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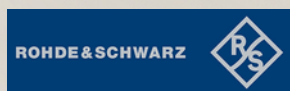
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Table of Contents

Message from the General Chair	i
Message from the Head of the Department of Electrical Engineering	ii
ISITIA 2026 Organizing Committee	iii
ISITIA 2026 Technical Program Committee and Reviewer	iv
Table of Contents.....	viii
Keynote Lectures	ix
ISITIA 2026 Technical Session Schedule	xxv
Technical Session 1	xxvii
Session 1: AI and Optimization in Power Systems, Room Offline 1	xxvii
Session 1: Intelligent systems, Room Offline 2	xxviii
Session 1: Applications of IoT, Room Online 1	xxix
Session 1: AI and Optimization in Power Systems, Room Online 2	xxx
Session 1: IT Applications, Room Online 3	xxxi
Session 1: IT Applications, Room Online 4	xxxii
Session 1: Antenna and Communication Systems, Room Online 5	xxxiii
Session 1: Information Systems, Room Online 6	xxxiv
Technical Session 2	xxxv
Session 2: AI in Energy Conversion and Power Electronics, Room Offline 1	xxxv
Session 2: Intelligent Systems, Room Offline 2	xxxvi
Session 2: AI and Optimization in Power Systems, Room Offline 3	xxxvii
Session 2: Telecommunication and Networks, Room Online 1	xxxviii
Session 2: AI in Energy Conversion and Power Electronics, Room Online 2	xxxix
Session 2: AI Applications, Room Online 3	xl
Session 2: Power and Energy Systems, Room Online 4	xli
Session 2: Electronics and Sensors, Room Online 5	xl ii
Session 2: Robotics and Control Systems, Room Online 6	xl iii
Technical Session 3	xliv
Session 3: Power and Energy Systems, Room Offline 1	xliv
Session 3 : Computer engineering and Security, Room Offline 2	xl v

Session 3 : Energy Conversion and High Voltage Engineering, Room Offline 3	xlvi
Session 3 : AI in Healthcare, Room Online 1	xlvii
Session 3 : Battery and Advanced Metering Infrastructure, Room Online 2	xlvi
Session 3 : Biomedical and AI, Room Online 3	xlix
Session 3 : Software development and security, Room Online 4	i
Session 3 : Power Systems, Room Online 5	li

Author Index	lii
---------------------------	------------

A101 - 1571272165

Short Term Load Forecasting Using Sliding-Window LSTM in DKI Jakarta Power Subsystems (<i>Hadeta P (Institut Teknologi Sepuluh Nopember, Indonesia & PT PLN (Persero), Indonesia); Rony Seto Wibowo and Suwito (Institut Teknologi Sepuluh Nopember, Indonesia)</i>)	1
---	----------

A102 - 1571265618

Optimal Load Shedding for Remedial Action Scheme: A Study on the 150 kV Grati Subsystem (<i>Muhammad Abdika Az Zakiy (Institut Teknologi Sepuluh Nopember, Indonesia & PT PLN (Persero), Indonesia); Ni Ketut Aryani and Yurid E. Nugraha (Institut Teknologi Sepuluh Nopember, Indonesia); Ahmad Murdani and Faisol Sidqi (PT PLN (Persero), Indonesia)</i>)	7
--	----------

A103 - 1571279353

Optimal Feeder Reconfiguration (OFR) in Medium Voltage and Low Voltage Distribution Networks Using Simulated Annealing (SA) (<i>Eka Revi Ruswandi and Rudy Dikairono (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia)</i>)	13
--	-----------

A104 - 1571281684

Development of Fault Location, Isolation and Service Restoration Algorithm by Considering Keypoint Equipment Indications at PLN UID West Kalimantan (<i>Yosefariko (Institut Teknologi Sepuluh Nopember, Indonesia & PT PLN (Persero), Indonesia); Rony Seto Wibowo and Yurid E. Nugraha (Institut Teknologi Sepuluh Nopember, Indonesia)</i>)	20
---	-----------

A105 - 1571281613

Inverse Overcurrent Relay Coordination Using Modified Adaptive Particle Swarm Optimization and Definite Time Settings in a Fertilizer Power System (<i>Harfiana Maharani, Margo Pujiatara and Yurid E. Nugraha (Institut Teknologi Sepuluh Nopember, Indonesia)</i>)	26
---	-----------

A106 - 1571281662

Enhancing Economic and Emission Dispatch Through Turbulent Flow of Water Based Optimization in a Case Study on Exothermic Driven Power Generation (<i>Moh Imamuddin Suria Saputra and Ni Ketut Aryani (Institut Teknologi Sepuluh Nopember, Indonesia); Ontoseno Penangsang (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia)</i>)	32
---	-----------

A107 - 1571281688

Optimization of Overcurrent Relay in Radial Networks Based on Zone Selective Interlocking and Adaptive Modified Firefly Algorithm Method (<i>Muhammad Nadir, Margo Pujiatara and Eko Setijadi (Institut Teknologi Sepuluh Nopember, Indonesia)</i>)	38
--	-----------

B101 - 1571281443

Cost Map-Integrated Model Predictive Control for Safe Path Following of Mobile Robots (<i>Trihastuti Agustinah (Institut Teknologi Sepuluh Nopember, Indonesia); Fadlan Hafiz Harahap (Institut Teknologi Sepuluh Nopember, Indonesia); Yurid E. Nugraha, Zulkifli Hidayat and Putri Aqila Naifah (Institut Teknologi Sepuluh Nopember, Indonesia)</i>)	44
--	-----------

B102 - 1571268821

Adaptive Local Path Planning for Mobile Robot Navigation with Temporal Awareness Using Time Pressure Ratio and Dynamic Window Approach (<i>Agung Purwanto, Trihastuti Agustinah, Yurid E. Nugraha and Putri Aqila Naifah (Institut Teknologi Sepuluh Nopember, Indonesia)</i>)	50
---	-----------

B103 - 1571281568

Object Detection and Attention-Enhanced Digit Recognition for Automation Meter Reading on Real-World Analog kWh Meters (Muhammad Iqbal (Institut Teknologi Sepuluh Nopember, Indonesia); Lhuqita Fazry (Universitas Indonesia, Indonesia); Ahmad Sirojuddin and Ari Santoso (Institut Teknologi Sepuluh Nopember, Indonesia)) B104 - 1571271761	56
An Improved Deep Reinforcement Learning Routing Algorithm in LEO Networks (Agung Sunaryadi, Ajib S. Arifin and Muhamad Asvial (Universitas Indonesia, Indonesia)) B105 - 1571281926	62
Multi-Quadcopter Formation and Monocular Triangulation for SAR Victim Localization (Ravi Maulana Syaputra, Madelyne Candra, Phillip Putra and Djati Wibowo Djamari (Sampoerna University, Indonesia)) B106 - 1571243864	68
Orbital Safety Analysis and Collision Risk Reduction in the 500-600 km Altitude Range (Septiaini Dela Subiakto, Heroe Wijanto and Meiditomo Sutyarjoko (Telkom University, Indonesia)) B107 - 1571281739	74
Performance Evaluation of LSTM, GRU, and Transformer Models with Incremental Learning for Real-Time Streaming Load Forecasting in the West Kalimantan (Arif Rahman Hakim (Institut Teknologi Sepuluh Nopember, Indonesia & PT PLN (Persero), Indonesia); Djoko Purwanto (Institut Teknologi Sepuluh Nopember, Indonesia); I Made Yulistya Negara (ITS, Indonesia)) D101 - 1571280710	80
PCA-Driven Edge Intelligence for Digital Twin Environmental Monitoring: A Lightweight IoT Concept (Haider Al-juboori (South East Technological University, Ireland)) D102 - 1571270379	86
Impact of Priority-Based Caching on Cache Performance for Smart Building IoT Sensors in Named Data Networking (Ratna Widya Ningrum (Universitas Telkom, Indonesia); Leanna Vidya Yovita and Istikmal (Telkom University, Indonesia)) D103 - 1571259088	92
Structured Pruning and Quantization for Human Steps Forecasting from IoT Wearables Using LSTM (Raden Muhammad Reffa Maulana (Universitas Telkom, Indonesia); Aji Gautama Putrada and Ikke Dian Oktaviani (Telkom University, Indonesia)) D104 - 1571264048	98
Toward a Trust-Centric IoT Adoption Framework for Smart Horticulture Supply Chains: Preliminary Evidence from Farmers (Hanif Zaidan and Imam Baihaqi (Institut Teknologi Sepuluh Nopember, Indonesia); Reny Nadlifatin (Institut Teknologi Sepuluh Nopember (ITS), Indonesia)) D105 - 1571263324	104
Characterising Sleep Mode Energy Savings for Integrated Optical-Wireless Access Network Infrastructure (Maria Qusyairi (Universiti Teknologi Brunei, Brunei Darussalam); Nurazmina Lingas (UTB, Brunei Darussalam); Nor Asiah Muhamad (Universiti Teknologi Brunei, Brunei Darussalam & Universiti Sains Malaysia, Malaysia)) D106 - 1571282438	110
Design and Implementation of a Programmable Smart Energy Meter with Integrated Backup Power and GSM-Based Communication (Mumba Mukabe Moise (MAPON University, Congo (Democratic Republic, Zaire)); Hikma Shabani (Papua New Guinea University of Technology, Papua New Guinea); Muhammad Rusydi Muhammad Razif (Universiti Tun Hussein Onn Malaysia, Malaysia)) D107 - 1571281814	116
Development of an IoT System to Support an Implementation of Adaptive Office Energy Management System (Dedi Harianto Panjaitan (Institut Teknologi Sepuluh November, Indonesia); Eko Setijadi (Sepuluh Nopember Institute of Technology, Indonesia); Prasetyono Hari Mukti (Institut Teknologi Sepuluh Nopember, Indonesia)) E101 - 1571270765	122

Design of an Electrical Energy Monitoring System Using Branch Current Based State Estimation in Radial Distribution Networks (Clairina Elora Laili and Dedet Riawan (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia)) E102 - 1571281266	128
Optimization of Overcurrent Relay Coordination Using Grasshopper Algorithm for a Zero down Time System in the Capital City of Nusantara (IKN) (Rizky Prima Nugraha, Margo Pujiانتارا and Yurid E. Nugraha (Institut Teknologi Sepuluh Nopember, Indonesia)) E103 - 1571281686	134
Optimization of Loop Distribution Network Reconfiguration Using Adaptive Modified Firefly Algorithm (Prasetio Hamiseno, Ardyono Priyadi, Muhammad Rivai and Agus Suwardono (Institut Teknologi Sepuluh Nopember, Indonesia)) E104 - 1571280327	140
Ground Fault Relay Evaluation of Distribution Line System Using PSO Approach (Akhmad Rizal Efendi (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Anton Asfani (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); I Made Yulistya Negara (ITS, Indonesia)) E105 - 1571281842	146
Optimal Time Dial Setting of Overcurrent Relays in a Parallel 20/150 kV Supply Scheme Using Modified Adaptive Particle Swarm Optimization (Sanynita Kiskindy, Margo Pujiانتارا and Djoko Purwanto (Institut Teknologi Sepuluh Nopember, Indonesia)) E106 - 1571281612	152
Forecasting Distribution Transformer Parameters Using Machine Learning Algorithm and Advanced Metering Infrastructure (AMI) Data (Agik Promento Yahya (Institut Teknologi Sepuluh Nopember, Indonesia); I Gusti Ngurah Satriyadi Hernanda (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); Hendra Kusuma (Institut Teknologi Sepuluh Nopember, Indonesia)) E107 - 1571281693	158
Improvement of Overcurrent Relay Coordination in Isolated Distribution System Using Grasshopper Optimization Algorithm (Rizki Adi Wijaya, Margo Pujiانتارا and Hendra Kusuma (Institut Teknologi Sepuluh Nopember, Indonesia)) E108 - 1571269183	164
Optimal Relay Coordination in Kampong Cham Radial System Based on Adaptive Protection Scheme Using Modified Grasshopper Optimization Algorithm (Chhao Rath Yin, Margo Pujiانتارا, Ardyono Priyadi and Phanit So (Institut Teknologi Sepuluh Nopember, Indonesia)) F101 - 1571270532	170
Augmented Reality as Contextual Support in Puzzle-Based Technical Simulation (Tri Ika Jaya Kusumawati, Tijk (Universitas Budi Luhur, Indonesia); Mauridhi Hery Purnomo (Institut of Technology Sepuluh Nopember, Indonesia); Reza Fuad Rachmadi (Institut Teknologi Sepuluh Nopember, Indonesia)) F102 - 1571281447	176
A VR-Based Multi-Camera Learning System Integrating Drone for Spatio-Temporal Decision-Making in Cultural Live Production (Citra Murdaningtyas (Electronic Engineering Polytechnic Institute of Surabaya, Indonesia); Surya Sumpeno (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Rudy Dikairono (Institut Teknologi Sepuluh Nopember, Indonesia); Dwi Susanto, Halimatus Sa'dyah and Idris Winarno (Politeknik Elektronika Negeri Surabaya, Indonesia)) F103 - 1571262763	182
Enterprise Generative AI Adoption and Workforce Impact: A Data-Driven Analysis (Lianna Wijaya (Binus University, Indonesia); Mehdi Houichi (High School of Communication TUNISIA, Tunisia)) F104 - 1571281853	188
Knowledge-Sharing Behavior Recognition in Social Media Text with Probability Calibration	194

(Yuliazmi Fnu (<i>Institut Teknologi Sepuluh Nopember & Universitas Budi Luhur, Indonesia</i>); Bruri Trya Sartana (<i>Institut Teknologi Sepuluh November (ITS), Indonesia & Universitas Budi Luhur, Indonesia</i>); Diana Purwitasari (<i>Institut Teknologi Sepuluh Nopember, Indonesia</i>); Surya Sumpeno (<i>Institut Teknologi Sepuluh Nopember (ITS), Indonesia</i>); Mauridhi Hery Purnomo (<i>Institut of Technology Sepuluh Nopember, Indonesia</i>))	
F105 - 1571282067	
A Novel Hybrid Swarm Optimizer Integrating Quasi-Reflective Learning and RRT for Gear Train Design	200
(Maulana Alirridlo, Dwi Sunaryono, Yudhi Purwananto and Misbakhul Munir Irfan Subakti (<i>Institut Teknologi Sepuluh Nopember, Indonesia</i>); Joko Siswantoro (<i>Universitas Surabaya, Indonesia</i>))	
F106 - 1571291642	
Two-Stage YOLO11n Pipeline with Entropy Gating for Real-Time UAV-Based Power Line Insulator Inspection at the Edge	206
(Yan Sheng Kang (<i>Tunku Abdul Rahman University of Management and Technology, Malaysia</i>); Wong Jee Keen Raymond (<i>Universiti Malaya, Malaysia</i>); Kin Yun Lum (<i>Tunku Abdul Rahman University of Management and Technology, Malaysia</i>))	
G101 - 1571282112	
The Influence of Utility and Attitude on the Actual Usage of QRIS in Indonesia MSMEs	212
(Felicia Cahya Susanto, Jeremy Moses, Kevin Lodewyk Berhitsu and Stephanie Surja (<i>Bina Nusantara University, Indonesia</i>))	
G102 - 1571279438	
The Rise of Digital Immortality: A Study of AI-Mediated Posthumous Interaction Systems	218
(Sujoy Sen (<i>Symbiosis International (Deemed University), India & Symbiosis Institute of Business Management, Pune, India</i>); Sanjeev Kadam (<i>Symbiosis International (Deemed University) & Symbiosis Institute of Business Management, Pune, India</i>); Shiladitya Verma (<i>Higher Colleges of Technology, Abu Dhabi, United Arab Emirates</i>); Anshul Agrawal (<i>GNIOT Institute of Management Studies Greater Noida, India.</i>); Shaima'a Al Hijawi (<i>Higher Colleges of Technology, Abu Dhabi, United Arab Emirates</i>); Tanuj Mathur (<i>Symbiosis Institute of Business Management Pune, India & Symbiosis International (Deemed University) Pune, India</i>))	
G103 - 1571266586	
Predicting on-Time Graduation in Higher Education Using Institutional Administrative Data	224
(Wiratmoko Yuwono and Siti Nafiatul Fatimah (<i>Politeknik Elektronika Negeri Surabaya (PENS), Indonesia</i>); Arna Fariza and Idris Winarno (<i>Politeknik Elektronika Negeri Surabaya, Indonesia</i>))	
G104 - 1571282344	
Time Series Analysis and Forecasting of Student Admission Data Using a Decomposition-Based Forecasting Method with Structural Breaks	230
(Charisa L. Abalie (<i>MSU - Tawi-Tawi College of Technology and Oceanography, Philippines</i>); Irene A. Bakili (<i>MSU Tawi-Tawi College of Technology and Oceanogrphay, Philippines</i>); Nerico L. Mingoc, Romeo L. Panares Jr and Jul-Habir U. Kali (<i>MSU Tawi-Tawi College of Technology and Oceanography, Philippines</i>); Ramat Hailaya (<i>MSU TCTO, Philippines</i>); Dayang Farha Julambri and Estelita Cheng G. Lim (<i>Mindanao State University TCTO, Philippines</i>); Abdul-aziz Tiblan (<i>MSU Tawi-Tawi College of Technology and Oceanography, Philippines</i>); Urbano B Patayon (<i>Jose Rizal Memorial State University, Philippines</i>))	
G105 - 1571282029	
Driver Behavior Based Assignment on Ride-Hailing Dispatch: A Local Ride Hailing Use Case	237
(Septia Nusa, Diana Purwitasari and Bilqis Amaliah (<i>Institut Teknologi Sepuluh Nopember, Indonesia</i>))	
G106 - 1571245727	
Toward Intelligent Accounting: An Explainable Machine Learning Framework for Risk-Oriented Transaction Outcome Prediction	244
(Johannes Kristian Siregar (<i>UNIBI, Indonesia</i>); Astari Dianty, Antonius Bimo Rentor, Anike Putri and Nur Alamsyah (<i>Universitas Informatika dan Bisnis Indonesia, Indonesia</i>); Budiman (<i>Universitas Informatika dan Bisnis Indonesia, Indonesia & Universitas AMIKOM Yogyakarta, Indonesia</i>))	
G107 - 1571280280	
Democratising STEM Through Frugal Innovation: An International Evaluation of Microimaging in Sustainable Engineering Education	250
(Haider Al-juboori (<i>South East Technological University, Ireland</i>))	
H101 - 1571270528	

Design and Fabrication of Microstrip Antennas for Electromagnetic Compability Measurements Using the Patch Cut and Ground Slot Methods (Imam Syafi'e and Muhammad Kodrat (Telkom University, Indonesia); Sudarmono Sasmono (Telkom University & PT Quadran Energi Rekayasa, Indonesia); Rizki Amalia Pratiwi (Telkom University, Indonesia)) H102 - 1571282038	256
Surrogate-Based Performance Prediction and Optimization of Metamaterial-Inspired Phased Array Antennas Using Supervised Learning (Kaysa Adara Karim, Muhammad Rendra Perdana Kusuma Djaka, Muhammad Rafi Gunawan and Rahardian Rafi Satria Hutama (Telkom University, Indonesia)) H103 - 1571284880	262
Code-Domain Resource Mapping for Adaptive Power Allocation in Multiuser Visible Light Communication Systems Using CD-NOMA (Dhabita Audrea Belindra, Ms, Muhammad Rendra Perdana Kusuma Djaka and Edo Lutfi Mahanani (Telkom University, Indonesia)) H104 - 1571253373	268
Design and Implementation of Low-Cost ESP32-Based FSO Transmission System Under Simulated Atmospheric Disturbances (A. Kiflan Jiyaad Mafazi. A (Universitas Telkom, Indonesia); Aminah Indahsari Marsuki (Telkom University, Indonesia); Aris Hartaman (Telkom University & School of Electrical Engineering, Indonesia); Muhammad Rizki Akbar (Universitas Telkom, Indonesia)) H105 - 1571272803	274
Performance Analysis of a Ku-Band Planar Array Antenna for HTS User Terminals Applications (Dyatisa Hanifah, Heroe Wijanto and Meiditomo Sutyarjoko (Telkom University, Indonesia)) H106 - 1571269235	280
Scattering-Induced Ranging Bias of Compact ToF LiDAR in Turbid Water: Implications for Water Level Sensing (Ryu Khalfani Hidayat, Aminah Indahsari Marsuki and Akhmad Hambali (Telkom University, Indonesia)) I101 - 1571281979	286
Integrating WRBS and NPS Models for Veterinarian Rating Feature (Amanda Razkya Aprianona (Universitas Telkom, Indonesia); Rahmat Yasirandi (Telkom University, Indonesia); Wilsandi Saefuloh (Bandung Food Security and Agriculture Office, Indonesia)) I102 - 1571269099	292
Mapping the Research Frontier of Business Continuity Management: A Bibliometric Analysis (Yusrida Muflihah, Apol Pribadi Subriadi and Reny Nadlifatin (Department of Information Systems, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia)) I103 - 1571269207	298
Integrating Technology, Human, and Knowledge Dimensions in Electronic Health Record Implementation: A Systematic Literature Review of Socio-Technical (Erna Selviyanti and Apol Pribadi Subriadi (Institut Teknologi Sepuluh Nopember, Indonesia); Tining Haryanti (Universitas Muhammadiyah Surabaya, Indonesia)) I104 - 1571284757	304
Understanding ERP Adoption in Agribusiness: An Empirical Study Using Extended Technology Acceptance Model PLS-SEM and IPMA (Bunga Khairun Nisa (Universitas Telkom, Indonesia); Widia Febriyani and Taufiq Maulana Firdaus (Telkom University, Indonesia)) I105 - 1571269529	310
Understanding the Intention of Live and Online Purchasing Among Indonesian User: An Application of Unified Theory of Acceptance and Use of Technology (Rahma Wahyu Idayani and Renny Pradina Kusumawardani (Institut Teknologi Sepuluh Nopember, Indonesia)) I106 - 1571282080	316
Performance Evaluation of API Gateways in Microservices System: No Gateway, Kong, and Native (Novi Maria Natalia (Universitas Telkom, Indonesia); Rahmat Yasirandi and Sheina Fathur Rahman (Telkom University, Indonesia)) A201 - 1571281667	322

Multi-Period Distribution System Reconfiguration Considering PV-Wind Uncertainty and Voltage Stability Using QBPSO (Muhammad Radif Jomansyah (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Ni Ketut Aryani (Institut Teknologi Sepuluh Nopember, Indonesia)) A202 - 1571267408	328
Design of Adaptive Hysteresis Current Control Based on Artificial Neural Network for a Single-Phase Bidirectional Voltage Source Inverter (Ludviatul Amanah and Feby Agung Pamuji (Institut Teknologi Sepuluh Nopember, Indonesia); Mochamad Ashari (Sepuluh November Institute of Technology, Indonesia)) A203 - 1571281243	334
Two-Stage Feeder Load Forecasting with Behind-the-Meter Rooftop Photovoltaic Using XGBoost (Intan Nur Fadlillah, Ardyono Priyadi and Eko Setijadi (Institut Teknologi Sepuluh Nopember, Indonesia)) A204 - 1571281716	340
Horizon-Aware Wind Power Forecasting Using Industrial Supervisory Control and Data Acquisition Measurements and Long Short-Term Memory-Informer Models (Unggul Wahyu Tri Purnomo Putro, Djoko Purwanto and Feby Agung Pamuji (Institut Teknologi Sepuluh Nopember, Indonesia)) A205 - 1571281859	346
Cleaning Prioritization of Distributed Photovoltaic Systems Using Counterfactual Inference and Calibrated Stacking Ensembles (Made Darmayasa, Adi Soeprijanto and Suwito (Institut Teknologi Sepuluh Nopember, Indonesia)) A206 - 1571275776	352
Optimization of BESS Capacity to Mitigate Wind Power Output Intermittency Using PSO Algorithm: A Case Study of Jeneponito Wind Power Plant (Tria Tiara Putra (Institut Teknologi Sepuluh Nopember, Indonesia & PT PLN (Persero), Indonesia); Rony Seto Wibowo and Vita Lystianingrum (Institut Teknologi Sepuluh Nopember, Indonesia)) B201 - 1571269097	359
Breast-to-Uterine Tumor Transfer Learning and Data Augmentation: Addressing Limited Ultrasound Data for Uterine Malignancy Classification (Kamala Qurrota Ayun (Institut Teknologi Sepuluh Nopember, Indonesia); Tri Arief Sardjono (Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia); Rachmad Setiawan (Institut Teknologi Sepuluh Nopember, Indonesia)) B202 - 1571285197	365
A Robust Multi-Metric Approach for Social Assistance Targeting Using Machine Learning Techniques (Debora Chrisinta, Budiman Baso, Yasinta Oktaviana Legu Rema, Ernes Josias Blegur, Justin Eduardo Simarmata and Regolinda Maneno (Universitas Timor, Indonesia)) B203 - 1571280323	371
Tuladha: A Techno-Humanistic Learning Framework Based on Ki Hajar Dewantara's Leadership Trilogy Through AdminQuiz for Digital Character Transformatio (Ong Hansel Santoso and Reza Fuad Rachmadi (Institut Teknologi Sepuluh Nopember, Indonesia); Mauridhi Hery Purnomo (Institut of Technology Sepuluh Nopember, Indonesia); Darren Susanto and Esther Irawati Setiawan (Institut Sains dan Teknologi Terpadu Surabaya, Indonesia)) B204 - 1571274908	378
55 GHz Dual-Wavelength Laser at Zero-Dispersion Telecommunication Wavelength (L. W. Lohano (Photonics Research Centre, Universiti Malaya, Kuala Lumpur, Malaysia); Bilal Nizamani (Universiti Malaya, Malaysia); Muhamad Zharif Samion (Photonics Research Center, University of Malaya, Malaysia); Harith Ahmad (Photonics Research Centre (PRC), University of Malaya (UM), Malaysia); Hazlie Mokhlis (Universiti Malaya, Malaysia)) B205 - 1571282105	384
Performance Evaluation of Fuzzy-PID Controller for ROV Path Following Under Ocean Current (Yuda Apri Hermawan and Wasis Dwi Aryawan (Institut Teknologi Sepuluh Nopember, Indonesia); I Ketut Aria Pria Utama (Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia); Danar Guruh Pratomo and Muhammad Ikhsan Suryadarma (Institut Teknologi Sepuluh Nopember, Indonesia)) B206 - 1571281855	390
A Comparative Study on the Impact of Antenna Height in Okumura-Hata Propagation Model for	396

VHF/UHF in Mataram City (Prasetiyono Hari Mukti, Muhammad Ali Akbar, Mohammad Rifqi Firmansyah, Acmad Affandi and Puji Handayani (Institut Teknologi Sepuluh Nopember, Indonesia))	
C201 - 1571281068	
Optimal Operational Configuration of a Planned Gas Engine Power Plant to Improve Reliability in the Sangihe Isolated Power System (Dimas Adhi Prabowo (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Adi Soeprijanto (Institut Teknologi Sepuluh Nopember, Indonesia))	401
C202 - 1571282091	
Optimization of Capacitor Placement Using Grey Wolf Optimizer (GWO) and Particle Swarm Optimization (PSO) on the Kenduruhan Feeder to Reduce Power Los (Zainul Rahmawan, Ardyono Priyadi, Yurid E. Nugraha and Firas Quthbi Sidqi (Institut Teknologi Sepuluh Nopember, Indonesia))	406
C203 - 1571281283	
Simultaneous Optimization of Hydropower Penetration Level and Power Factor to Improve Power Quality in the 20 kV Kuala-Binjai Distribution Network (Hans Andrew Simon Putra Siregar, Ni Ketut Aryani, Eko Setijadi and Omar Fabian (Institut Teknologi Sepuluh Nopember, Indonesia); Nathan Saputra Sitohang (Universiti Tenaga Nasional, Malaysia & PT PLN (Persero), Indonesia))	412
C204 - 1571284999	
Diagnosis and Classification of Stator Bar Insulation Defects in Generators Using Partial Discharge Image Processing and Neural Networks (Tito Candra Hutajulu (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Anton Asfani (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); Ahmad Sirojuddin (Institut Teknologi Sepuluh Nopember, Indonesia))	418
C205 - 1571282109	
A Combination of Partial Discharge Signal Envelope Analysis and Artificial Neural Networks for Identifying Faults in High-Voltage Cable Joints (Gama Prayoga (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Anton Asfani and Astria Nur Irfansyah (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia))	424
C206 - 1571281957	
Comparative Study of Machine Learning Models for Intrusion Detection in SCADA Communication Based on IEC 60870-5-104 (Sofyan Asyzauri (Institut Teknologi Sepuluh Nopember, Indonesia); Achmad Affandi (Sepuluh Nopember Institute of Technology, Indonesia); Prasetiyono Hari Mukti (Institut Teknologi Sepuluh Nopember, Indonesia); Ahmad Murdani (PT PLN (Persero), Indonesia); Fransiska Sisilia Mukti (Institut Teknologi dan Bisnis Asia Malang, Indonesia & Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); Abdul Hamid (PT PLN (Persero), Indonesia))	430
D201 - 1571284931	
Inter-Satellite Network for Smart City Based on Amplified Soliton-like Pulses Transmission (Ucuk Darusalam (Universitas Nasional, Indonesia); Sholeh Hadi Pramono (Universitas Brawijaya & Engineering Faculty, Indonesia); Purnomo Sidi Priambodo (Universitas Indonesia, Indonesia))	436
D202 - 1571281805	
Satellite Altimetry Signal Processing for Eddy Kinetic Energy Estimation in the Indonesian Seas: Toward Intelligent Ocean Monitoring (Eko Yuli Handoko, Salsabila Khairunnisa and Akbar Kurniawan (Institut Teknologi Sepuluh Nopember, Indonesia); Joko Budi Utomo (The Agency of Meteorology, Climatology, and Geophysics, Indonesia); Widodo Setiyo Pranowo (National Research and Innovation Agency, Indonesia); Mukhammad Muryono (Institut Teknologi Sepuluh Nopember, Indonesia))	444
D203 - 1571281846	
Integrated PoolCache and LRFU Caching Strategy for Efficient Content Distribution in Named Data Networking (Muhammad Farhan (Universitas Telkom, Indonesia); Leanna Vidya Yovita and Istikmal (Telkom University, Indonesia))	450
D204 - 1571248400	
OBFSFP: Service-Rate Based AQM with BDP Gating and Stochastic Binning for BBR-CUBIC Fairness in	456

Single-Queue Networks

(Muhammad Arief Nugroho, Ibnu Asror and Dadang Setiawan (Telkom University, Indonesia))

D205 - 1571281883

A Study on Radio Network Planning Based on LoRa Technology for DCS and PLC System Integration 462
(Abdi Prasetyo, Devy Kuswidiastuti and Prasetyono Hari Mukti (Institut Teknologi Sepuluh Nopember, Indonesia))

D206 - 1571281888

Performance Evaluation of VoIP Services in PLN Centralized Control Center: A Data-Calibrated Simulation of MCC-DRC Network Architecture 468

(Achmad Yulias Amir (Institut Teknologi Sepuluh Nopember, Indonesia); Achmad Affandi (Sepuluh Nopember Institute of Technology, Indonesia); Prasetyono Hari Mukti (Institut Teknologi Sepuluh Nopember, Indonesia))

E201 - 1571259841

A Sea-Horse Optimizer-Based Global MPPT Algorithm for Centralized PV String Systems Under Partial Shading 474

(Niam Tamami, Feby Agung Pamuji and Mochamad Ashari (Institut Teknologi Sepuluh Nopember, Indonesia))

E202 - 1571279512

Priority Aware Under Frequency Load Shedding via Particle Swarm Optimization for Low Inertia Island Power Systems 480

(Rangga Tristanto Rahmat Alwijaya (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Adi Soeprijanto (Institut Teknologi Sepuluh Nopember, Indonesia))

E203 - 1571281840

Power Plant Efficiency Prediction Using MrMiMaxG Feature Selection and Consensus Voting Mechanism 486

(Ainal Irham, Diana Purwitasari and Bilqis Amaliah (Institut Teknologi Sepuluh Nopember, Indonesia))

E204 - 1571281685

Hybrid Photovoltaic Power Forecasting Using Onsite and ERA5 Data Based on LSTM Algorithm in an Islanded System: A Case Study of Selayar Island 493

(Hasbi Nur Ashshiddiq, Ardyono Priyadi and Feby Agung Pamuji (Institut Teknologi Sepuluh Nopember, Indonesia))

E205 - 1571281700

Short-Term Reservoir Inflow Forecasting Using Long Short-Term Memory with Hydrometeorological Inputs and Wavelet Denoising 499

(Herrizon Okto Yaskie (Institut Teknologi Sepuluh Nopember, Indonesia & PT PLN (Persero), Indonesia); Rony Seto Wibowo and Suwito (Institut Teknologi Sepuluh Nopember, Indonesia))

E206 - 1571270400

Design and Simulation of ANN-Based Direct Torque Control for BLDC Motor Speed in Bangkits Cendrawasih e-Trail 505

(Feby Agung Pamuji, Dedet Riawan and Nawang Adita Jayanti (Institut Teknologi Sepuluh Nopember, Indonesia); Bambang Sudarmanta (INstitut Teknologi Sepuluh Nopember, Indonesia); Mohammad Khoirul Effendi (Institut Teknologi Sepuluh Nopember, Indonesia); Nurvita Arumsari and Putri Nur Rahayu (Shipbuilding Institute of Polytechnic Surabaya, Indonesia); Ohn Zin Lin (Technical University of Ostrava, Czech Republic))

E207 - 1571255617

Comparative Analysis of Mamba, iTransformer, and DLinear Models on Spatial Dynamic Wind Power Dataset 511

(Alvrian Timotius Hinandra and Ariadi Nugroho (Binus University, Indonesia))

F201 - 1571281634

Customer Complaint Classification in Point of Sale (Pos) Applications Using Machine Learning and Deep Learning 517

(Mohamad Alfauzan Azzubaidi (Kalla Institute, Indonesia); Rezty Amalia Aras (Institut Teknologi dan Bisnis Kalla, Indonesia); Aulia Rahmawati (Institute Teknologi dan Bisnis Kalla, Indonesia))

F202 - 1571281980

LLM-Based Interpretation of Student Talent-Interest Profiles for Personalized Career Guidance 523
(Pujo Satrianto (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); Surya Sumpeno (Institut

Teknologi Sepuluh Nopember (ITS), Indonesia); Mauridhi Hery Purnomo (Institut of Technology Sepuluh Nopember, Indonesia))

F203 - 1571281913

Support Vector Machine Hyperparameter Optimization for Speech Command Classification Using MFCC Features 529

(Santoso (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Tri Sardjono and Djoko Purwanto (Institut Teknologi Sepuluh Nopember, Indonesia))

F204 - 1571262778

XAI Using LIME in Masking Augmented Fall Detection with Accelerometers and LSTM 535

(Alexander Descayodi Pasca Romadhona Sartono (Universitas Telkom, Indonesia); Aji Gautama Putrada and Ryan Lingga Wicaksono (Telkom University, Indonesia))

F205 - 1571285335

LLM-Assisted Sentiment Analysis for Indonesia's Coretax Policy: A Knowledge Distillation and Human-in-the-Loop Approach 541

(Novialdi Ashari (Universitas Negeri Medan, Indonesia); Ulfah Oktarida Sihalo (Universitas Sumatera Utara, Indonesia); Novi Aulia Sari (Universitas Negeri Yogyakarta, Indonesia))

F206 - 1571280402

A Probabilistic Comparison of Parsimonious and Deep Learning Models for Diurnal Ammonia Prediction in Shrimp Farming 547

(Reynaldo Ted L Peñas II (Ministry of Science and Technology, Philippines & University of the Philippines Diliman, Philippines))

F207 - 1571263107

Cost-Complexity Pruning for Efficient Tomato Plant Health Detection with Random Forest 553

(Esterlin Imanuela Siahaya (Universitas Telkom, Indonesia); Aji Gautama Putrada and Hassan Rizky Putra Saillellah (Telkom University, Indonesia))

G201 - 1571284870

Reliability Assessment of Exhaust Bellows Based on Resonance Characteristics and Failure Correlation in Gas Engine Power Plants 559

(Yuda Lestari and Harus Laksana Guntur (Institut Teknologi Sepuluh Nopember, Indonesia))

G202 - 1571257625

Understanding the Structural Challenges of Energy Autarky in Biomass-Based Cogeneration: A System Dynamics Analysis of Sugar Industry 565

(Arief Sandi Destianto, Erma Suryani and Arif Wibisono (Institut Teknologi Sepuluh Nopember, Indonesia))

G203 - 1571281619

Sustainable DC Power Supply Using High Gain Passive Quadratic-Boost Converter (PQ-BC) with High-Current Low-Voltage Battery Cells 572

(Erpan Sahiri (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Mochamad Ashari (Sepuluh November Institute of Technology, Indonesia); Heri Suryoatmojo (Institut Teknologi Sepuluh Nopember, Indonesia))

G204 - 1571279598

Comparative Evaluation of Grounding Configurations for a 275 kV Standalone Lattice Tower Subjected to Lightning Transients Using EMTP 579

(Roski Renaldo (Institut Teknologi Sepuluh Nopember, Indonesia); Daniar Fahmi (Sepuluh Nopember Institute of Technology, Indonesia); Dedet Riawan (Institut Teknologi Sepuluh Nopember, Indonesia))

G205 - 1571280072

Voltage Stability Enhancement of an Islanded Microgrid Using Static VAR Compensator and Static Synchronous Compensator: A Case Study of Medang Island 585

(Ibnu Shina (Institut Teknologi Sepuluh Nopember, Indonesia); Daniar Fahmi (Sepuluh Nopember Institute of Technology, Indonesia); Ari Santoso (Institut Teknologi Sepuluh Nopember, Indonesia))

G206 - 1571281784

Analysis and Implementation of Adaptive Defense Scheme for Island Operation Stability on the Bangka Subsystem 591

(Muhammad Ikil (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Muhammad Rivai (Institut Teknologi Sepuluh Nopember, Indonesia))

G207 - 1571278931

MCDM Approach with AHP to Obtain the Weighting Factor of Medium Voltage Power Cable Health Index Based on Condition and Profile Factors (Andika Syalom (Institut Teknologi Sepuluh Nopember, Indonesia); I Gusti Ngurah Satriyadi Hernanda (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); Suwito (Institut Teknologi Sepuluh Nopember (ITS), Indonesia)) G208 - 1571274469	597
Improving Reliability of a 20 kV HRG Distribution Feeder Using Directional Ground and VROC Relays (Yuniar Machmud Genda (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Anton Asfani and Dedet Candra Riawan (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia)) H201 - 1571284689	604
Frequency-Dependent Performance of Dual Surface Acoustic Wave Mixing in a Hexagonal Micromixer (Halah Basim Al-Mudhafar (Babylon University, Iraq); Qais Al-Gayem (University of Babylon, Iraq & College of Engineering, Iraq)) H202 - 1571280686	610
Discrimination of Durian Ripeness Using Gas Sensor Array Optimization (Azizah Maulidiya Hasanah (Telkom University Surabaya, Indonesia); Anifatul Faricha, Chaironi Latif and Rifki Dwi Putranto (Telkom University, Indonesia)) H203 - 1571276853	616
Detecting Anak Krakatau Tsunami with Machine Learning: Insights from Marina Jambu Tide Gauge Data (Muhammad Luqman Hakim and Muhammad Rivai (Institut Teknologi Sepuluh Nopember, Indonesia); Iyan E. Mulia (Bandung Institute of Technology, Indonesia); Rahmat Triyono (BMKG, Indonesia); Hanif Andi Nugraha (Universitas Indonesia, Indonesia); Fisilmi Rahman (Saga University, Japan)) H204 - 1571285214	621
An Objective Color Analysis System for Color TV Broadcast Calibration Using Microcontroller-Based Sensing and CIEDE2000 (Jan Cedrick Q. Adajar, Enzo Greg A. Cervantes, Justin Randolph N. Labios, Joules Darren P. Soldevilla and Gerino P Mappatao (De La Salle University, Philippines)) H205 - 1571282103	627
Low-Cost Voltammetric Electronic Tongue for Classification of Rawon Seasoning Formulation Using Machine Learning (Ahmad Athoillah, Muhammad Rivai, Totok Mujiono and Suwito (Institut Teknologi Sepuluh Nopember, Indonesia); Ferina Ayu Pusparani (State University of Malang, Indonesia)) H206 – 1571284820	632
Design and Simulation of Fiber Bragg Grating Based Pressure Sensors for Early Detection of Bridge Settlement and Structural Deformation (Ryan Prasetya Utama (Badan Riset dan Inovasi Nasional, Indonesia); Aditya Inzani (Universitas Indonesia, Indonesia & National Research and Innovation Agency, Indonesia); Yus Natali Suprpto (Telkom University, Indonesia); Catur Apriono (Universitas Indonesia, Indonesia)) H207 – 1571262557	638
Autoencoder for Efficient IPS on the UJIIndoorLoc Dataset Using WKNN and PSO (Zezca Agustin (Universitas Telkom, Indonesia); Aji Gautama Putrada and Ayu Qatrunnada Istiqfarri (Telkom University, Indonesia)) H208 - 1571281691	643
Post-Layout Evaluation of Input Offset Voltage in Differential-Pair OTA Using Moment-Matching (Muhammad Dzaki Roihan Andriansyah (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia); Fajar Budiman (Munich Institute of Robotics and Machine Intelligence, Technische Universität München, Germany & Institut Teknologi Sepuluh Nopember, Indonesia); Ademas Fazri Sunaryo (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia)) I201 - 1571281459	649
Integrated AVO-IFDS Methods for Quadcopter Path Planning and Obstacle Avoidance Under Wind Disturbances (Muhammad Fadhil Wigananto, Trihastuti Agustinah and Imam Arifin (Institut Teknologi Sepuluh Nopember, Indonesia)) I202 - 1571280390	654

Wind Estimation for Fixed-Wing UAV Using Interacting Multiple Model Adaptive Unscented Kalman Filter (Dharma Abiyyu Allam (Insitut Teknologi Sepuluh Nopember, Indonesia); Trihastuti Agustinah and Yurid E. Nugraha (Institut Teknologi Sepuluh Nopember, Indonesia)) I203 - 1571285390	660
Control of Sloshing Dynamics via Gravity Decomposition (Auralius Manurung, Heru Syah Putra and M Darfyma Putra (Telkom University, Indonesia)) I204 – 1571280466	666
Indoor Gas Source Localization Using a Mobile Robot with Stereo Electronic Nose and Ultra-Wideband Navigation (Basry A Sihotang, Muhammad Rivai and Muhammad Attamimi (Institut Teknologi Sepuluh Nopember, Indonesia)) I205 – 1571281529	672
An Adaptive Distance-Velocity Weighted Force Field for Real-Time Obstacle Avoidance in Unmanned Ground Vehicles (Muhammad Aqil Rayhan Majid (Institut Teknologi Sepuluh Nopember Indonesia, Indonesia); Mochammad Sahal and Ari Santoso (Institut Teknologi Sepuluh Nopember, Indonesia)) I206 - 1571281886	678
Vehicle Maintenance Prediction System Based on on-Board Diagnostics and Neural Network (Bara Satria Sakti Raharja, Muhammad Rivai and Muhammad Qomaruz Zaman (Institut Teknologi Sepuluh Nopember, Indonesia)) I107 - 1571280160	684
Fuzzy FMEA for Risk-Based FLISR Reliability Enhancement: Comparison with Conventional RPN and Case Study of PLN UP2D Jawa Barat (Iwan Setiawan (Institut Teknologi Sepuluh Nopember, Indonesia); I Gusti Ngurah Satriyadi Hernanda and Astria Nur Irfansyah (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia)) I108 - 1571267579	690
Hybrid Positioning Method for Quadcopter Indoor/Outdoor Positioning Using Ultra-Wide Band and Global Positioning System (Martin Adytia (Sepuluh Nopember Institute of Technology, Indonesia); Rudy Dikairono and Astria Nur Irfansyah (Institut Teknologi Sepuluh Nopember, Indonesia)) A301 - 1571277416	696
Experimental Analysis of Voltage-Capacity Characteristics for State of Health Evaluation of LFP Battery Cell and Pack (Sucipto Hening and Eka Firmansyah (Universitas Gadjah Mada, Indonesia); Oyas Wahyunggoro (UGM, Indonesia); Rizky Toyibah, Maylani Tiarna Riasmin and Feby Suzetta (PT Century Batteries Indonesia, Indonesia)) A302 - 1571272539	702
Operational Impact of IBT-4 Integration at Cilegon on Reliability and Economic Dispatch in the Banten Power System (I Nengah Sri Dana Merta, Rony Seto Wibowo and Mochammad Sahal (Institut Teknologi Sepuluh Nopember, Indonesia)) A303 - 1571281680	708
Enhancing Transformer Protection Coordination Using IEC 61850 GOOSE-Based Non-Cascade Scheme Under Breaker Failure Conditions (Supriadi Sirait, Margo Pujiantara and Eko Setijadi (Institut Teknologi Sepuluh Nopember, Indonesia)) A304 - 1571281994	714
Long-Term Performance Evaluation of a Commercial AEM Electrolyzer with Intelligent Control and Monitoring System (Wigas Digwijaya (Indonesia National Electricity Company & PLN Research Institute, Indonesia); Casmika Saputra, Ismudiati Puri Handayani and Ekki Kurniawan (Telkom University, Indonesia); Handrea Bernando Tambunan (PLN, Indonesia); Achmad Nurfanani (PT PLN Research Institute, Indonesia)) A305 - 1571279508	720
Study on Placement and Sizing of STATCOM in the Southern Sulawesi Power System to Improve System Stability (Bagus Handoko (Institut Teknologi Sepuluh Nopember, Indonesia & PT. PLN (Persero) Technology	726

<i>and Engineering Division, Indonesia); Muhammad Haidar Syahab (Institut Teknologi Sepuluh Nopember, Indonesia); Trinurkalid Sumarwoto (PT. PLN (Persero), Indonesia); Rony Seto Wibowo and Ronny Mardiyanto (Institut Teknologi Sepuluh Nopember, Indonesia))</i>	
A306 - 1571280293	
Dynamic Dispatch of Power Generation Considering Cost and Transmission Losses: A Case Study of Sulbagsel System, Indonesia	733
<i>(Pinanggih Rahayu (Institut Teknologi Sepuluh Nopember, Indonesia & PT. PLN (Persero), Indonesia); Rony Seto Wibowo and Mochammad Sahal (Institut Teknologi Sepuluh Nopember, Indonesia); Fermi Trafianto (PLN, Indonesia); Retno Dwi Lestari (PT. PLN (Persero), Indonesia))</i>	
A307 - 1571281500	
Analysis of the Application of Single-Pole Auto-Reclosing on 70 kV Transmission Networks Using High Resistance Grounding	738
<i>(Mochamad Ardi Arsuwenda, Rony Seto Wibowo and Mochammad Sahal (Institut Teknologi Sepuluh Nopember, Indonesia))</i>	
A308 - 1571267803	
Frequency Stability Analysis of the Ambon-Seram Interconnection System in 2033 with the Implementation of a SYNDEM-Based Synchronverter	744
<i>(Ivan Rajendra and Adi Soeprijanto (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Ammar Syahid Rabbani, Almerfarras Izadd and Akilla Farri Santoso (PLN Enjiniring, Indonesia))</i>	
B301 - 1571283033	
Security and Assurance Evaluation of RAG-Based AI Assistants in Learning Management Systems: A Pilot Study on Prompt Injection and Data Leakage	750
<i>(Aditya Nur Cahyo (Universitas Muhammadiyah Surakarta, Indonesia); Muhammad Kopravi (Universitas Amikom Yogyakarta, Indonesia); Jan Wantoro (Universitas Muhammadiyah Surakarta, Indonesia))</i>	
B302 - 1571285195	
A Covert Payload Delivery Chain Using Audio LSB Steganography and LOLBins	756
<i>(Maulana Basith Irvany, Muhammad Rafif Irfan and Dyah Ayu Citra Maharani (Politeknik Siber dan Sandi Negara, Indonesia); Amiruddin (Politeknik Siber dan Sandi Negara & Badan Siber dan Sandi Negara, Indonesia); Dimas Febriyan Priambodo (Politeknik Siber dan Sandi Negara, Indonesia); Naufal Hafiz Syahidan (Badan Siber dan Sandi Negara, Indonesia))</i>	
B303 - 1571283902	
Analysis of the ClickFix Social Engineering Technique in Malware Distribution via PowerShell	762
<i>(Crypto Indiaz Wijaya, Alwan Muhammad Fajar and Chandra Andjar Putra (Politeknik Siber dan Sandi Negara, Indonesia); Septia Ulfa Sunaringtyas (National Cyber and Crypto Polytechnic, Indonesia))</i>	
B304 - 1571264121	
Explainable and Robust Malware Detection in Portable Executables Using LightGBM with a Statistical Obfuscation Proxy	768
<i>(Dyah Ayu Citra Maharani, Aurelia Sandra Darmawan, Alwan Muhammad Fajar, Chandra Andjar Putra and Dimas Febriyan Priambodo (Politeknik Siber dan Sandi Negara, Indonesia))</i>	
B305 - 1571281599	
Classifying Multi-Labels of SDGs on Scientific Articles Using Keyword Extraction with Semantic Similarities	774
<i>(Christiant Dimas Renggana, Diana Purwitasari and Rizka Wakhidatus Sholikah (Institut Teknologi Sepuluh Nopember, Indonesia))</i>	
B306 - 1571285120	
Design and Implementation of RISC-V SoC with Memory-Mapped Neural Network on Caravel	780
<i>(Farsya Raisah Fadhillia and Totok Mujiono (Institut Teknologi Sepuluh Nopember, Indonesia); Astria Nur Irfansyah (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia))</i>	
B307 - 1571284764	
Hand Pose Recognition with Deep Learning Based on Edge Computing for DJI Ryze Tello Drone Control	786
<i>(Arief Kurniawan, Ardy Pratama Syahputra and Eko Mulyanto Yuniarno (Institut Teknologi Sepuluh Nopember, Indonesia))</i>	
B308 - 1571281110	
Can Machine Learning Improve Snort's Detection?	792

<i>(Shrinivas Khedkar (VJTI Mumbai, India); Deep Kasodariya and Aditya Yedurkar (Veermata Jijabai Technological Institute, India); Madhav Chandane (Veermata Jijabai Technological Institute (VJTI), India))</i>	
C301 - 1571282083	
Study of CFRP Composite for EMI Shielding and Lightning Protection	798
<i>(Diah Permata (Universitas Lampung, Indonesia); Reza Aditya Rahadi (Lampung University, Indonesia); Tio Dwi Kristian (University of Lampung, Indonesia); Aan Ridho Syaiful Iman (Lampung University, Indonesia))</i>	
C302 - 1571281502	
Time-Frequency Analysis of Acoustic Partial Discharge Signals in a 20 kV Switchgear: A Case Study Using an Acoustic Camera	803
<i>(Gregorius Satrio Kuncoro (Institut Teknologi Sepuluh Nopember, Indonesia); Daniar Fahmi (Sepuluh Nopember Institute of Technology, Indonesia); Hendra Kusuma (Institut Teknologi Sepuluh Nopember, Indonesia))</i>	
C303 - 1571284884	
Solar Photovoltaic Modules Degradation: A Comparison Between Electroluminescence and Infrared Thermal Imaging	809
<i>(Zhang Fengguo (Institute for Advanced Studies, Malaysia); Azimah Omar (Universiti Malaya, Malaysia); Md Rauf Islam Sharker (Institute for Advanced Studies, Malaysia))</i>	
C304 - 1571281023	
Design and Implementation of a Modular AGC System Based on OPC UA and RX3i PLC for TM2500 Gas Turbines at PLTG Suppa 2x25 MW	815
<i>(Wahyudi, Ari Santoso and Adi Soeprijanto (Institut Teknologi Sepuluh Nopember, Indonesia); Husna Putra Wijaya (Co-worker, Indonesia); Agus Wibowo and Dinda Alamsyah (Co-Worker, Indonesia))</i>	
C305 - 1571281671	
Shunt FACTS Devices Sizing for Voltage Profile Improvement in the Southern Sulawesi Baubau Interconnection System	821
<i>(Abdul Hafidh (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Fajar Uman Putra (Institut Teknologi Sepuluh Nopember (ITS), Indonesia); Prasetyono Hari Mukti (Institut Teknologi Sepuluh Nopember, Indonesia))</i>	
C306 - 1571281759	
Study of Disturbance-Dependent Ferroresonance in Single-Phase 150 kV Capacitive Voltage Transformer	827
<i>(Ahmad Anung Probo Kuncoro (Institut Teknologi Sepuluh Nopember, Indonesia); Dimas Anton Asfani and I Gusti Ngurah Satriyadi Hernanda (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia))</i>	
C307 - 1571271484	
Grid Impact Analysis of 100 MWac Solar Power Plant with BESS Integration in the North Sulawesi System	833
<i>(Saifi Sabiq, Mario Dwi Prasetyo, Arif Rahman, Ammar Syahid Rabbani, Fauzan Akbar Sahri and Rayhan Alifa Dewantara (PLN Enjiniring, Indonesia))</i>	
C308 - 1571282041	
Lightning Performance Analysis of a 500kV Overhead Transmission Line Using Electromagnetic Transient Program (EMTP)	839
<i>(Khalil Akbar Manullang and Andika Bagaskara (PT. PLN (Persero), Indonesia))</i>	
D301 - 1571271728	
High Performance Hybrid CNN CBAM Framework for High Sensitivity Heart Disease Classification	844
<i>(Giant Prakoso Amukti Wibowo and Slamet Riyadi (Universitas Muhammadiyah Yogyakarta, Indonesia); Arlina Dewi (Magister of Hospital Administration, Indonesia); Mahendro Prasetyo Kusumo Mahendro Prasetyo (University of Pittsburgh, Indonesia); Muhammad Abdul Haq (Universitas Muhammadiyah Yogyakarta, Indonesia); Imam Riadi (Universitas Ahmad Dahlan, Indonesia))</i>	
D302 - 1571281835	
Low-Cost TinyML for Pneumonia Detection Using Custom AutoKeras Architecture on Low Resolution PneumoniaMNIST Images	850
<i>(Darla Gempita Darris Purba and Disa Fajar Aidha (Universitas Telkom, Indonesia); Auralius Manurung, Husneni Mukhtar and Heru Syah Putra (Telkom University, Indonesia))</i>	
D303 - 1571281890	

Integrating MIAFEx Feature Extraction with Ensemble Learning for Breast Cancer Classification (Muhammad Falah Abdurrohman, Arvin Azmi Sava, Moch.Ghulam Abrari Binuri, Nanik Suciati and Daffa Muhamad Azhar (Institut Teknologi Sepuluh Nopember, Indonesia))	856
D304 - 1571281836	
Data-Centric Oversampling for Imbalanced Multi-Class Acne Lesion Detection: A Comparative Study (Disa Fajar Aidha and Darla Gempita Darris Purba (Universitas Telkom, Indonesia); Heru Syah Putra, Salsabila Aurellia and Husneni Mukhtar (Telkom University, Indonesia); Dessy Triana (University of Bengkulu, Indonesia))	862
D305 - 1571244648	
An Adaptive Segment Selection Framework for Transcranial Doppler Signals: Leveraging Signal Quality Assessment for Hemodynamic Classification (Muhammad Farhan Arya Wicaksono, Satrio Puji Danutirto, Joe Hanzen Goenawan, Imam Mustafa Kamal, Sr and Misbakhul Munir Irfan Subakti (Institut Teknologi Sepuluh Nopember, Indonesia))	868
D306 - 1571244650	
Evaluating Chi-Square-Based Discretization and Ensemble Learning for Patient Care Classification Using Structured Electronic Health Records Data (Anadya Ghina Salsabila, Retno Anjarwati, Imam Mustafa Kamal, Sr and Moch. Nafkhan Alzamzami (Institut Teknologi Sepuluh Nopember, Indonesia))	874
D307 - 1571264625	
Classification of Chronic Obstructive Pulmonary Disease from Exhaled Breath Using a VGG-1D in an Electronic Nose System (Sheva Aulia, Wiwik Anggraeni, Dava Aulia, Muhammad Rivai and Retno A Vinarti (Institut Teknologi Sepuluh Nopember, Indonesia); Annisa Fitria Nur (Universitas Pembangunan Nasional Veteran Jakarta, Indonesia))	880
E301 - 1571281512	
Techno-Economic Analysis of the Advanced Metering Infrastructure Implementation Plan in Electric Power Distribution Systems (Yusuf Irfani, Heri Suryoatmojo and Rudy Dikairono (Institut Teknologi Sepuluh Nopember, Indonesia))	886
E302 - 1571282071	
Multi Criteria Prioritization of Advanced Metering Infrastructure Ecosystem in Urban Areas Based on Fuzzy Analytical Hierarchy Process (Lutfi Nur Rachmad, Heri Suryoatmojo and Achmad Affandi (Institut Teknologi Sepuluh Nopember, Indonesia))	892
E303 - 1571282140	
Securing the Integrity of Postpaid Electricity Billing Processes via MobileNetV2-Based Image Validation (Rendy Alfasyah, Djoko Purwanto and Devy Kuswidiastuti (Institut Teknologi Sepuluh Nopember, Indonesia))	898
E304 - 1571282081	
Implementation of Fuzzy Inference System (FIS) for Electricity Theft Detection Using Advanced Metering Infrastructure (AMI) Data in Smart Grid Network (Ihsan Kurnia Ramadhan, Suwito and Prasetyono Hari Mukti (Institut Teknologi Sepuluh Nopember, Indonesia))	904
E305 - 1571281511	
Back Flashover Analysis on 150 kV Kayu Agung-Gumawang Line Using ATPDraw Simulation for Insulation Coordination Evaluation (Joefrinaldo (Institut Teknologi Sepuluh Nopember, Indonesia); I Made Yulistya Negara (ITS, Indonesia); Daniar Fahmi (Sepuluh Nopember Institute of Technology, Indonesia))	910
E306 - 1571281335	
Design and Experimental Implementation of a Bidirectional SEPIC-Zeta Converter for Fuel Cell Electric Vehicle Battery (Feby Agung Pamuji (Institut Teknologi Sepuluh Nopember, Indonesia); Mochamad Ashari (Sepuluh November Institute of Technology, Indonesia); Muhammad Taufiq (Sepuluh Nopember Institute of Technology, Indonesia); Bambang Sudarmanta (INstitut Teknologi Sepuluh Nopember, Indonesia); Mohammad Khoirul Effendi (Institut Teknologi Sepuluh Nopember, Indonesia); Nurvita Arumsari and Putri Nur Rahayu (Shipbuilding Institute of Polytechnic Surabaya, Indonesia); Ohn Zin Lin (Technical	916

University of Ostrava, Czech Republic))

E307 - 1571281499

Design and Simulation Analysis of Diesel-Battery Hybrid Trains for Intercity Mass Transportation 922
(Yunior Lanang Satrio (*Institut Teknologi Sepuluh Nopember, Indonesia*); Dimas Anton Asfani (*Institut Teknologi Sepuluh Nopember Surabaya, Indonesia*); Devy Kuswidiastuti (*Institut Teknologi Sepuluh Nopember, Indonesia*))

E308 - 1571284847

Techno-Economic Feasibility of a Hybrid PV-BESS-FESS System for Islanded Power Systems: A Case 928
Study of Nusa Penida, Indonesia
(Kadek Ferry Gunawan and Rony Seto Wibowo (*Institut Teknologi Sepuluh Nopember, Indonesia*))

F301 - 1571271854

ECG Arrhythmia Classification Using Kullback-Leibler Divergence Features Derived from Wavelet 934
Packet Transform
(Hinis Lutvia Mardiatu Sarifah (*Universitas Telkom, Indonesia*); Annisa Humairani, Tito Waluyo Purboyo, Dziban Naufal and M Darfyma Putra (*Telkom University, Indonesia*))

F302 - 1571281095

Development of a Visual-Based Medication Packaging Recognition System Supported by Generative 940
AI for the Visually Impaired
(Indri Aulia Ulfa, Hendra Kusuma and Totok Mujiono (*Institut Teknologi Sepuluh Nopember, Indonesia*))

F303 - 1571245989

Hand Gesture Classification for Elderly in Low-Light Conditions Using MSCNN with CLAHE 946
Enhancement
(Nia Umilazah (*Universitas Sjakhyakirti, Indonesia & Universitas Sriwijaya, Indonesia*); Ermatita (*Sriwijaya University & Computer Science Faculty, Indonesia*); Abdiansah (*Universitas Sriwijaya, Indonesia*); Mariana Purba (*Universitas Sjakhyakirti, Indonesia*))

F304 - 1571262778

Federated Learning and Differential Privacy for GRU-Based Fall Detection with Wearable Sensors 952
(Alexander Descayodi Pasca Romadhona Sartono (*Universitas Telkom, Indonesia*); Aji Gautama Putrada and Ryan Lingga Wicaksono (*Telkom University, Indonesia*))

F305 - 1571279054

Implicit Solver for Embedded Real-Time Simulation of Nonlinear ECG Dynamics 958
(Auralius Manurung and Dziban Naufal (*Telkom University, Indonesia*); Lisa Kristiana (*Institut Teknologi Nasional Bandung, Indonesia*))

F306 - 1571281014

Explainable Machine Learning for Type 2 Diabetes Screening: A NHANES-Based Approach Using SHAP 964
Feature Attribution
(Helen Sastypratiwi (*Universitas Tanjungpura, Indonesia & Universiti Malaya, Malaysia*); Teh Ying Wah and Saaidal Razalli Azzuhri (*University of Malaya, Malaysia*))

G301 - 1571270601

Conflict Detection of Functional Requirements Based on Clustering and Rule-Based System with 970
Multi-Agent Escalation
(Andrea Bemantoro Jati, Sarwosri and Diana Purwitasari (*Institut Teknologi Sepuluh Nopember, Indonesia*))

G302 - 1571259921

PET for Personalized Exercise: Protecting Gymnasium Data Privacy with RSA Homomorphic 976
Encryption
(Raditya Wicaksono Prihatnoko (*Universitas Telkom, Indonesia*); Aji Gautama Putrada (*Telkom University, Indonesia*); Khalis Sofi (*Universitas Telkom, Indonesia*))

G303 - 1571282013

Cache Poisoning Attack Detection in Vehicular Named Data Networking Using Threshold-Based 982
Reputation Algorithm
(Zhikya Sekar Lutfi Purnomo, Leanna Vidya Yovita and Istikmal (*Telkom University, Indonesia*))

G304 - 1571263237

Comparative Analysis of Feature Selection in Gradient Boosting Classification for Multiclass IoT 988
Botnet Detection
(Juwari and Tohari Ahmad (*Institut Teknologi Sepuluh Nopember, Indonesia*); Dandy Pramana

Hostiadi (Institut Teknologi dan Bisnis STIKOM Bali, Indonesia); Muhammad Aidiel Rachman Putra (Universitas Gadjah Mada, Indonesia))

G305 - 1571281988

Evaluation of Transformer and Gradient Boosting Models for Indonesian Mental Health Text Classification 994

(Evi Dwi Wahyuni (University of Muhammadiyah Malang, Indonesia & Institut Teknologi Sepuluh Nopember, Indonesia); Wiwik Anggraeni and Reza Fuad Rachmadi (Institut Teknologi Sepuluh Nopember, Indonesia); Mauridhi Hery Purnomo (Institut of Technology Sepuluh Nopember, Indonesia))

G306 - 1571265884

Real-Time DDoS Detection and Monitoring Dashboard with Multi-View Statistical Visualization: An Adaptive Approach for Indonesian Cyber Resilience 1000

(Deni Utama (Universitas Negeri Jakarta, Indonesia); Lipur Sugiyanta (State University of Jakarta, Indonesia); Rauhil Fahmi and Fitrah Izul Falaq (Universitas Negeri Jakarta, Indonesia); Della Novita Sari (University of Nebraska Omaha, USA))

H301 - 1571282072

Classification of Fault Characteristics in Transmission Networks Based on Disturbance Fault Recorder (DFR) Using CNN-LSTM 1006

(Hafizh Tri Januar, Djoko Purwanto and Devy Kuswidiastuti (Institut Teknologi Sepuluh Nopember, Indonesia))

H302 - 1571281549

Optimization of Hybrid Power System Operation in the Sangihe I System Using the Grey Wolf Algorithm 1012

(Husein Zakka Mubarak, Ardyono Priyadi and Ahmad Sirojuddin (Institut Teknologi Sepuluh Nopember, Indonesia))

H303 - 1571281450

Impact of Subsystem Reconfiguration on Reliability and Generation Cost: A Case Study of the Sumatera Power System 1018

(Ziqri Umardi. ST, Ni Ketut Aryani and Ronny Mardiyanto (Institut Teknologi Sepuluh Nopember, Indonesia))

H304 - 1571282034

Power Smoothing Strategy Using Supercapacitor for Fluctuating Load Mitigation in Upstream Oil and Gas Power System 1024

(Henrie Paulinus Manga Lapu and Vita Lystianingrum (Institut Teknologi Sepuluh Nopember, Indonesia); Dedet Candra Riawan.D (Institut Teknologi Sepuluh Nopember (ITS), Indonesia))

H305 - 1571281899

Predicting Potential Customers for Electricity Power Capacity Upgrades Using Gradient Boosting Based on Electricity Consumption Patterns 1030

(Asep Sumpena (Institut Teknologi Sepuluh Nopember, Indonesia); Achmad Choiruddin (Institut Teknologi Sepuluh Nopember Surabaya, Indonesia))

H306 - 1571277304

Health Index Stator Generator Evaluation with Random Forest Algorithm: A Case Study of PLTU Tanjung Awar-Awar 1036

(Mukhlis Nur Afifi (Institut Teknologi Sepuluh Nopember, Indonesia); Daniar Fahmi (Sepuluh Nopember Institute of Technology, Indonesia); Rudy Dikairono (Institut Teknologi Sepuluh Nopember, Indonesia))

H307 - 1571281564

Grid Buffered Synchronization and Load Matched Islanding for Non Dispatchable PV Integration in a Microgrid Testbed 1042

(Farhan Rizqy Governilahnsyah (Gadjah Mada University, Indonesia); Fransisco Danang Wijaya and Yohan Fajar Sidik (Universitas Gadjah Mada, Indonesia))

H308 - 1571272724

Reliability Analysis of 6 IBT Operation in Krian Subsystem Based on N-1 Contingency Using Failure Mode and Effects Analysis (FMEA) Method 1049

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Augmented Reality as Contextual Support in Puzzle-Based Technical Simulation

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Abstract—Technical education increasingly requires environments that enable learners to demonstrate procedural competence rather than merely conceptual understanding. Although augmented reality and serious-game simulations are widely used to enhance visualization and engagement, they are typically designed as instructional media and rarely support observation of user behavior during task execution. This paper proposes a puzzle-based technical simulation framework in which augmented reality is positioned as a contextual support within procedural interaction rather than as a primary learning content. The system integrates rule-based component configuration, optional AR inspection, and interaction log to capture user decision processes during task completion. Implemented as a lightweight mobile-based application, the framework supports realistic procedural simulation while maintaining accessibility and scalability. The proposed approach contributes (1) a procedural simulation framework with contextual AR support, (2) a rule-based interaction model that enables behavioral observation, and (3) a lightweight implementation suitable for scalable deployment. These contributions provide a foundation for future research on simulation-based competency assessment in technical training environments

Index Terms—augmented reality, procedural simulation, rule-based interaction, behavioral observation, interaction logging, mobile interactive systems

I. INTRODUCTION

According to the International Telecommunication Union (ITU), global Internet usage reached 5.4 billion users in 2023, representing approximately 67% of the world's population [1]. This rapid expansion of digital connectivity has significantly increased the dependence of industries and public services on computer and network infrastructures. Labor market analyses further indicate that digital and technical competencies remain among the most demanded skills worldwide. The World Economic Forum reports that technology-related roles, including network specialists and digital infrastructure operators, continue to grow as organizations accelerate digital transformation [2]. Similarly, industry surveys consistently highlight operational computer and network skills as fundamental entry-level requirements in technical and administrative job postings [3].

Despite this growing demand, a critical question remains: how do educational institutions determine whether students are truly ready to perform these tasks in practice? In technical education, passing a course does not necessarily mean that a student is prepared to execute real procedures. Students may

understand the concepts of computer and network systems, yet still struggle to configure devices, interpret their functions, or troubleshoot problems. This reveals a persistent gap between knowledge certification and capability demonstration. When real practice opportunities are limited, what is needed is not merely additional infrastructure, but environments that can simulate technical tasks and reveal how users act when facing realistic problems. Such environments would allow both practice and evaluation of job-relevant competencies in a structured and scalable way.

Simulation technologies provide controlled environments for representing technical procedures without requiring physical infrastructure. Game-based simulations support sequential task execution and decision making, while augmented reality (AR) enhances visualization of technical components and device structures.

Previous studies have demonstrated the potential of AR-based serious games and learning systems for computer and network education. For example, AR has been used to enhance visualization and engagement in networking instruction [4], to support serious-game-based learning design [5], and to structure technical learning interactions through cognitive-level frameworks [6]. More recent studies have shown that puzzle-based immersive learning environments can promote critical thinking, engagement, and problem-solving behavior during task execution [11], [12]. Furthermore, research on 3D programming puzzle games has highlighted the influence of interaction characteristics and task execution strategies on user performance and perceived difficulty [13]. These findings indicate that immersive and interactive technologies can improve user understanding and interaction with technical content while also providing opportunities to observe procedural problem-solving behavior. However, most existing implementations position simulation and AR primarily as instructional tools. Their evaluation mechanisms typically focus on learning outcomes, usability, or motivation, rather than examining how users perform procedures or seek assistance while solving technical problems.

Despite advances in AR-supported learning and serious-game environments, simulation is still rarely used to evaluate procedural competency. Existing approaches mainly emphasize content delivery and engagement, while mechanisms

for observing how users execute technical procedures and seek assistance remain limited. This highlights the need for simulation environments capable of revealing user behavior during problem solving.

In response to this gap, this study proposes a puzzle-based technical simulation framework in which augmented reality is positioned as contextual support rather than primary instructional content. The proposed system enables users to access AR visualizations of technical components during task execution, allowing them to relate simulated procedures to real-world device representations. By structuring AR as optional support within the simulation process, the system aims to provide a lightweight yet informative environment that can be used both for practice and for observing competency-related behavior. This paper focuses on the system design and interaction model of the proposed framework, providing a foundation for future work on behavior-aware technical assessment.

Unlike the authors' previous AJAR system, which focused on AR-based learning delivery and learner engagement, this paper contributes (1) a procedural simulation framework with contextual AR support, (2) a rule-based interaction model for behavioral observation and competency-related analysis, and (3) a lightweight architecture suitable for scalable deployment.

To guide the development of the proposed framework, three research questions are formulated as summarized in Table I.

TABLE I
RESEARCH QUESTIONS AND FRAMEWORK COMPONENTS

RQ	Research Question	Addressed By
RQ1	How can AR be integrated as contextual support within a procedural technical simulation environment?	Contextual AR Module
RQ2	How can user interactions during procedural task execution be captured and recorded?	Interaction Logging Module
RQ3	How can interaction traces support future behavioral analysis and competency assessment?	Behavioral Observation Framework

II. PROPOSED SIMULATION FRAMEWORK

To address the limitations of conventional competency evaluation, this study proposes a simulation-based environment that represents procedural technical tasks while enabling observation of user behavior during task execution. The framework integrates puzzle-based procedural simulation, optional augmented reality (AR) support, and interaction logging within a lightweight architecture. Puzzle activities represent sequential technical procedures, while AR provides contextual assistance for interpreting simulated components. User interactions are recorded to capture both task outcomes and problem-solving processes. The overall architecture of the proposed framework is illustrated in Fig. 3.

Fig. 3 illustrates the integration of the puzzle-based simulation module, AR contextual support, and interaction logging components. Together, these modules provide an environment

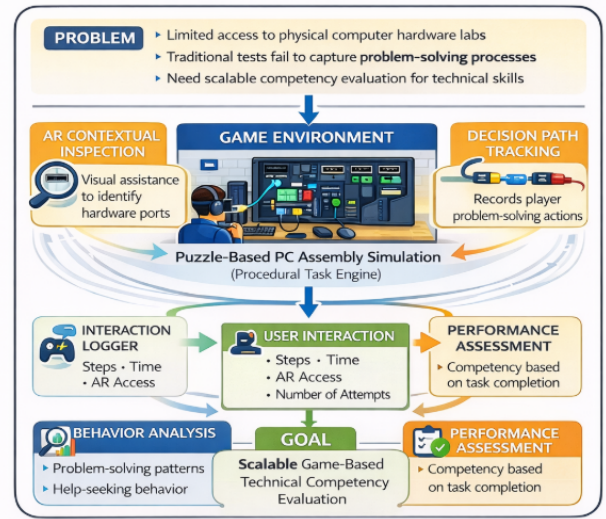


Fig. 1. Proposed simulation framework integrating puzzle simulation, AR support, and behavior logging.

capable of representing procedural tasks while enabling observation of user behavior. Each framework component is described in the following subsections.

A. System Architecture

The proposed framework consists of three primary components: the puzzle-based simulation module, the augmented reality support module, and the interaction logging module. These components operate as an integrated system in which user interactions within the simulation environment trigger visualization support and generate observable behavioral traces.

The puzzle simulation module serves as the core environment where procedural tasks are represented and executed. The augmented reality module functions as contextual assistance that can be activated when users require additional interpretation of simulated components. Meanwhile, the interaction logging module continuously records user actions to capture procedural engagement throughout task execution. Through the integration of these modules, the framework enables both structured task representation and process observation within a single lightweight system architecture.

B. Puzzle-Based Simulation Module

The proposed simulation represents technical tasks as structured puzzle scenarios in which users must complete procedural steps to achieve a functional system configuration. Simulation-based learning environments have been shown to support experiential interaction, skill development, and procedural understanding in technical education [14], [15]. By structuring tasks as puzzles, the system transforms procedural operations into observable interaction sequences, allowing evaluation to focus on how users approach a problem rather than solely on the final result. Recent studies further indicate that puzzle-based and immersive learning environments can

support stepwise reasoning, critical thinking, and problem-solving processes during task execution [11]–[13].

The puzzle environment is implemented in a lightweight two-dimensional interface to ensure accessibility across diverse devices and network conditions. Within each level, users interact with visual representations of technical components and must arrange or configure them according to logical constraints. Incorrect actions do not immediately terminate the session; instead, the system allows retries, enabling the capture of iterative problem-solving behavior.

Through this design, the simulation module produces interaction traces that reflect user strategies, persistence, and decision patterns. Such behavioral traces are increasingly considered valuable indicators of competency in simulation-based assessment environments [7].

C. Augmented Reality Support Module

The augmented reality module provides contextual visualization of technical components appearing in the simulation environment. When users encounter uncertainty regarding the structure, placement, or role of a device, they may activate AR visualization associated with the selected component. The AR interface presents a three-dimensional representation that allows users to inspect the object and better interpret its relation to the simulated configuration.

Unlike instructional AR systems that deliver learning content, the proposed module functions as contextual assistance within the procedural simulation. By providing visual reference only when needed, AR supports interpretation while preserving the task-solving process. This design allows the simulation to remain lightweight while still providing meaningful support for understanding technical components.

D. Interaction Logging Module

A central component of the proposed framework is the interaction logging mechanism, which records user behavior during task execution. Rather than focusing solely on whether a task is completed successfully, the system captures process-related information such as action sequences, retry attempts, time spent on each step, and the activation of AR support. These interaction traces provide observable evidence of how users approach procedural problems within the simulation environment.

Process-oriented data have increasingly been recognized as valuable indicators in digital assessment contexts, as they reveal decision making patterns and problem solving strategies that are not visible from final outcomes alone [10]. By collecting such traces, the framework enables the observation of behavioral characteristics such as persistence, exploration patterns, and dependence on contextual assistance. While the present study focuses on system design and implementation, these logged interactions establish the foundation for future work on behavior-based competency evaluation.

III. SYSTEM DESIGN SCENARIO

To illustrate how the proposed framework operates in practice, this section presents a representative interaction scenario

within the simulation environment. The scenario demonstrates how procedural tasks, contextual AR support, and interaction logging are integrated during user activity, enabling observation of user behavior during task execution.

A. Task Environment and Interface Design

The simulation environment presents a workstation-configuration task in which users assemble a functional computer system by arranging hardware components within a predefined workspace. The interface displays system ports, peripheral devices, and target connection slots, while users determine the correct configuration based on their understanding of device functions and relationships.

To support interpretation without interrupting the problem-solving process, the system provides two optional assistance mechanisms: textual hints and augmented reality visualizations of selected components. These features serve as contextual support rather than instructional guidance, allowing users to remain responsible for procedural decisions.

Fig. 2 illustrates the simulation workspace and available interaction elements.



Fig. 2. Puzzle-based workstation configuration interface with optional AR support.

B. Interaction Procedure

When a simulation level begins, the workspace and available devices are displayed simultaneously. Users may freely explore the interface and begin arranging components according to their interpretation of the system configuration. Each placement action is processed by the simulation rules, but feedback is intentionally minimal to encourage reasoning rather than step-by-step following.

If uncertainty arises regarding a component, users may activate the AR feature to inspect the device in three-dimensional form. The AR visualization provides contextual information about structure, orientation, and connection interfaces without revealing the correct procedural step. Users may repeatedly adjust placements, request assistance, or verify configurations until a valid arrangement is achieved. Once the system detects a functional configuration, the level is marked as complete and progression becomes available.

C. System Response and Validation Logic

The system evaluates each user action through rule-based validation that compares component placement with predefined configuration constraints. Instead of blocking incorrect actions, the simulation allows iterative adjustments so that users can refine their configurations over time. This design enables the capture of interaction patterns that reflect users' reasoning strategies rather than only their final outcomes.

The procedural interaction cycle, including placement attempts, validation checks, optional AR activation, and retry loops, is summarized in Fig. 3.

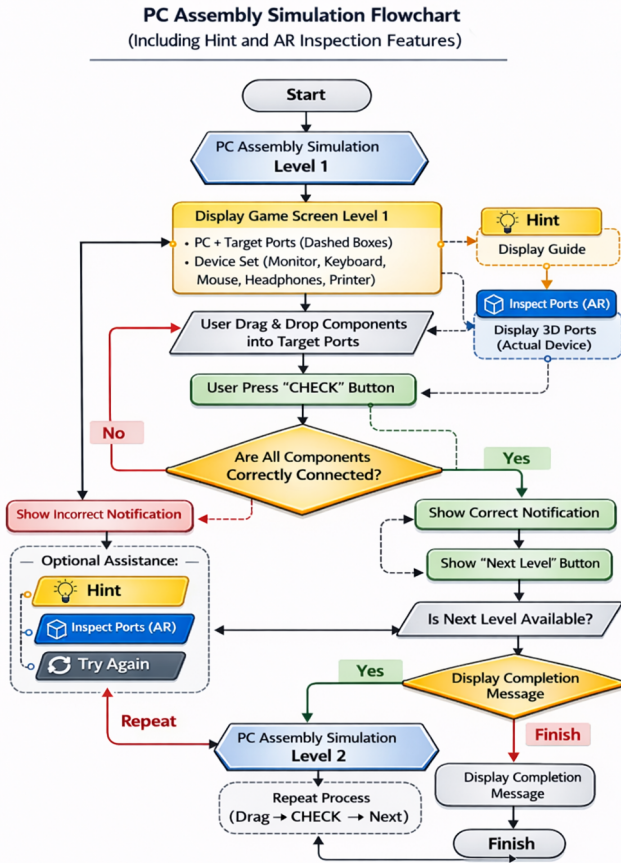


Fig. 3. Interaction flow of the puzzle-based simulation showing validation loops and optional AR assistance.

D. Observability of User Behavior

Throughout the interaction process, the system continuously records user activity, including component placement sequences, retry frequency, timing information, and AR activation events. These traces provide observable indicators of how users approach procedural tasks, revealing patterns such as systematic reasoning, exploratory behavior, or reliance on contextual visualization.

By enabling both procedural interaction and behavioral observation within a lightweight environment, the presented scenario demonstrates how the proposed framework functions not only as a simulation platform but also as a tool for

examining competency-related interaction processes. This capability forms the basis for future work on behavior-informed assessment in technical training contexts.

IV. IMPLEMENTATION DETAILS

To realize the interaction scenario described in Section III, the proposed framework was implemented as a mobile-based system integrating puzzle interaction, contextual augmented reality visualization, and interaction logging. This implementation enables procedural task execution and observable user interaction within a lightweight simulation environment.

A. System Architecture Realization

The implemented system integrates three subsystems: puzzle interaction, contextual AR visualization, and interaction logging. The puzzle module manages component placement, the AR module provides on-demand device inspection, and the logging module records user interactions for behavioral observation. Their functional roles are summarized in Table II.

Together, these components operationalize the interaction model illustrated in Fig. 2 and Fig. 3.

TABLE II
SYSTEM MODULES AND FUNCTIONAL ROLES

Module	Functional Role
Puzzle Interface	Handles drag-and-drop placement of components, triggered by user touch interaction, and produces placement events.
AR Visualization	Displays device structure in 3D view, triggered by AR inspection request, and produces contextual visualization.
Validation Engine	Checks configuration rules, triggered by validation request, and produces functional/non-functional state.
Logging Module	Records user interaction sequences from all interaction events and produces event trace data.

B. Puzzle Interaction Implementation

The workspace interaction described in Section III-A is implemented using a rule-based placement mechanism. Each device is associated with predefined connection constraints that determine valid target ports. Drag-and-drop actions generate placement events that are evaluated by the validation engine.

Incorrect placements remain possible until users explicitly request validation. This design enables iterative problem solving and allows the system to capture procedural reasoning patterns rather than enforcing linear steps, consistent with the interaction loop illustrated in Fig. 3.

C. AR Contextual Support Integration

The AR feature described in Section III-B is implemented as an optional visualization module linked to each hardware component. When activated, the system loads a corresponding three-dimensional model and presents it in an inspection view.

The AR module operates independently from the puzzle logic and does not provide procedural instructions. Instead, it serves as contextual support that helps users interpret device structure and port orientation during task execution. The device

models used in this module were adapted from prior AR-based hardware visualization development, ensuring realistic representation while maintaining implementation efficiency.

D. Interaction Logging Mechanism

To support behavioral observation, the system records interaction events throughout each simulation session. Each event entry includes a timestamp, action type, and associated object identifier, forming a sequential trace of user activity. The recorded event categories and associated behavioral data captured during simulation activities are summarized in Table III.

This logging approach enables the system to capture not only final task outcomes but also the procedural paths taken by users, providing observable indicators of interaction patterns and decision sequences.

TABLE III
RECORDED INTERACTION EVENTS

Event Type	Description	Data Captured
Placement Attempt	User drops component into workspace	Component ID, target slot, timestamp
Validation Check	User requests configuration evaluation	Result flag, timestamp
AR Activation	User inspects component in AR view	Component ID, activation duration
Retry Action	User modifies placement sequence	Sequence index, timestamp
Completion Event	Configuration becomes functional	Total attempts, completion time

E. Implementation Feasibility

The simulation was deployed on mobile devices to ensure portability and accessibility in technical learning environments. The two-dimensional interface design minimizes computational load, while AR visualization is invoked only when requested, allowing stable performance on typical hardware.

These results demonstrate that the procedural interaction scenario described in Section III can be realized within a lightweight system architecture suitable for practical deployment and future scalability.

V. DISCUSSION AND FUTURE WORK

The design considerations of the proposed framework are informed by findings from earlier work involving augmented reality based learning environments. A previous study on the AJAR augmented reality learning application [4] evaluated the system using a three-group experimental design consisting of a game-with-instruction group, a game-only group, and a control group. The evaluation results indicated measurable improvements in learning outcomes for participants who interacted with the game-based environment. The average post-test score increased from 25.05 to 38.03 in the game-with-instruction group and from 24.03 to 33.22 in the game-only group, compared with 22.42 to 27.43 in the control group. Statistical analysis using ANCOVA demonstrated a significant

TABLE IV
AJAR-TO-COMPASS EVOLUTION

AJAR Evidence	Limitation Identified	COMPASS Extension
Game + Instruction gain: +12.98	Learning outcome was measured only from score improvement	Interaction process is captured through task execution logs
Game Only gain: +9.19	User decision process during gameplay was not observed	Action sequence, retry behavior, and task progression are recorded
Control gain: +5.01	Lower gain indicates limited interaction-driven learning support	Puzzle-based simulation is used as the primary activity
ANCOVA result: $F(2, 79) = 4.12$, $p < 0.001$	Significant differences were found, but behavioral causes were not analyzed	Behavioral features are extracted from time, frequency, sequence, exploration, and performance data
AR as primary learning medium	AR usage was not treated as an observable behavioral indicator	AR activation and material access are recorded as optional assistance logs

difference among groups ($F(2,79) = 4.12$, $p < 0.001$). These findings suggest that interactive simulation and game-based environments can positively influence learner engagement and learning performance. Similar outcomes have also been reported in recent simulation-based learning studies, where structured simulation activities and feedback mechanisms contributed to learning outcomes, skill development, and learner engagement [14], [15]. However, the earlier study primarily focused on learning outcomes, while the interaction processes occurring during gameplay were not systematically analyzed.

Table IV shows how the proposed COMPASS framework extends the previous AJAR study from outcome-based evaluation toward process-based behavioral observation. While AJAR demonstrated measurable learning gains in game-based learning conditions, the earlier evaluation did not capture how users interacted with the system during task execution. COMPASS addresses this limitation by recording interaction traces such as action sequences, retry behavior, hint usage, AR activation, material access, completion time, and task performance. These logs are intended to support feature extraction and future behavioral analysis of procedural competency development. Recent studies in serious game analytics and learning analytics have demonstrated that gameplay trace data can be transformed into meaningful indicators of learner performance, progression, and behavioral characteristics through systematic feature extraction and analytical modeling [16], [17]. These findings further support the integration of interaction logging mechanisms within the proposed framework.

The proposed framework demonstrates how augmented reality can be repositioned from a primary instructional medium toward contextual support within a procedural technical simulation environment. By integrating AR as an optional inspection tool rather than a direct source of instructional guidance, the system allows users to rely primarily on their own reasoning during task execution while still providing visual assistance when needed. This design preserves the authenticity of the problem-solving process and enables the observation of

how users interpret technical components during procedural interaction.

The puzzle-based simulation structure further supports the representation of operational technical tasks in an interactive environment. Instead of presenting conceptual exercises, the simulation models procedural activities that require users to arrange and configure system components according to predefined rules. Through this design, the system captures interaction traces that reflect how users approach a problem, including action sequences, retry attempts, response timing, and contextual assistance usage. These interaction traces provide observable evidence of procedural engagement, enabling the simulation environment to function not only as a training platform but also as a source of behavioral process data.

The implementation results demonstrate that such a simulation environment can be realized within a lightweight mobile-based architecture. By combining rule-based procedural simulation, contextual AR visualization, and interaction logging within a unified system, the framework establishes the foundation for capturing rich interaction data during technical task execution. This capability is particularly relevant for competency-oriented training contexts, where understanding how users perform a task can be more informative than evaluating final outcomes alone.

To verify the logging mechanism before user-based evaluation, a simulated interaction-log scenario was generated using ten task-completion sessions. The simulated sessions were designed to represent different interaction patterns, including independent completion, repeated validation attempts, contextual AR assistance usage, and material-access behavior. This validation was used to examine whether the proposed logging structure can capture the intended behavioral indicators before conducting formal user testing.

TABLE V
SIMULATED INTERACTION-LOG SUMMARY FOR LOGGING VALIDATION

Behavioral Indicator	Range	Observed Pattern
Completion time	6–15 min	Varied task efficiency
Retry count	0–5	Repeated attempts indicate uncertainty
Hint usage	0–3	Assistance-seeking behavior
AR activation	0–4	Contextual visualization support
Material access	0–2	Conceptual support request
Validation checks	1–6	Trial-and-error behavior

The simulated interaction-log scenarios summarized in Table V indicate that the proposed framework can capture multiple behavioral indicators associated with procedural task execution.

The simulated sessions exhibited several observable behavioral patterns, including independent completion, assistance-oriented completion, trial-and-error behavior, and exploratory interaction. Although these patterns were derived from simulated sessions rather than formal user evaluation, they demonstrate the feasibility of using interaction logs to distinguish different problem-solving approaches and assistance-seeking behaviors during technical task execution.

Future work will extend the proposed framework toward behavior-informed competency evaluation. Interaction process

data generated during simulation activities will be transformed into computational features representing user decision patterns, including action sequences, retry behavior, response time, and contextual assistance usage. These features will support behavioral modeling for identifying problem-solving strategies and competency-related characteristics during task execution. Consistent with recent studies utilizing interaction traces and process-oriented analytics in serious games for skill assessment and competency evaluation [18], the proposed framework may evolve into a process-based competency assessment environment that integrates procedural simulation, behavioral modeling, and adaptive competency inference within a unified technical training platform.

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