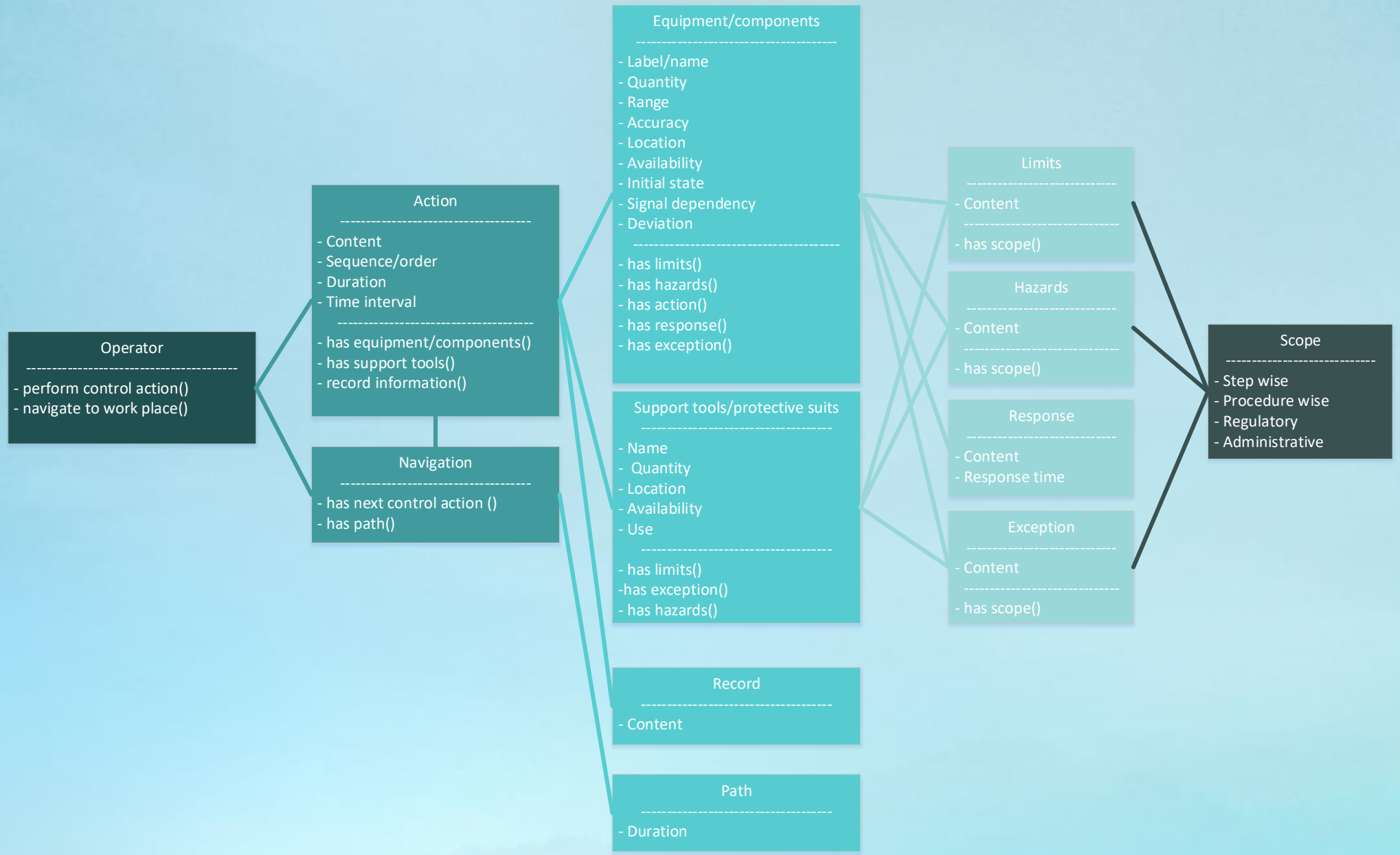
Document analysis:
Investigate NPP field operation stages, factors considered by field operators at each stage.

Modified Delphi study:
- Obtain experts' opinions on human error mechanisms and root causes
- Phase 3 - Validation of the study





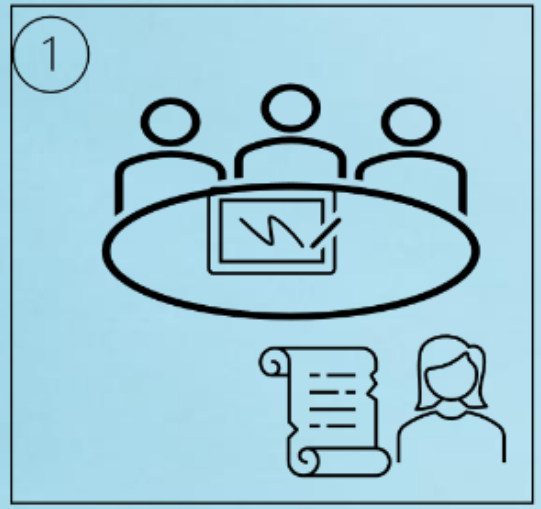




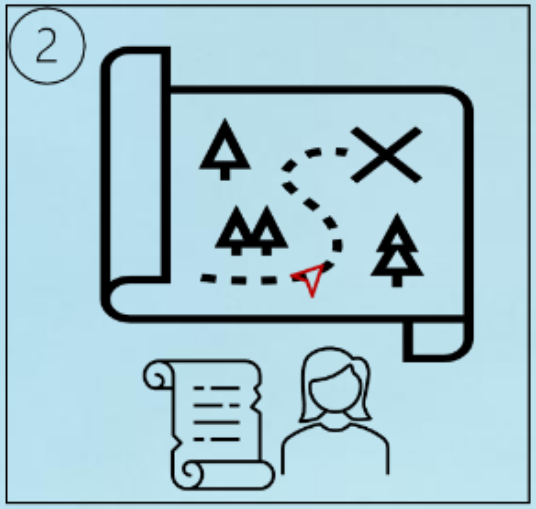
Identified factors that impact NPP field operation safety and efficiency

A Speech for the Construction Industry Institute (CII)

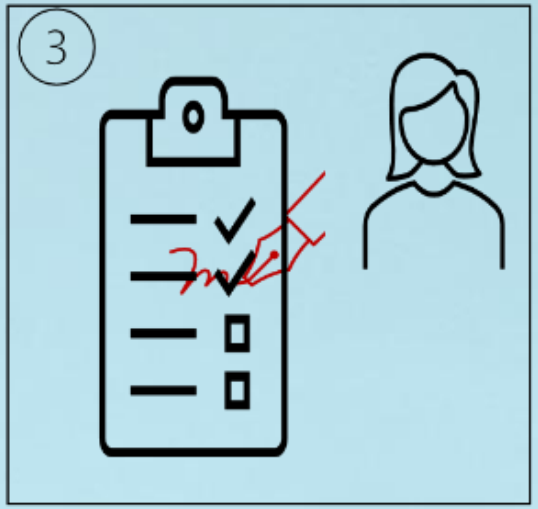
Stages of NPP Field Operations



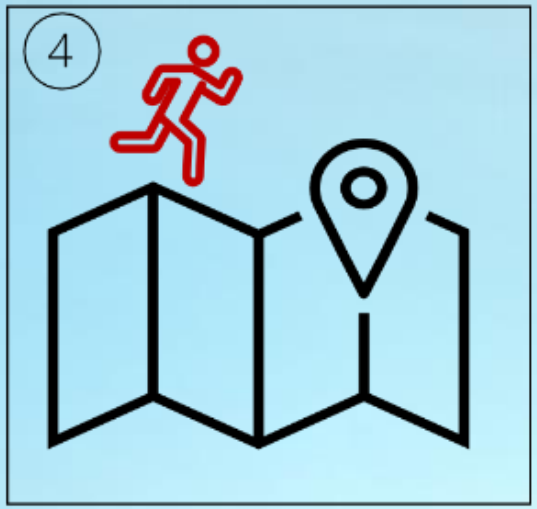
Pre-job briefing



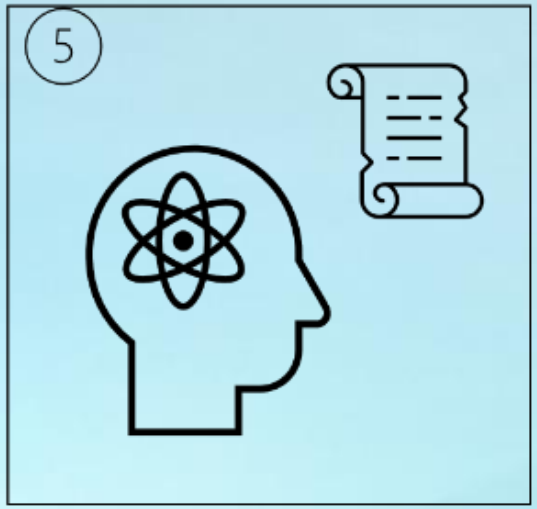
Walkdown the procedure



Place-keeping



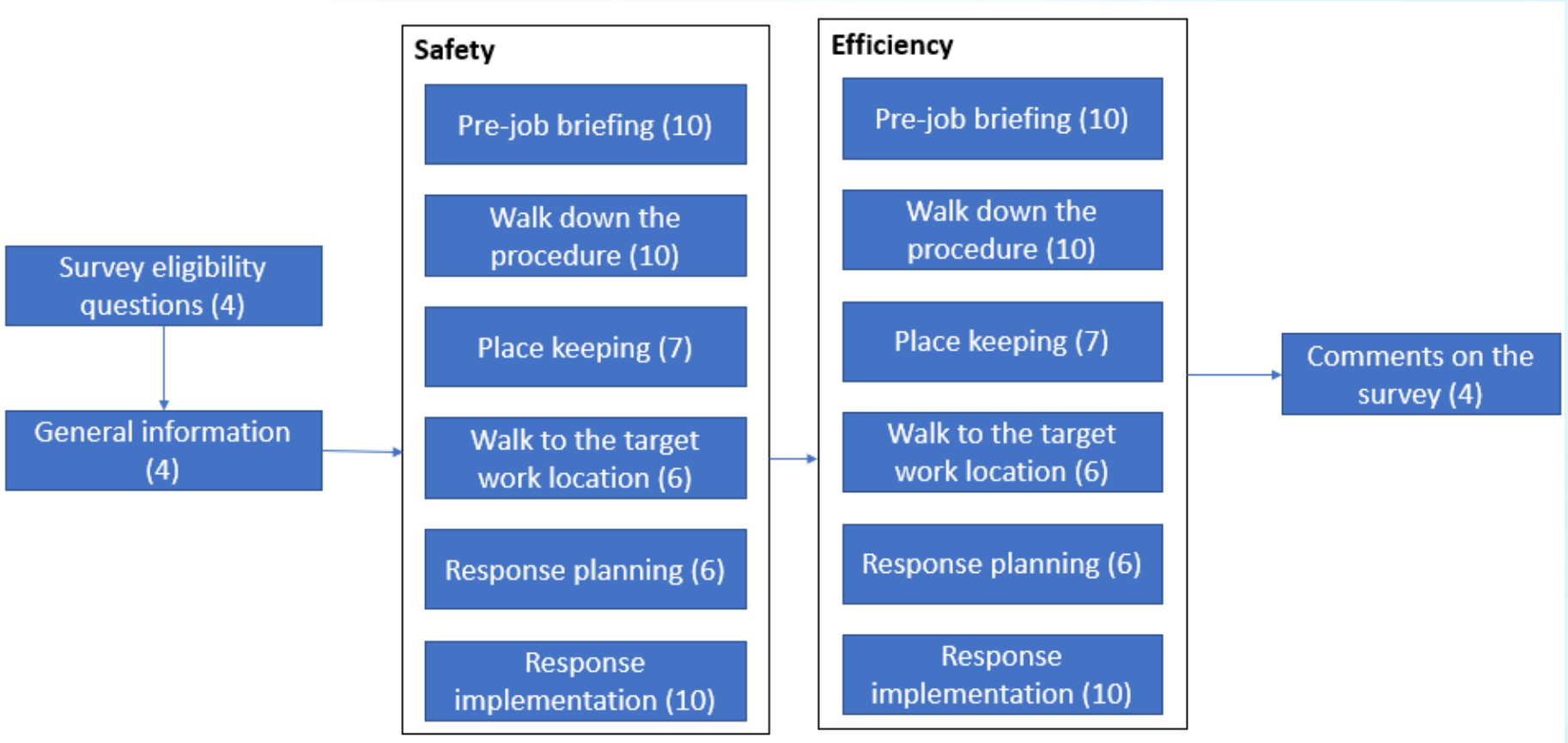
Walk to the target work location



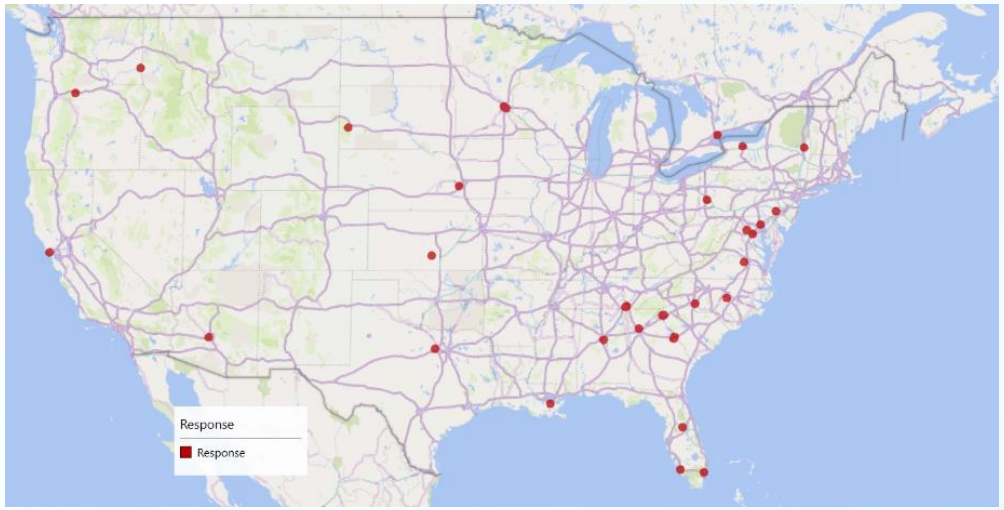
Response planning

Response implementation

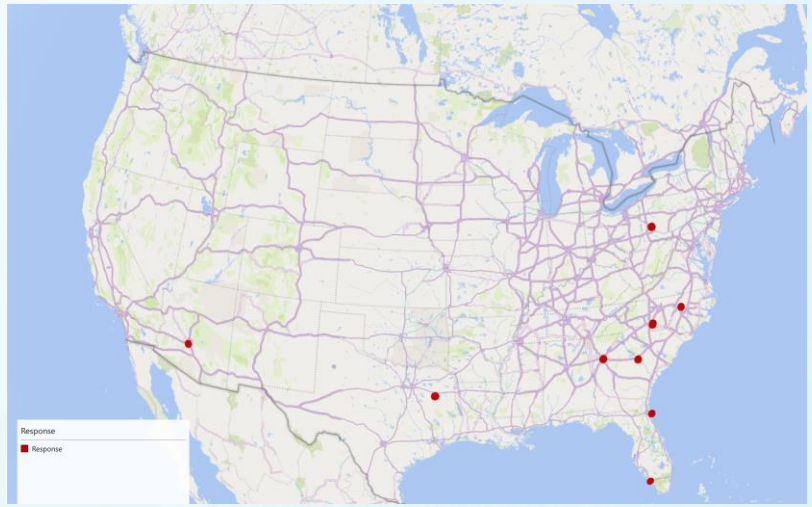
Survey Design



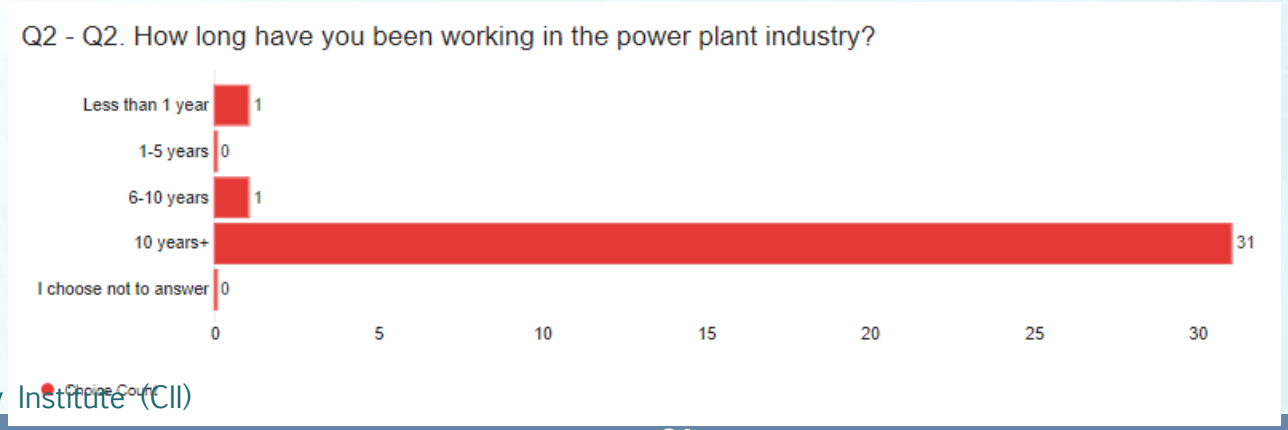
Survey Distribution



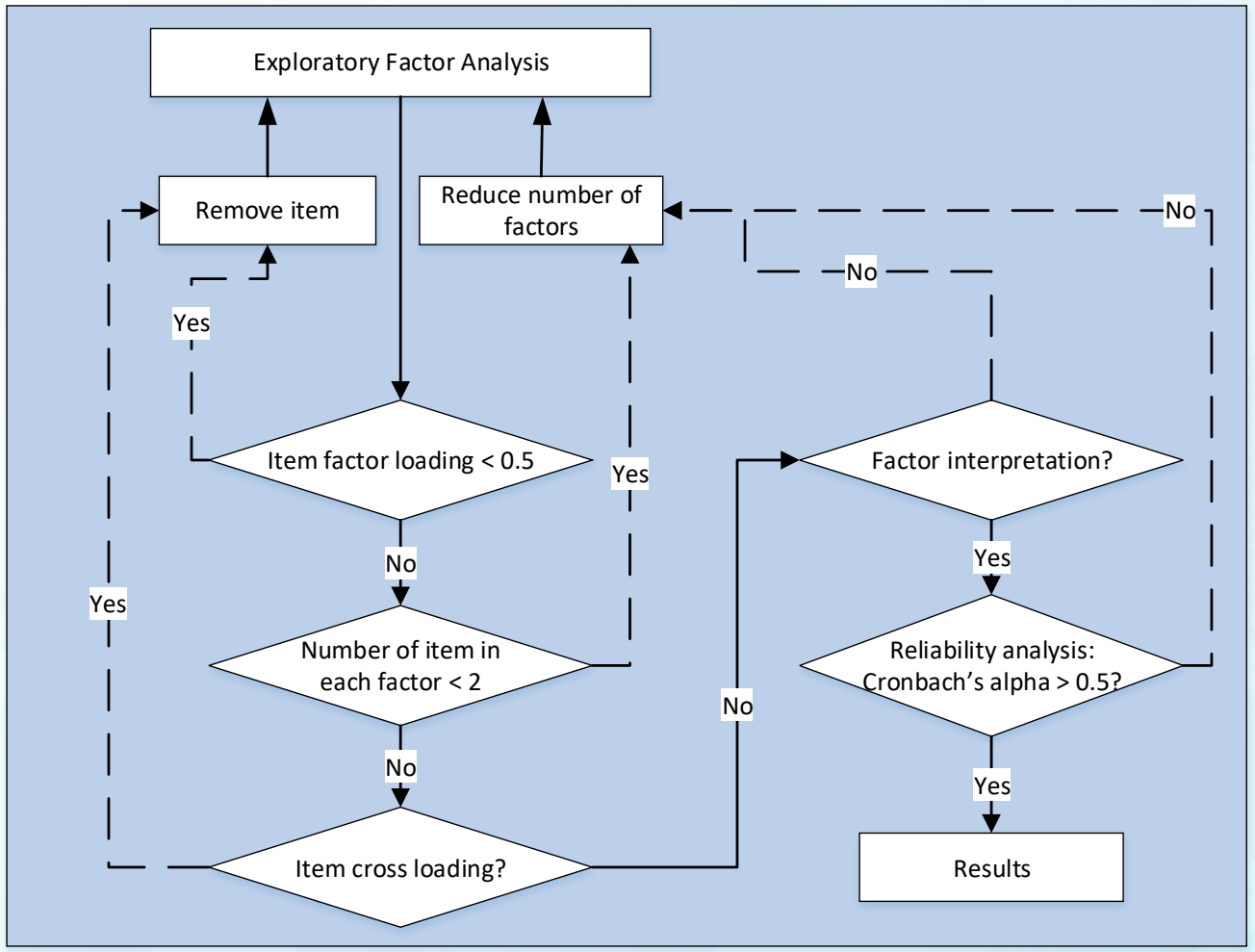
Response map of round 1 (33 participants)



Response map of round 2 (11 participants)

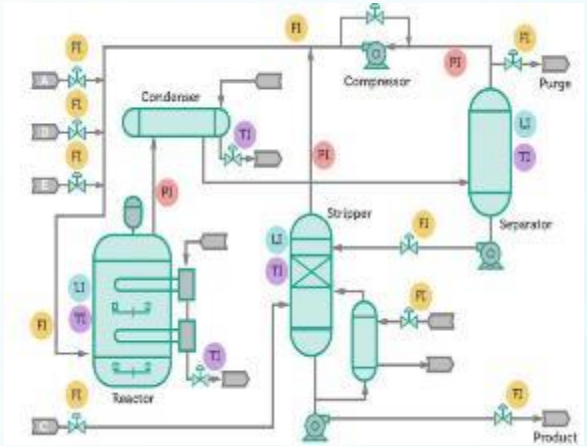


Survey Data Analysis



Survey Results

Main Finding - Three categories of factors play a crucial role in determining worker safety and operational efficiency in NPP field operations



Workspace dynamics:

- Physical space: function, location, dimension
- Mechanical component within the space: location, label, state, name

Workflow prognostics:

- Function of component, e.g., increase flow

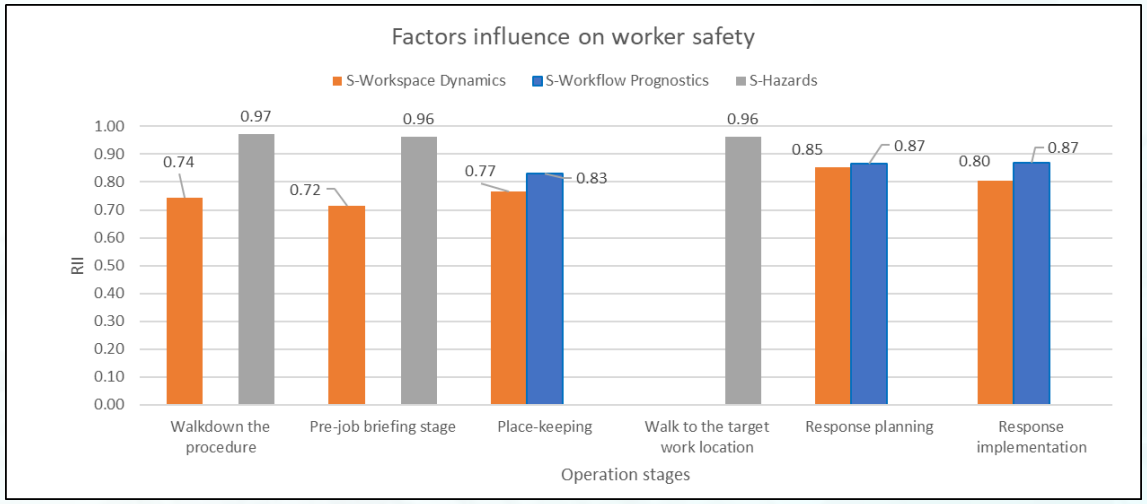
Hazards:

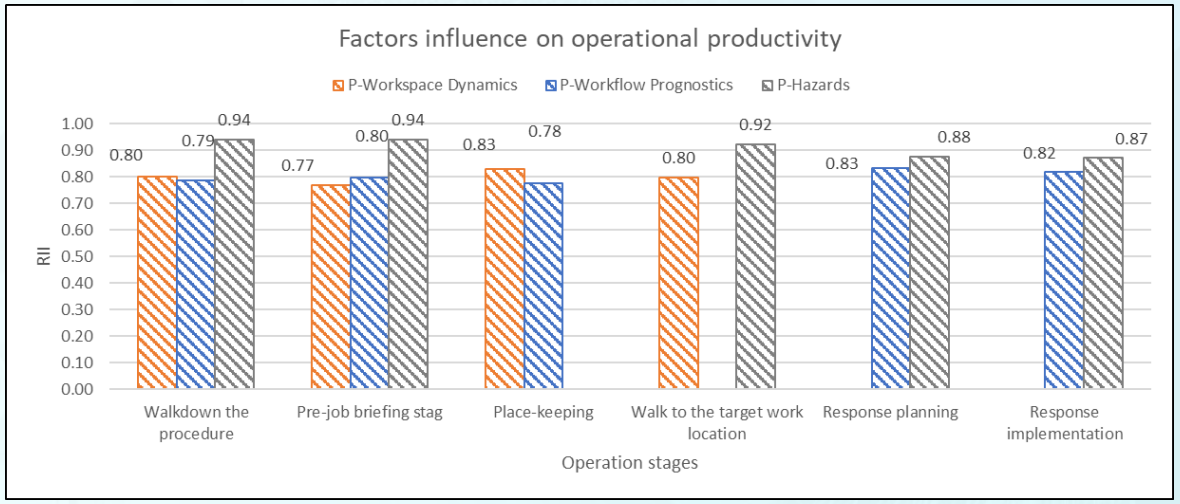
- From workspace: confined space
- From workflow: uncontrolled release of energy, e.g., heat, pressure

Survey Results

Uncovering the Fluctuating Importance Levels of Different Information in Different Stages of NPP Field Operations

- In different work stages, the operator considers different factors.
- Each factor impact safety and productivity in certain work stages
- The hazards factor plays a critical role in shaping the trend of safety and productivity





How to Achieve Context-Aware Safety Information Display for Nuclear Field Workers?

Context-Aware Safety Information Display for Nuclear Field Workers

Objectives

- The developed display should integrate the real-time overlay of physical workspaces with maintenance processes and safety information visually displayed through Augmented Reality (AR) glasses.
- The purpose of the display is to assist and guide field workers in assessing workspace risks, locating task-relevant objects, and carrying out the tasks in the correct order in a safe manner.

Research areas

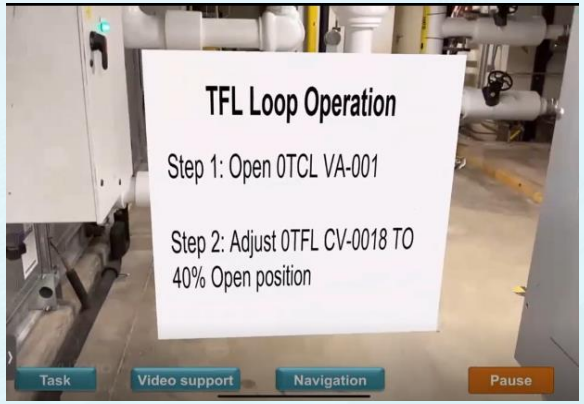
- Human reliability
- Work process modeling
- Operational safety

Major techniques

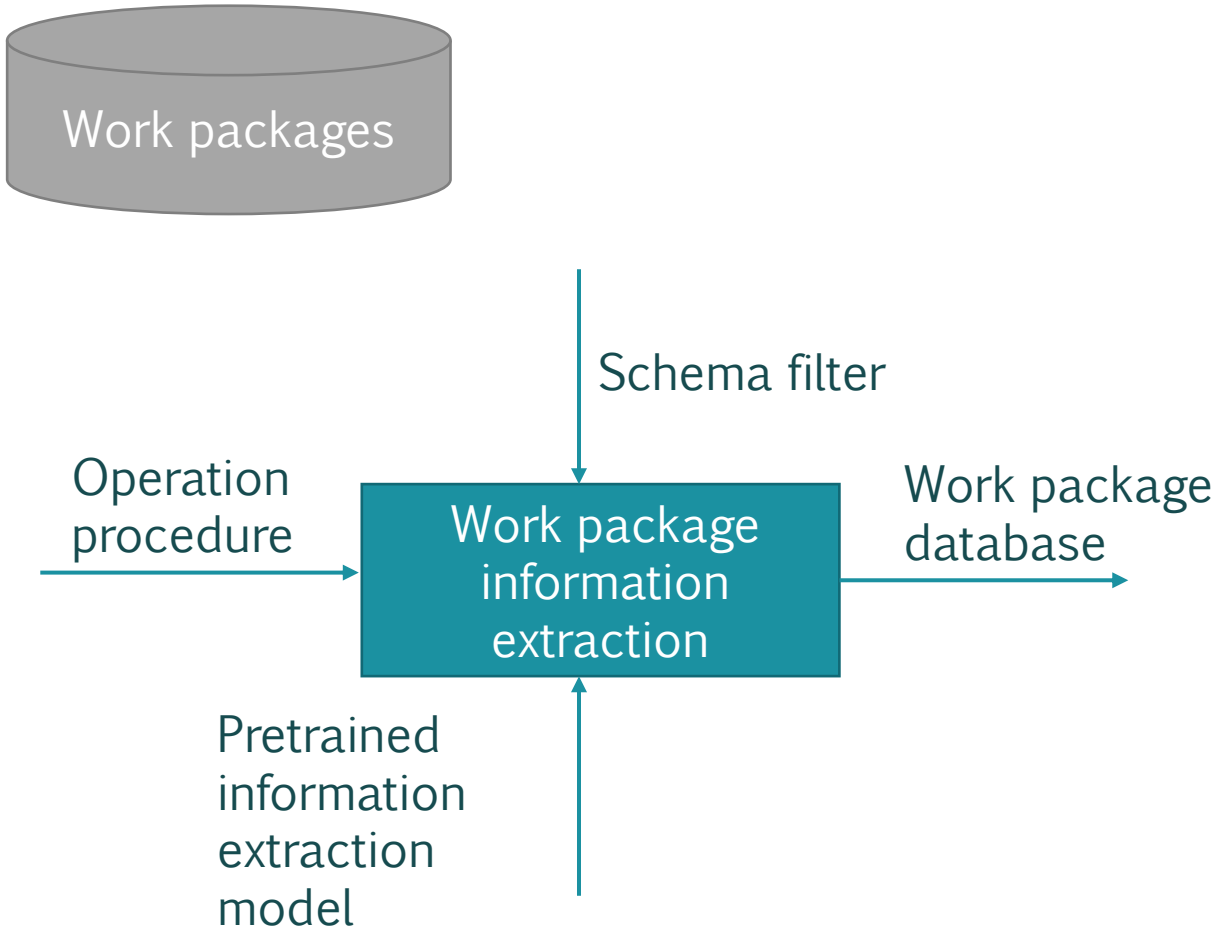
- Sensor Log Analysis
- Survey and interview
- Natural language processing
- Computer vision
- Augmented Reality

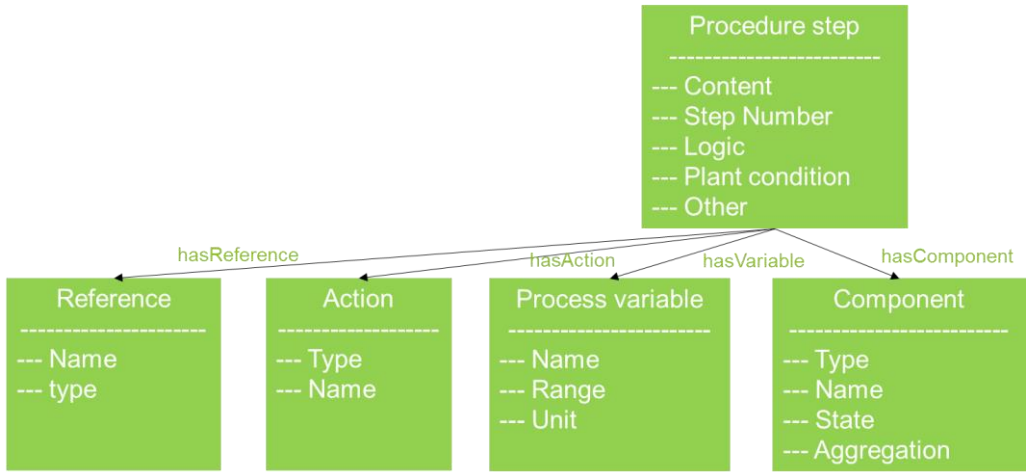
Outcomes

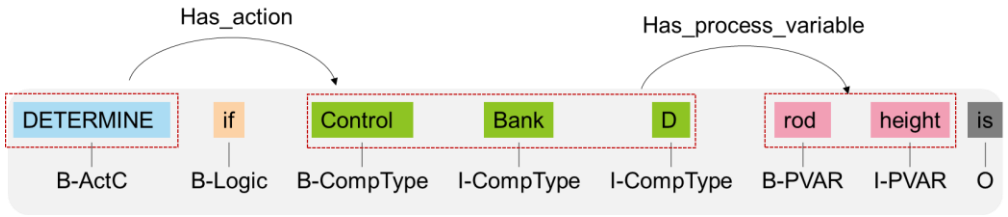
- AR Glasses with context-aware safety information display functions
- Real-time dynamic instructions for safe and efficient NPP field operations



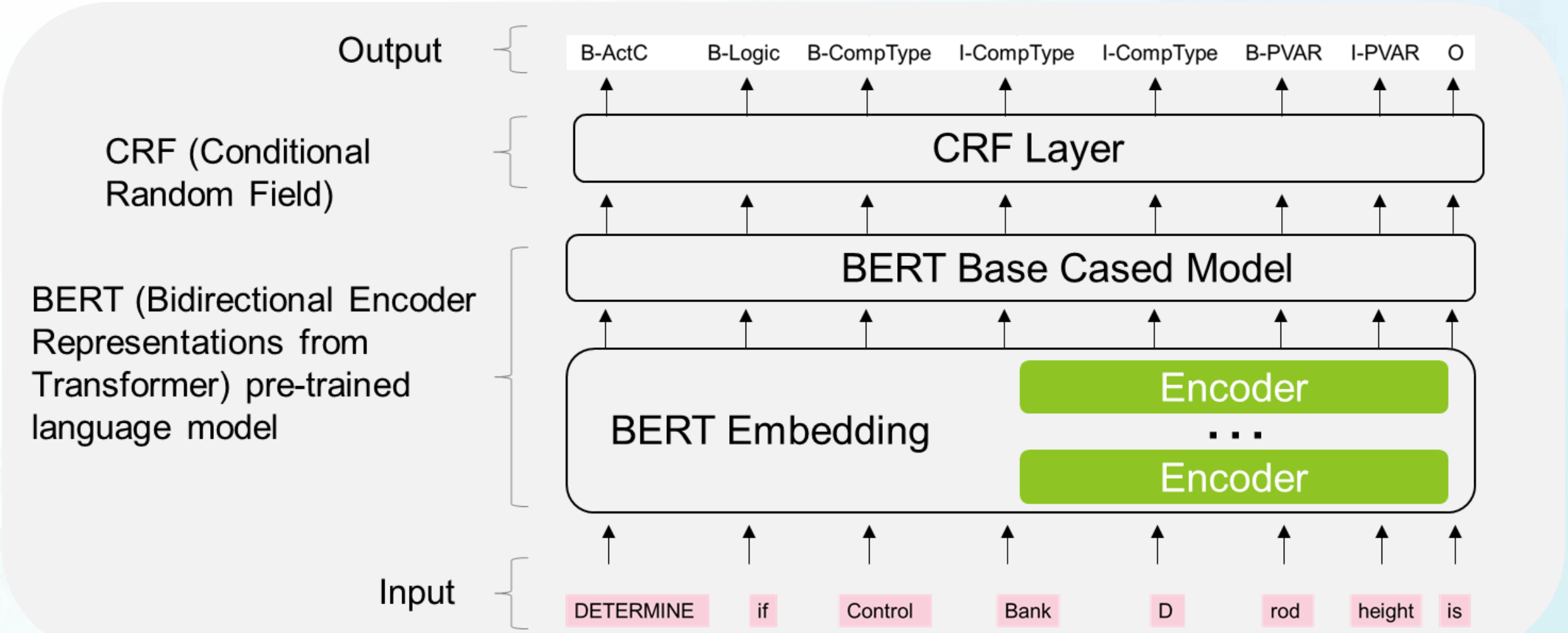
Natural Language Processing for Work Order Analysis and Risk Prediction



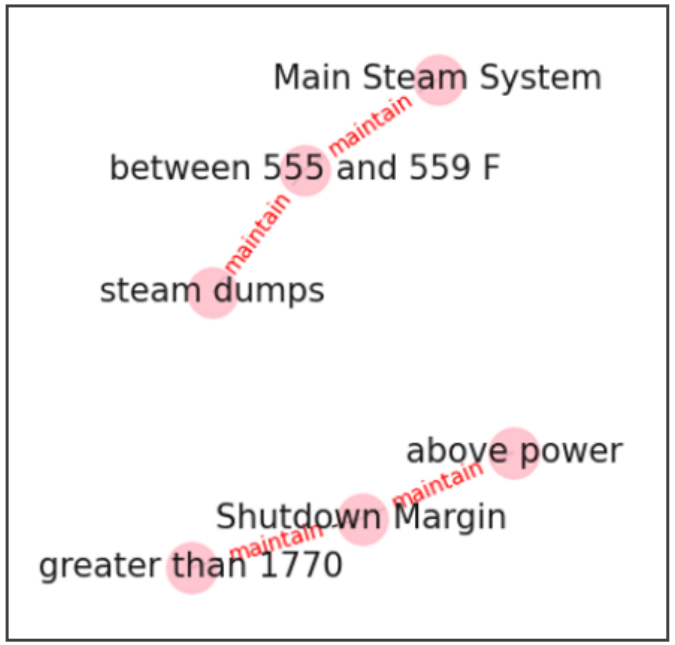




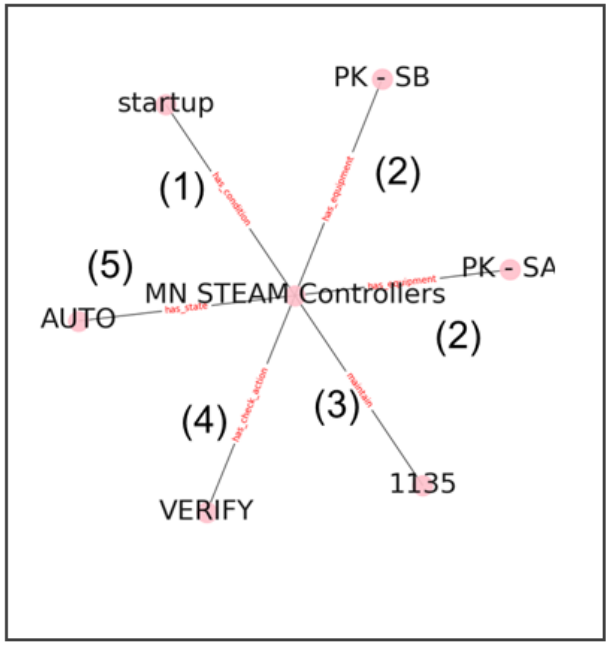
BERT-CRF model for Recognizing Named Entities in NPP Field Work Orders



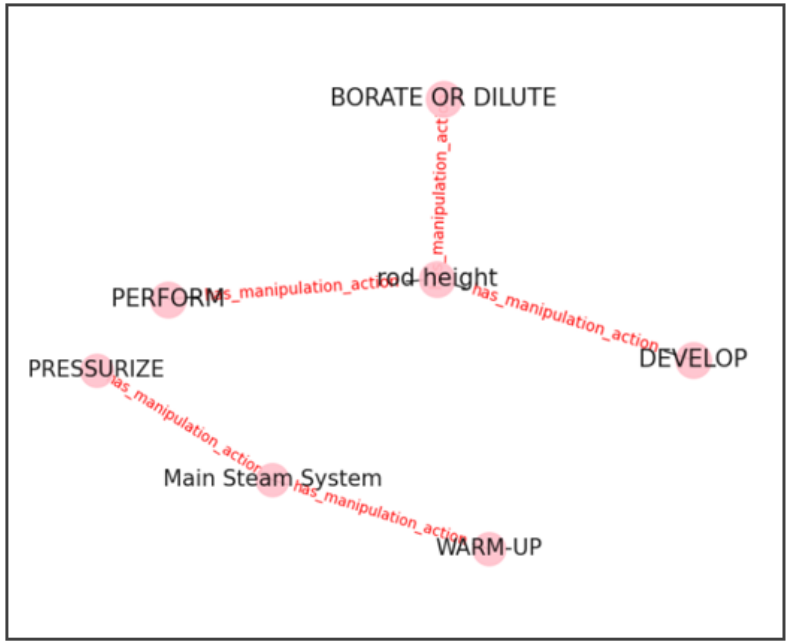
- Visualizing and reasoning process safety constraints, component properties by querying the knowledge graph.



Maintain



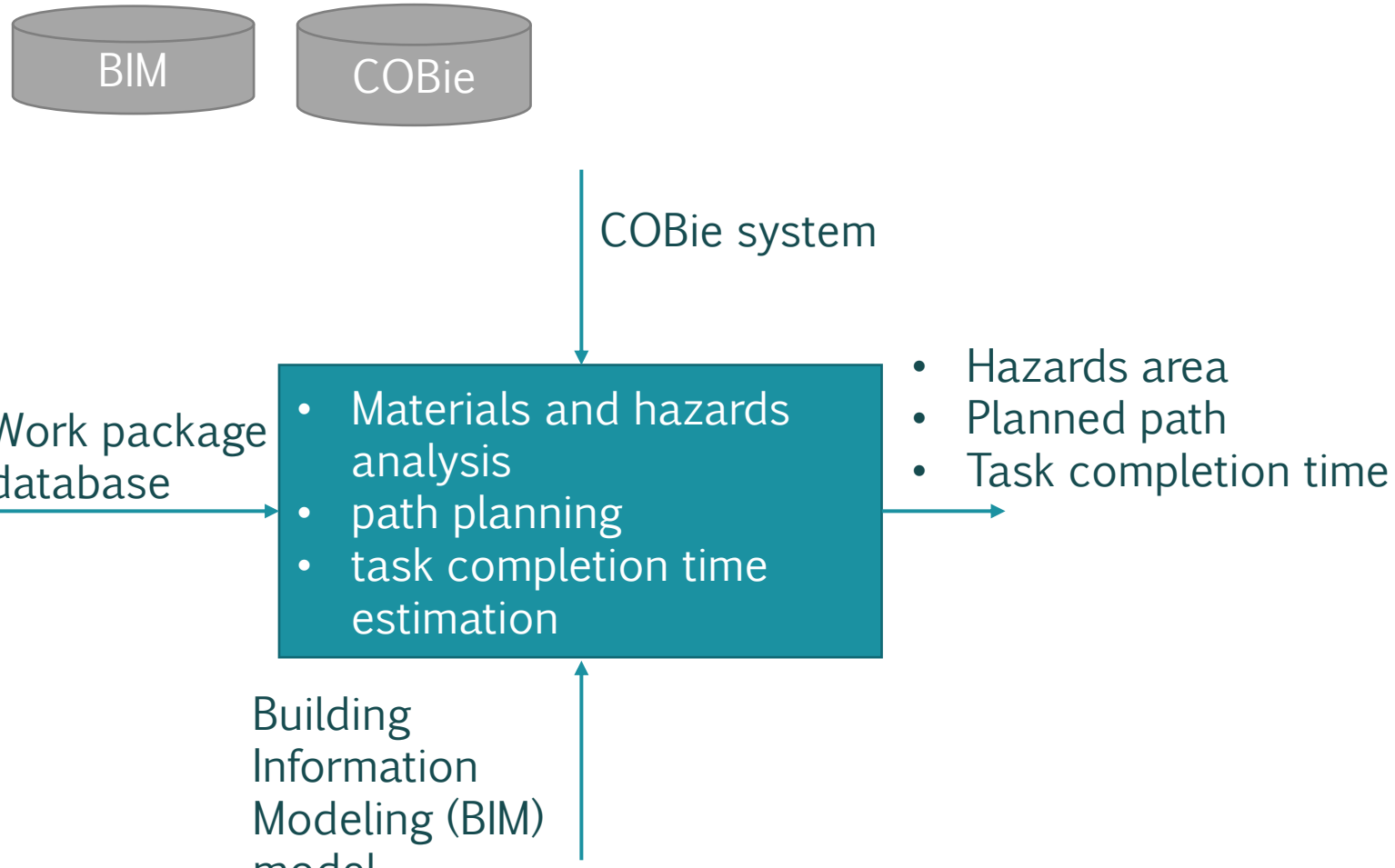
Component properties

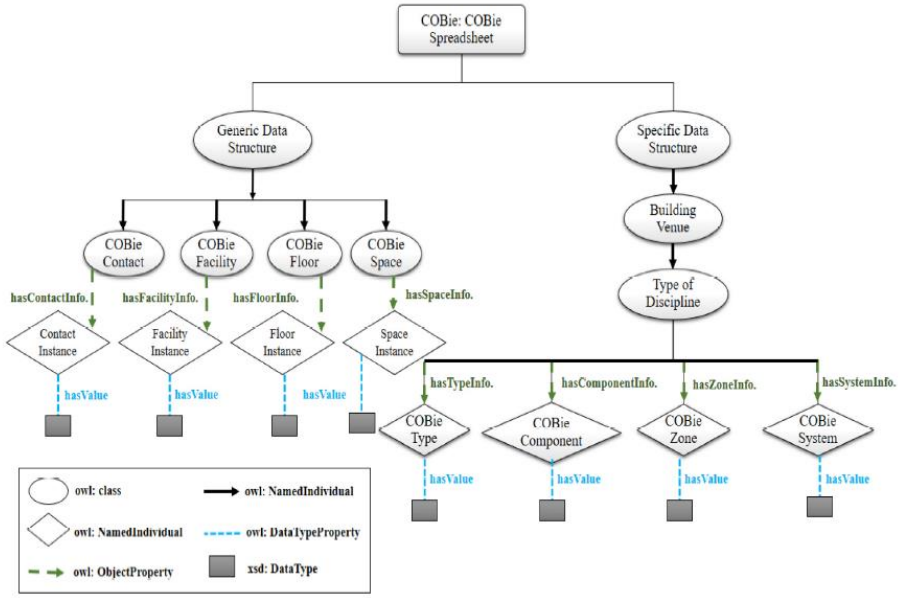


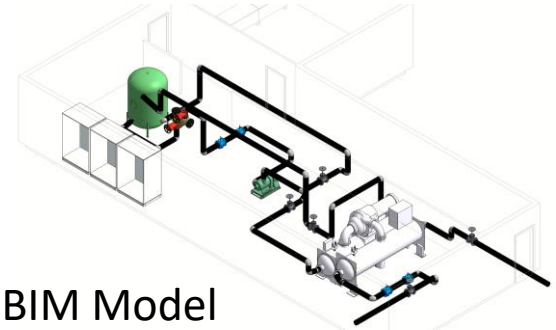
Control action: manipulation (left), check (right)

*Component properties: (1) has_condition, (2) has_equipment, (3) maintain, (4) has_check_action, (5) has_state.

Work Package Analysis – Ongoing Research for Predicting Operational Risks







BIM Model

How to Achieve Context-Aware Safety Information Display for Nuclear Field Workers?

Context-Aware Safety Information Display for Nuclear Field Workers

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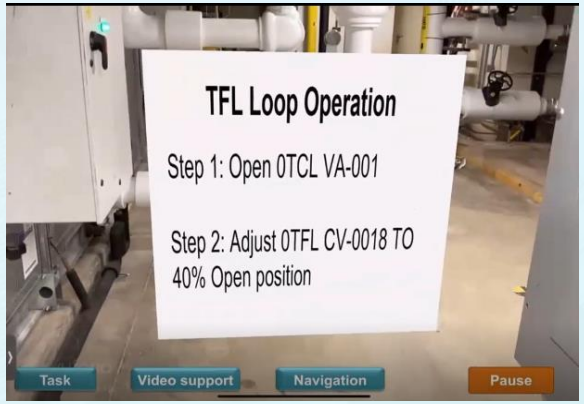


Safety Control Object Detection: Computer Vision

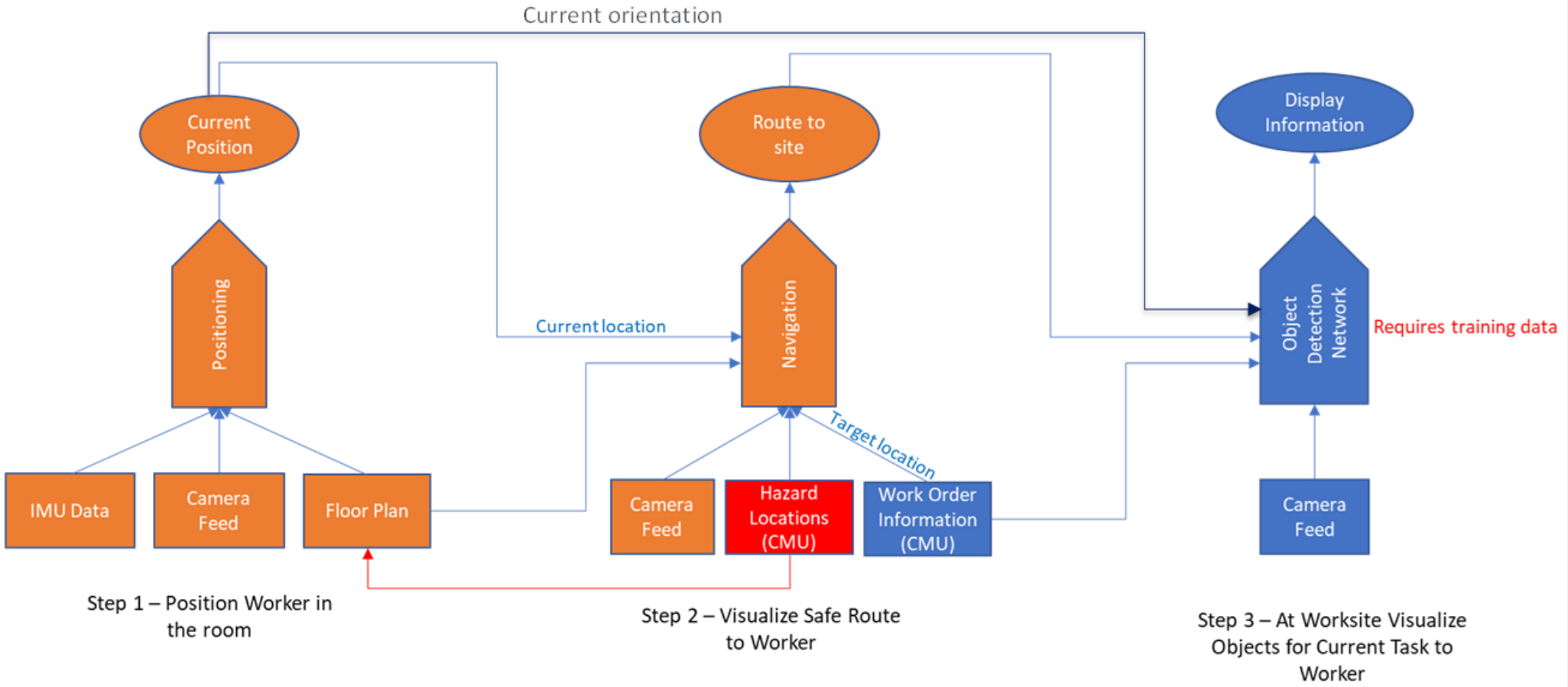
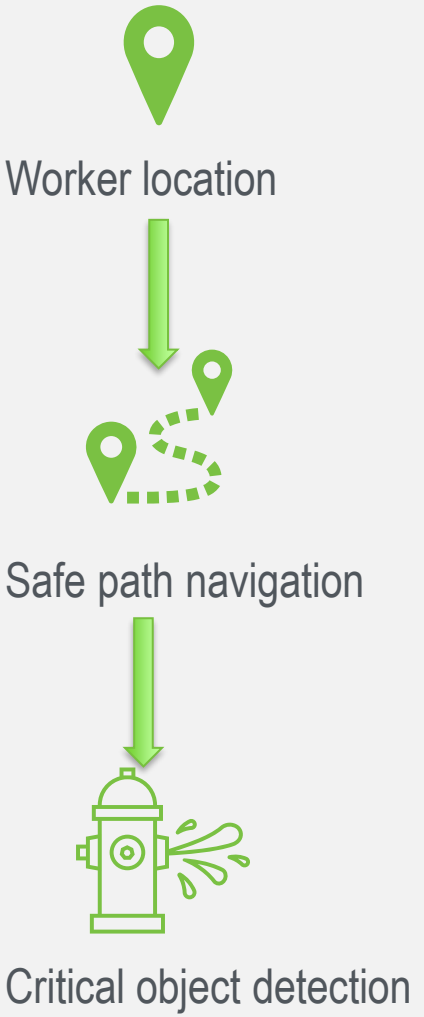
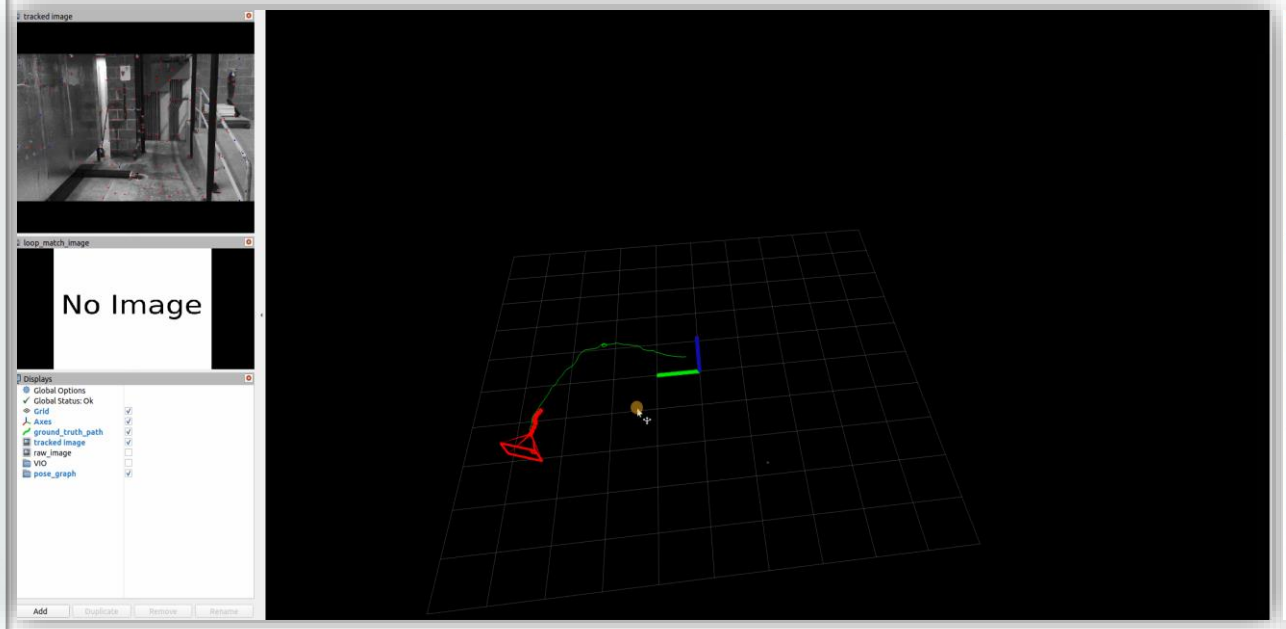


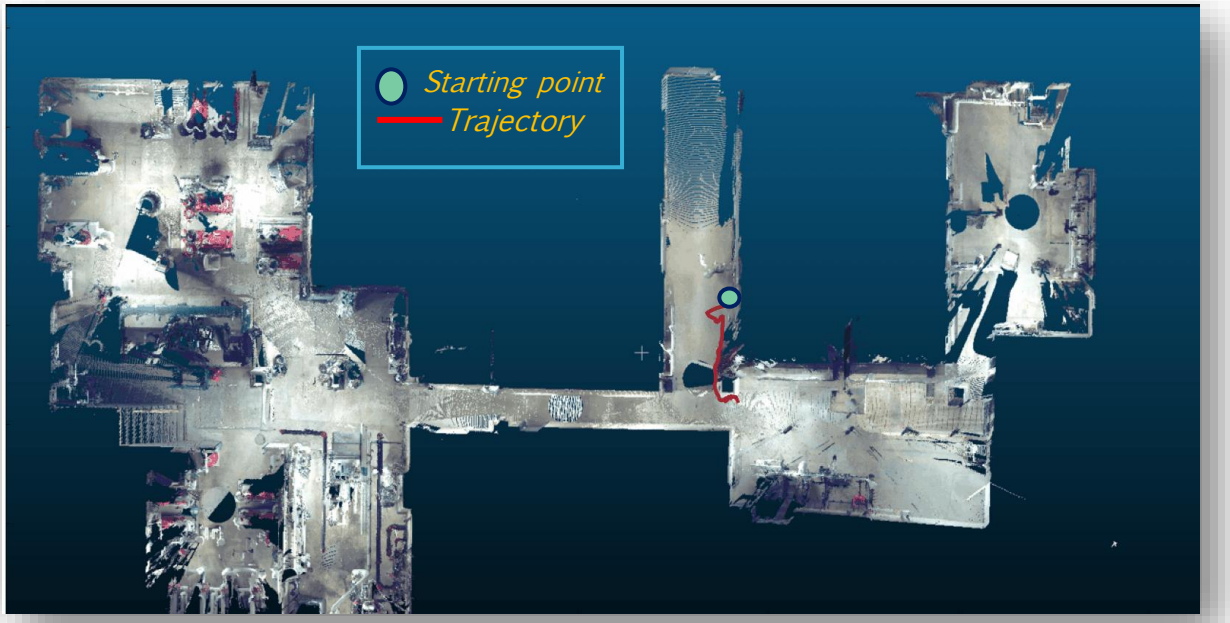
Figure 2. Computer vision research



Dynamic Indoor Navigation- Navigation

- Visual odometry is the process of determining the position and orientation of a robot/worker usually using:
  - Images (RGB camera)
  - Inertial Measure Units(IMU)

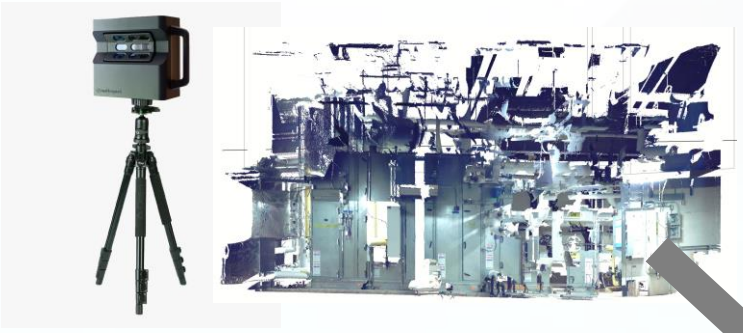




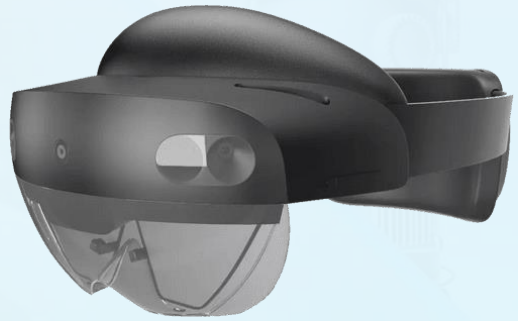
Putting Things Together - Augmented Reality Development

Marker-less AR for the NPP field operations

Matterport



3D scan of the campus mechanical room (Matterport scanner)



HoloLens 2 AR display for Nuclear Field workers

Vuforia area target generator to extract visual features for AR tracking and registration of the augmented information

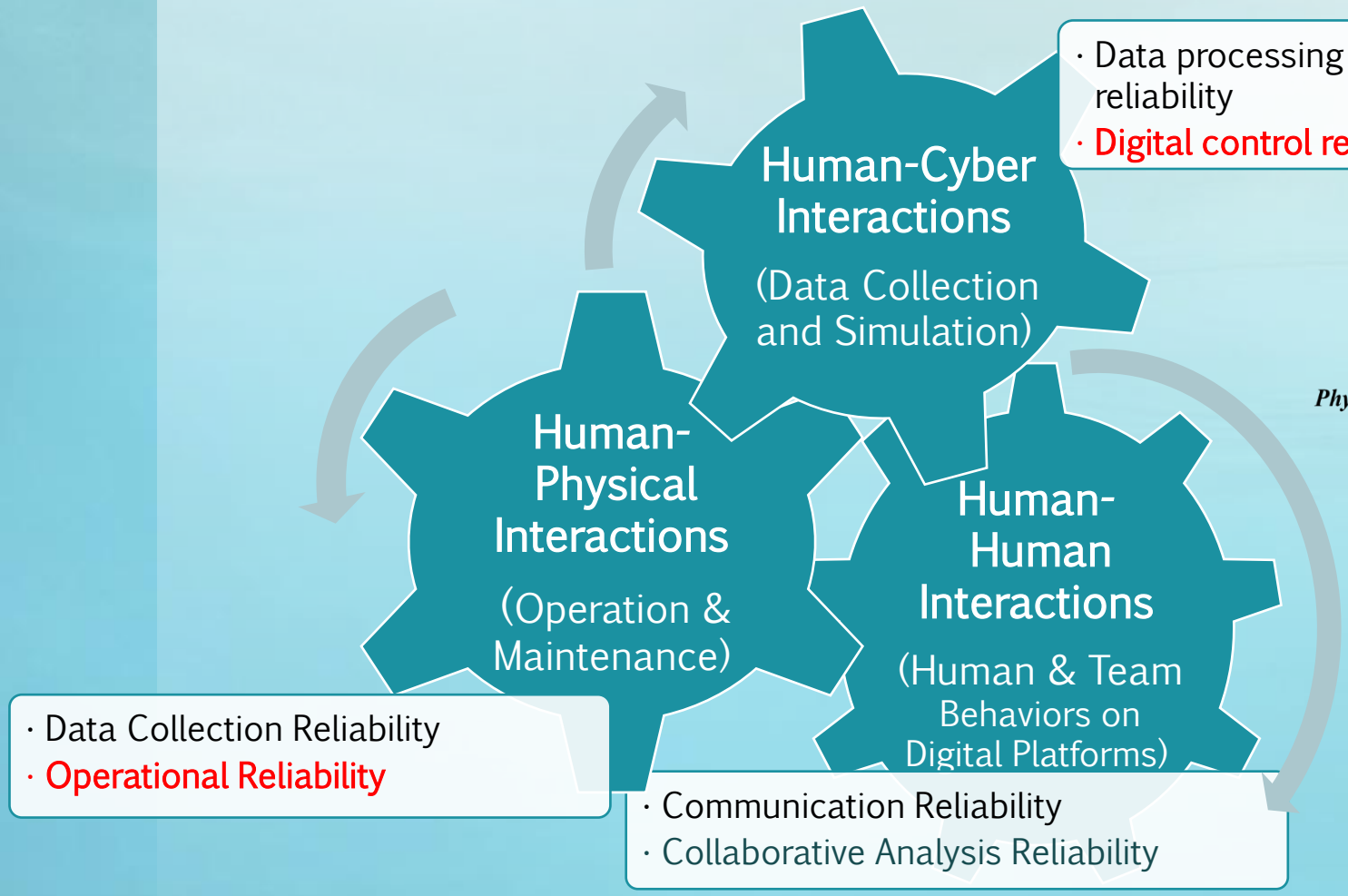
unity

Unity engine as the development platform

NLP-based work package information extraction

Scan the QR code to view the AR demo video

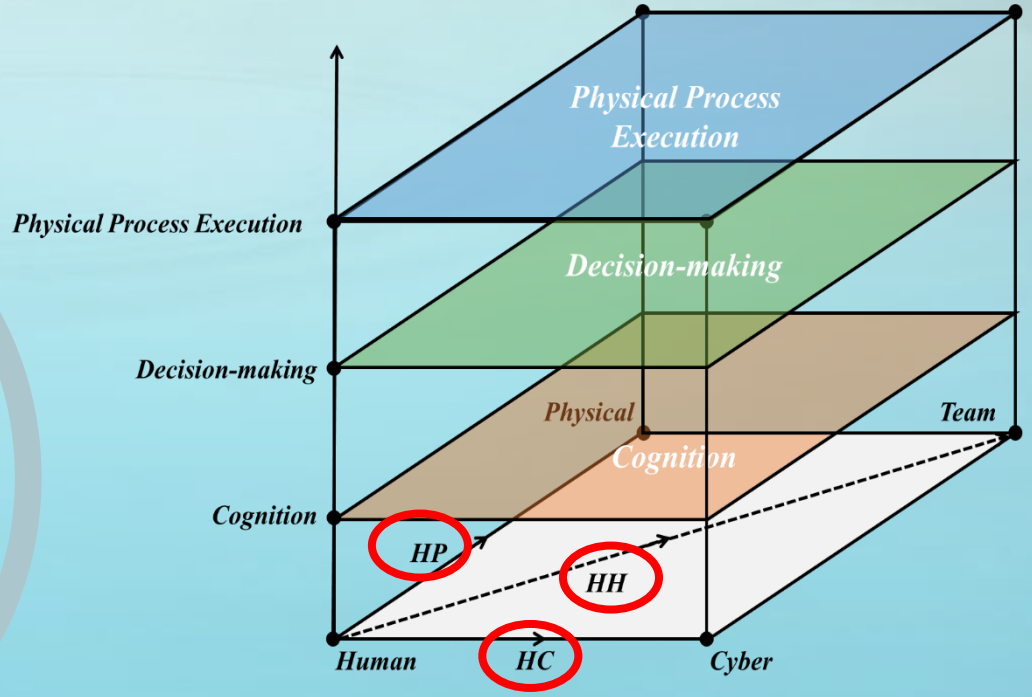
Reliability Analysis of Human-Cyber-Physical Infrastructure Systems (H-CPS) for Predictive Control



· Data processing & interpretation reliability
· Digital control reliability

· Data Collection Reliability
· Operational Reliability

· Communication Reliability
· Collaborative Analysis Reliability



Back to the Domain Problem – Safe Control for Civil Infrastructure Operations, What are the Challenges?

Cyber

Control Actions

Physical

Analog Control Room

https://www.pbs.org/wgbh/nova/tech/nuclear-control-room.html

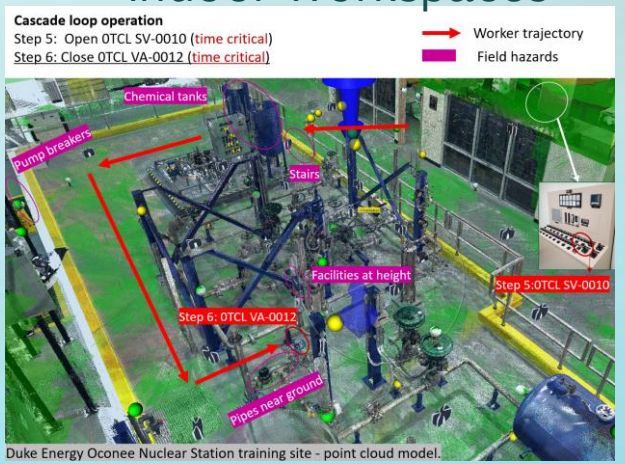
Digital Control Room

https://e360.yale.edu/features/when-it-comes-to-nuclear-power-could-smaller-be-better

Outdoor Workspaces

https://www.power-eng.com/nuclear/sandia-labs-working-on-water-reduction-options-at-3-gw-palo-verde-nuclear-plant/#gref

Indoor Workspaces



Duke Energy Oconee Nuclear Station training site - point cloud model.

Feedback

Nuclear Power Plant Operations – operators are collaborating to drive dynamic and complex systems, much more complicated than driving a car …

Back to the Domain Problem – Safe Control for Facility Management, What are the Challenges?

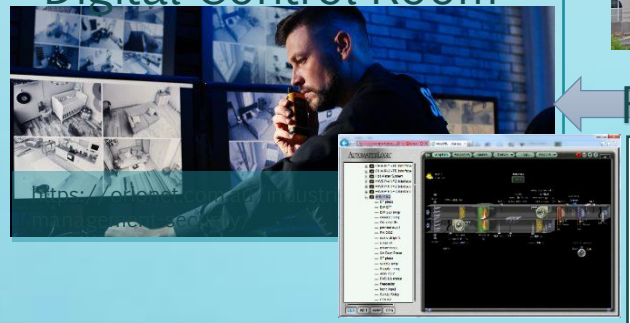
Cyber

Control Actions

Physical

Analog Control Room

Digital Control Room



CMU Campus Buildings

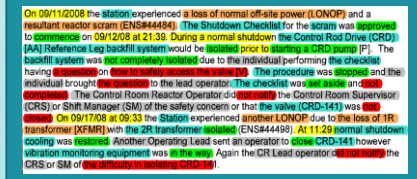
Indoor Workspaces

Feedback

Facility Management – facility manager are collaborating to drive dynamic and complex systems, much more complicated than driving a car …

Data-Driven Decision Challenges – All together!

Historical Reports


On 09/11/2008 the station experienced a loss of normal off-site power (LONOP) and a resultant reactor scram (ENS#44484). The Shutdown Checklist for the scram was approved to commence on 09/12/08 at 21:39. During a normal shutdown the Control Rod Drive (CRD) [AA] Reference Leg backfill system would be isolated prior to starting a CRD pump [P]. The backfill system was not completely isolated due to the individual performing the checklist having a question on how to safely access the valve [V]. The procedure was stopped and the individual brought the question to the lead operator. The checklist was not sucessfully completed. The Control Room Reactor Operator did not notify the Control Room Supervisor (CRS) or Shift Manager (SM) of the safety concern or that the valve (CRD-141) was not closed. On 09/17/08 at 09:33 the Station experienced another LONOP due to the loss of 1R transformer [XFMR] with the 2R transformer isolated (ENS#44498). At 11:29 normal shutdown cooling was restored. Another Operating Lead sent an operator to close CRD-141 however vibration monitoring equipment was in the way. Again the CR Lead operator did not notify the CRS or SM of the difficulty in isolating CRD-141.

(Nuclear Power Plant Licensee Event Reports)

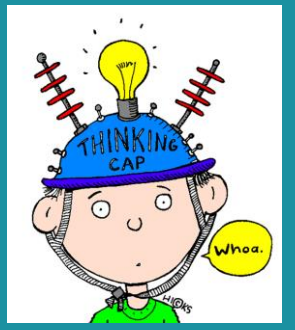
Regulations

(sources: https://www.barnesandnoble.com/w/nuclear-power-plant-reactor-training-manual-progressive-management/1114699408; https://res.digital/main-health-safety-regulation)

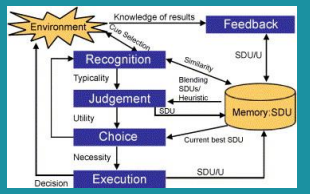
Real-Time Data

Conditions of Facilities, Human Behaviors (e.g., Communications)

Intelligent Real-Time Data Interpretation



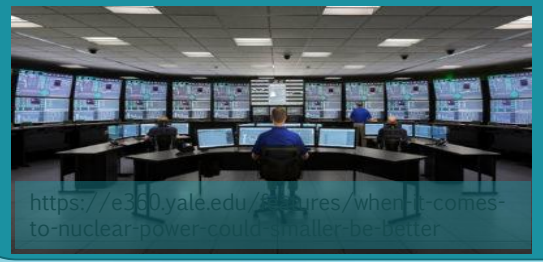
https://pixy.org/466964/



(Gonzalez, 2003)

Real-Time Decision Making

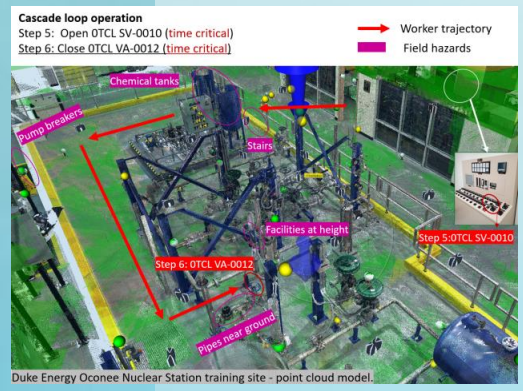
Context Matching, Simulation, Consequence Analysis, Control



https://e360.yale.edu/features/when-it-comes-to-nuclear-power-could-smaller-be-better

https://orionet.com/industries/facility-management-electrical/

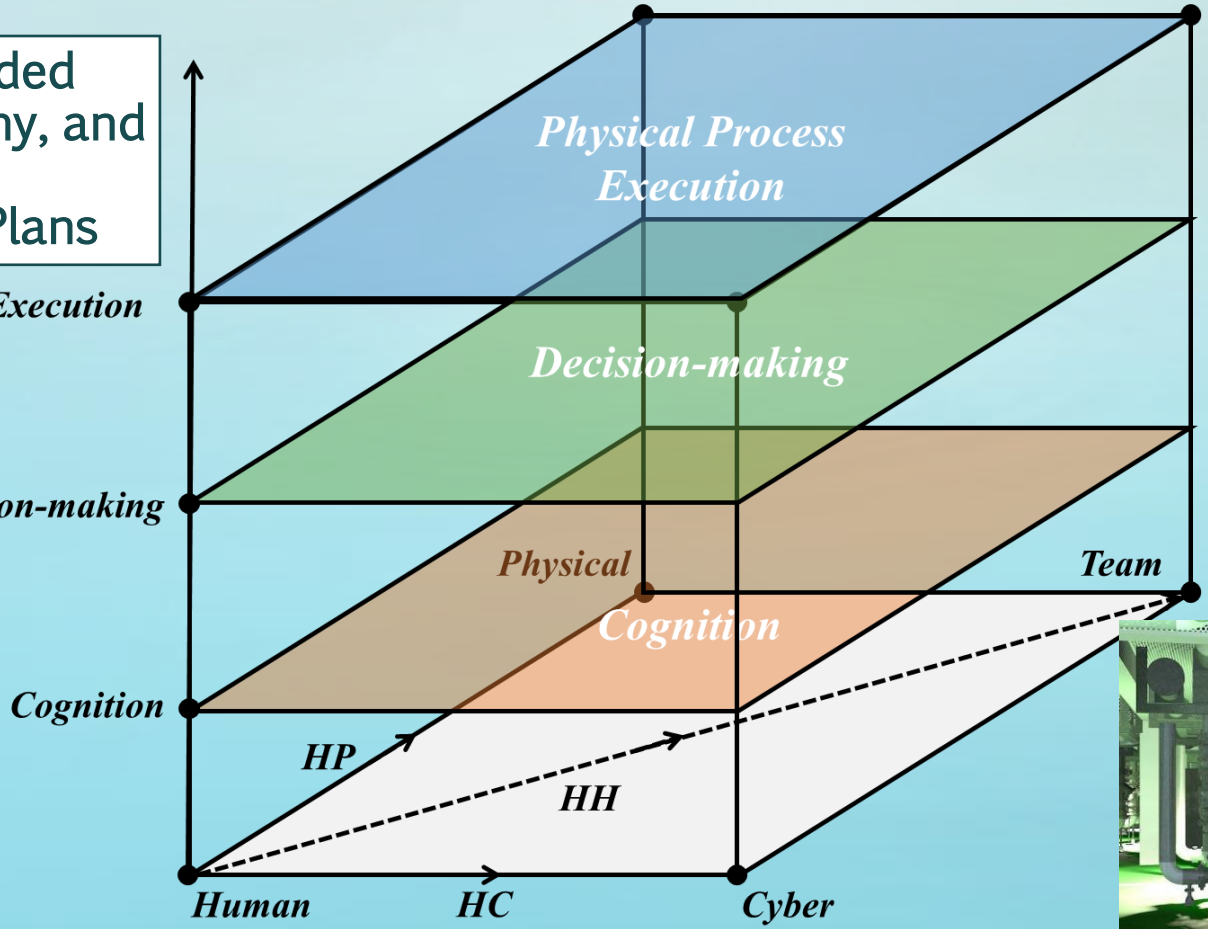
Vision – BIM and Explainable AI for Human-Centric CIO & FM



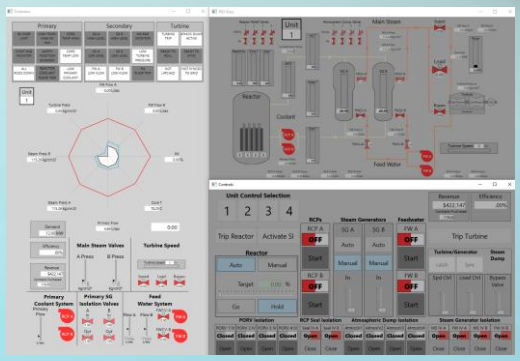
Recommended Safe, Healthy, and Efficient Operation Plans

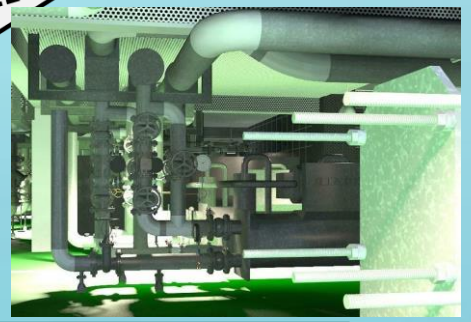
https://e360.yale.edu/features/when-it-comes-to-nuclear-power-could-smaller-be-better

Human Data and Digital Simulations of Human-in-the-Loop Processes



Simulations





Building Information Models (BIM)

Thank You All!

- Construction Industry Institute
- My institutions
- Funding agencies
- Collaborators, colleagues, and friends
- My students
- My family