PLANET 4

Practical Learning
of Artificial Intelligence
on the Edge for indusTry 4.0

PLANET4 TAXONOMY

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1 Industry 4.0 challenges and needs

1. **Process Optimization**

1.1 Equipment and Process Efficiency Improvement

1.1.1 Real-time Production and Process Monitoring [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130]

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1.1.6 Commissioning Process [217, 194, 260, 261, 262, 263, 264]

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1.2.1 PPE improvement [277]

1.2.2 Worker Attention and Mental State Monitoring [278, 229, 232, 279, 280]

1.2.3 Workers Navigation and Detection [281, 282, 283]

1.2.4 Remote Operation [228, 159]

1.3 Supply Chain Improvement [284, 273]

1.3.1 Vertical Integration [3, 285, 42, 65, 286, 208, 72, 287, 288, 289, 148, 154, 290]

1.3.2 Horizontal Integration [3, 291, 286, 208, 292, 287, 293, 294, 295, 296, 290]

1.3.3 On-Demand Custom Manufacturing [297, 206, 298, 299, 68, 300, 76, 301, 213, 146, 302]

1.3.4 Warehouse and Inventory Management [303, 304, 305, 306, 307, 281, 3, 308, 4, 309, 5, 310, 175, 208, 76, 181, 311, 312, 313, 6, 220, 11, 314, 315, 147, 316, 317, 318, 222, 126, 319, 320, 272, 321, 205, 322]

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1.3.6 Supply Chain Transparency [328, 329, 330, 305, 307, 4, 331, 332, 310, 333, 334, 293, 335, 336, 320, 337, 321, 33, 34]

1.3.7 Demand Forecasting [338, 204, 339, 340]

1.4 Mass Customization [281, 341, 217, 342, 146, 343, 344, 230, 152, 345, 27, 236, 126, 346, 347, 348, 349, 350]

1.5 Quality Assurance [265, 351, 3, 313, 6, 352, 147, 227, 353, 266, 263, 354, 355, 356, 30, 167, 357, 358, 48, 359, 49, 341, 360, 361, 362, 363, 173, 364, 61, 365, 366, 71, 367, 179, 333, 368, 369, 370, 255, 371, 372, 117, 192, 373, 210, 111, 118, 116, 374, 375, 335, 196, 198, 336, 376, 126, 272, 377, 204, 276]

1.6 Sustainable Industrial Practices [378, 379, 268, 380, 362, 60, 381, 382, 67, 85, 211, 383, 384, 196, 320, 290, 284, 10, 385, 15, 386, 266, 387, 388, 389, 390, 33, 34]

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1.8 Knowledge Management [413, 414, 129]

2. **Product Innovation**

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2.2 Usability Improvement [418, 416, 419, 420]

2.3 Smart Products [421, 422, 209, 423]

2.4 Components Reduction and Cost Optimization [424, 425, 3, 362, 381, 5, 136, 6, 417, 426, 427, 346, 428, 290, 429]

2.5 After-Sales Service [281, 276]

2 Industry 4.0 enabling technologies

1. **Big Data** [193]

1.1 Big Data Frameworks

- Apache Hadoop [357, 170, 308, 293, 210, 92, 188, 36]

1.2 Data Sources/Ingestion

1.2.1 Streaming and Messaging

- Apache Kafka [357, 71, 182, 293, 91, 426, 16, 29]
- Apache Flume [293]

1.2.2 Orchestration and Pipelines

- Talend Data Fabric [293]

1.2.3 Query/Data Flow

- Apache Drill [293]
- Presto [293]
- Impala [293]

1.3 Data Storage

1.3.1 Databases [131, 328, 2, 304, 307, 3, 60, 175, 176, 135, 415, 136]

1.3.1.1 Relational Databases [45, 430, 342, 66, 256, 97, 36]

- Microsoft SQL Server [308]
- MySQL DB [382, 179, 188, 314, 315, 151, 154, 235]
- MariaDB [188]
- PostgreSQL [137, 11, 161]
- SQLite3 [97, 387]
- NewSQL DB [357]
  - CrateDB [184]

1.3.1.2 NoSQL Databases [297, 206, 357, 170, 66, 245, 210, 90, 92, 256]

- Document databases
  - MongoDB [430, 426, 19, 150, 31, 36]
  - CouchDB [71]
- Time Series Databases (TSDBs) [297, 206, 302, 131, 328, 425, 329, 431, 132, 134, 1, 351, 3, 176, 177, 178, 135, 282, 136, 313, 6]

- Apache Druid [357]
- influxDB [432, 254, 16, 19]

- Column-Oriented Databases
  - Apache Cassandra [182]

1.3.2 Data Warehouses [265, 133, 208, 71]

- Apache Hive [170, 293]

1.4 Data Analytics [297, 206, 424, 302, 131, 328, 425, 329, 431, 132, 2, 306, 307, 281, 3, 4, 268, 175, 71, 135, 110, 113, 116, 193, 195, 126, 121, 197, 290, 284, 200, 273, 128, 214]

1.4.1 Unified Data Analytics Engines

- Apache Spark [357, 170, 182, 293, 184, 188, 426]

1.4.2 Unified stream-processing and batch-processing frameworks

- Apache Flink [184]
- Apache Storm [71]

1.4.3 Business Intelligence Tools [302, 2, 3, 4, 433, 5, 175]

- Microsoft PowerBI [133, 293, 314, 315, 148]
- IBM SPSS Statistics [10]
- QlikView/Qlik Sense [434]

1.4.4 Data Visualization Tools and Platforms [297, 206, 302, 131, 328, 425, 329, 431, 132, 133, 351, 2, 304, 305, 281, 3, 4, 135, 418, 9, 11, 15, 150, 160, 162, 36, 167, 41, 357, 46, 379, 171, 268, 380, 58, 60, 342, 382, 175, 71, 422, 179, 77, 245, 254, 188, 99, 115, 407, 121, 123, 127, 275, 340]

- Bokeh [62, 407]
- Wiz [30]
- Tableau [357, 293]
- Freeboard dashboard [45]
- Ubidots platform [31, 32]
- Kibana [117, 25, 29]
- Grafana [184, 16, 19]

1.4.5 Logging and Monitoring

- ElasticSearch,Logstash [413, 11, 29]

1.4.6 Spreadsheet Applications

- PowerPivot [308]

1.4.7 Data Mining [134, 351, 361, 366, 176, 71, 182, 136, 99, 435, 191]

- Python [424, 134, 148, 231, 154, 235, 239, 36, 37, 436, 167, 380, 62, 368, 249, 251, 254, 91, 97, 106, 108, 407, 437, 192, 412]
- MATLAB [134, 438, 207, 324, 92, 189, 191, 372, 137, 226, 386, 24, 439, 263, 390]
- R Programming [71, 91]

1.4.8 Process Mining [176, 7, 8]

2. AI [135, 282, 211]

2.1 Machine Learning [297, 329, 431, 132, 265, 1, 277, 3, 436, 357, 172, 366, 418, 293, 313, 6, 188, 221, 116, 193, 194, 119, 338, 126, 213, 121, 122, 124, 196, 197, 198, 376, 199, 284, 272, 128, 204, 205, 426, 153, 234, 159]

2.1.1 Supervised Learning

2.1.1.1 Regression

- Linear Regression [425, 166, 364, 207, 176, 10, 352, 36]
- Polynomial Regression [166, 167]
- Support Vector Regression (SVR) [184, 364]
- Gaussian process regression (GPR) [207, 91, 118]

- Decision Tree Regression [351, 176, 182]
- Lasso Regression [180]
- Loess [189, 143]
- Bayesian Linear Regression (BLR) [176]

2.1.1.2 Classification

- K Nearest Neighbour (KNN)/Case-Based Reasoning (CBR) [425, 351, 167, 168, 440, 413, 360, 64, 181, 248, 99, 435, 142, 161, 215, 355]
- Logistic Regression [168, 176, 248, 144]
- Decision Tree Classifier (DTC) [208, 182, 248, 99, 144]
- Support Vector Machine (SVM) [43, 169, 440, 360, 178, 248, 441, 93, 99, 118, 157, 161, 442]
- Gaussian Naive Bayes Classifier [99, 144]
- Gaussian Processes Classifier [362, 371]

2.1.1.3 Ensemble Methods

- Bagging
  - Random Forest [425, 167, 43, 169, 440, 176, 368, 248, 441, 91, 99, 435, 144, 161, 162, 163]
  - Bagged Decision Trees [441]
  - Decision Jungle (DJ) [176]
- Boosting
  - AdaBoost [99, 163]
  - XGBoost [425, 441, 163]
  - Gradient Boosted Decision Trees [176, 226]
- Extreme Learning [443]

2.1.2 Unsupervised Learning

2.1.2.1 Data Clustering

- K-means clustering [167, 440, 366, 182, 185, 189, 157]
- Bisecting K-Means [182]
- Fuzzy C-means clustering [372]
- Gaussian Mixture Models [182, 118]
- Hidden Markov Model (HMM) [166]

2.1.2.2 Dimensionality Reduction

- Principal Component Analysis (PCA) [56, 366, 435, 116, 157]
- Oversampling PCA [177]
- Piecewise Aggregate Approximation (PAA) [167]
- Adaptive Piecewise Constant Approximation (APCA) [167]
- Quadratic Discriminant Analysis (QDA) [435]
- Forward Selection Component Analysis (FSCA) [177]

2.1.2.3 Anomaly Detection [182, 313]

- One-class SVM (OCSVM) [64, 157]
- Isolation Forest [177, 157]
- Local Outlier Factor (LOF) [177, 157]

2.1.3 Deep Learning [424, 329, 132, 1, 369, 11, 340]

2.1.3.1 Discriminative (Supervised)

- Deep Neural Network (DNN) [299, 85]
  - Convolutional Neural Network (CNN) [436, 360, 366, 177, 85, 210, 184, 370, 97, 435, 444, 109, 118, 137, 22, 283, 412, 350]
    - U-Net [192]
    - PointNet [22]
    - AlexNet [97]

        * VGGNet [367, 248]
        * GoogleNet / Inception [249, 396]
        * ResNets [413, 360, 367, 97, 22, 355]
        * SqueezeNet [97]
        * Yolo v3 [360, 26]
        * Region-based Convolutional Neural Network (R-CNN) [360]
        * DenseNet [367]
        * Y-Net [107]
    - Recurrent Neural Network (RNN) [436, 366, 435, 118]
      - Long short-term memory (LSTM) [425, 43, 52, 85, 184, 112, 350]
      - Gated Recurrent Unit (GRU) [85]
    - Binary Neural Networks (BNN)
      - Hybrid Binary Neural Network (HBN) [437]

  2.1.3.2 Generative (Unsupervised)
    - Generative Adversarial Network (GAN) [438, 366]
    - Self-Organizing Map (SOM)/Kohonen Map [435]
    - Autoencoder (AE) [173, 64, 366]
      - Hybrid Binary AutoEncoder (HBAE) [437]
      - Feed Forward Autoencoder (FF-AE) [157]
      - Siamese Autoencoder [157]
      - Convolutional Siamese Autoencoder (CNN-SAE) [157]
      - Convolutional Autoencoder (CAE) [173]
      - Sparse Autoencoder [443]
      - Deep Belief Network (DBN) [366, 435]
    - Restricted Boltzmann Machine (RBM) [366]

  2.1.3.3 Hybrid
    - Several Discriminative Models
      - CNN + LSTM [354]
      - CNN + GRU [85]

2.1.4 Transfer Learning [52, 177, 249, 371, 355]

2.1.5 Reinforcement Learning [55, 212]

2.1.5.1 Model-Free RL
  - Policy Optimization
    - State-Action-Reward-State-Action (SARSA) [250]
    - Learning Automata [255]
  - Q-learning [438, 250, 255]

2.1.5.2 Inverse Reinforcement Learning (IRL) [445]

2.1.6 Deep Reinforcement Learning [438, 354]
  - Deep Q Networks (DQN) [366, 250, 446, 445, 419]
  - Multi-Agent Deep Deterministic Policy Gradient (MADDPG) [446]

2.1.7 Semi-Supervised Learning [134, 182]
  - Active Learning [181, 371]

2.1.8 Federated learning [444]

2.2 Computer Vision [424, 329, 1, 9, 236, 358, 216, 341, 363, 177, 221, 373, 283, 336, 376, 272, 275, 412]
  - Open CV [38, 248, 210, 192, 226, 26, 235, 237, 355, 239]
  - Tesseract OCR Engine [38]

2.3 Natural Language Processing, Natural Language Generation [115]

2.4 Intelligent Agents and Multiagent Systems [73, 221]

- AOS JACK [234]
- JADE (Java AgentDevelopment Framework) [441, 251, 212]

2.5 Soft Computing

2.5.1 Fuzzy Set Theory [369, 372]

- Adaptive-Neuro-Fuzzy Inference System [352, 12]
- Fuzzy Formal Concept Analysis (FCA) [183]
- Fuzzy Control [118, 141]
- Fuzzy Cognitive Maps [142, 143]

2.5.2 Neurocomputing

- Artificial Neural Networks (ANN) [206, 134, 351, 358, 169, 52, 309, 361, 447, 176, 180, 368, 249, 369, 441, 99, 435, 191, 372, 118, 139, 352, 426, 157, 442, 349]
- Time Delay Neural Network (TDNN) [43]

2.5.3 Optimization Techniques

- Meta-heuristic approaches
  - Evolutionary Computation [426]
    - Genetic Algorithms [381, 209, 89, 96, 295, 118, 296, 140, 24, 388]
    - Differential Evolution (DE) [91, 442]
  - Trajectory-based Algorithms
    - Simulated annealing [91]
  - Nature Inspired Algorithms [118]
    - Fish Swarm Optimization Algorithm [139]
    - Water Cycle Algorithm (WCA) [139]
    - Grey Wolf Optimizer (GWO) [139, 142, 143]
    - Particle Swarm Optimization (PSO) [297, 143]
    - Artificial Bee Colony (ABC) [143]
    - Simplified Swarm Optimization (SSO) [296]
- Quasi-Newton Methods (QNMs)
  - L-BFGSB [91]

2.5.4 Probabilistic Reasoning (PR)

- Bayesian Networks (BN) [99, 118]

3. **Cloud Computing** [277, 388, 125, 126, 290, 284, 200, 202, 275, 276, 214]

3.1 Infrastructure as a Service (IaaS) [11]

3.1.1 Cloud Data Storage and Computing [297, 206, 424, 302, 131, 328, 425, 329, 431, 1, 2, 304, 305, 306, 3, 37, 39, 378, 45, 430, 299, 379, 171, 380, 58, 381, 382, 63, 175, 71, 324, 219, 76, 78, 135, 79, 245, 246, 311, 313, 6, 90, 256, 295, 109, 139, 314, 145, 343, 344, 150, 266, 263, 235, 301, 195, 161, 165, 423, 33]

- Firebase Realtime Database [171]
- AWS S3 [214]
- Microsoft Azure Storage [132]
- AWS RDS [71]
- AWS EC2 [254, 13, 71]

3.1.2 Virtual Machines [150]

3.2 Platform as a Service (PaaS)

3.2.1 Device Management [328, 307, 281, 3, 4, 433, 5, 175, 135, 313, 6]

- Zerynth Device Manager [2, 304, 305]
- Azure IOT Hub [132, 265, 133, 330, 148, 19, 353]

- WinCC OA IOT OPA [432]
- Live Objects [11]

3.2.2 Operating System
- Siemens MindSphere [118]

3.3 Software as a Service (SaaS) [11, 340]

3.3.1 Media Streaming Software Platforms [409]
- Wowza [145]

3.3.2 Website Building
- Hostinger [314, 315]

3.3.3 IoT Analytics Software and Platforms [128]
- ThingSpeak [55]
- ThingWorx [155, 198]
- AllThingsTalk [410]

3.4 Infrastructure as Code (IaC)

3.4.1 Provisioning Tools
- Terraform [448]

3.5 Container Technology (Container as a Service) [306, 39, 242, 246, 106]

3.5.1 Containerization Platform
- Docker [368, 182, 91, 188, 288, 145, 148, 35]

3.5.2 Container Orchestration
- Kubernetes [91, 288]

3.6 Backend as a service (BaaS)
- Firebase Cloud Messaging [151]

3.7 Serverless Programming [131, 306, 307]
- Azure functions [132, 133]
- Apache Openwhisk [29]

3.8 Edge Computing [431, 277, 3, 37, 39, 379, 4, 433, 65, 71, 78, 432, 96, 188, 417, 109, 446, 445, 373, 198, 272, 296, 71, 153, 154, 212, 159, 160, 161, 29]
- AWS green grass [195]
- Azure Edge IoT [132, 265, 133]
- Multi-access edge computing (MEC) [449]
- HARTING MICA WSN 2.0 [353]

3.9 Fog Computing [417, 296, 159]
- Transport Layer (Uploading pre-processed data and secured data to cloud) [288, 289, 71]
- Security Layer (Encryption/Decryption, privacy and integrity measures) [67, 68, 288, 289]
- Temporary Storage Layer (Data distribution,replication and de-duplication) [288, 289, 13]
- Processing Layer (Data analysis, Data Filtering, Machine Learning, Rules Engines, Cognition) [144, 288, 385, 289, 71]
- Monitoring Layer (Monitoring of power, resource, activities, service and response) [288]
- Physical and Virtualization Layer (Network of virtual sensors and Things) [209]
  - Hypervisor Technology for embedded systems
    - PikeOS [289]
    - ACRN [289]
    - Xen [289]

4. **IoT and IoE**

4.1 Industrial IoT [279, 34, 450, 451, 402, 63, 438, 286, 67, 174, 332, 269, 366, 219, 75, 76, 77, 242, 244, 79, 81, 247, 452, 311, 82, 334, 86, 252, 90, 254, 186, 94, 98, 104, 107, 108, 110, 211, 113, 117, 118, 453, 383, 258, 419, 119, 120, 213, 121, 123, 124, 125, 199, 319, 126, 290, 284, 273, 129, 214]

4.1.1 Industrial Communication Protocols [302, 131, 328, 431, 134, 2, 304, 305, 6, 139, 140, 42, 209, 454, 83, 455, 103, 106]

- Point-to-point communication Protocols (IO-Link) [271, 203]
- Ethernet Protocols (EtherNet/IP,ProfiNET,Modbus,OPC,OPC UA, EtherCAT,MTConnect,Beckhoff ADS protocol) [133, 137, 226, 385, 289, 13, 148, 386, 233, 23, 266, 158, 456, 261, 262, 26, 28, 264, 239, 326, 163, 29, 442, 390, 423, 31, 35, 37, 38, 39, 378, 457, 285, 41, 45, 430, 47, 48, 51, 217, 60, 342, 458, 447, 63, 438, 69, 92, 114, 116, 453, 271, 198]
- Fieldbus Protocols (Profibus DP,Modbus RTU, GSK-Link communication protocol) [3, 54, 226, 241]
- Wireless Protocols (WirelessHART,WIA-FA,WIA-PA, IO-Link Wireless,ISA 100.11a) [281, 3, 40, 433, 64, 300, 70, 83, 100, 279, 289, 146, 32]

4.1.2 Industrial (IoT) Gateways and Data Acquisition Devices [37, 39, 357, 380, 58, 451, 64, 244, 259, 375, 200, 12, 459, 25, 162, 241]

4.1.3 Software Data Adapters

- Apache PLC4X [35]
- Eclipse Hono [16]

4.2 Physical Devices and Controllers

4.2.1 Embedded Computing [48, 207, 422, 78, 244, 245, 82, 86, 251, 90, 254]

4.2.1.1 Microcontroller programming and RTOS [424, 302, 131, 328, 431, 277, 306, 3, 433, 5, 154]

- Arduino [171, 51, 55, 59, 73, 453, 192, 410, 139, 12, 20, 233, 155, 237, 240]
- STM32 [134, 430, 282, 108, 437, 195, 271, 283]
- ESP32 [59]
- FPGA [101, 105, 153]
- MSP430 microcontroller [64]

4.2.1.2 Microprocessor programming and embedded Linux [424, 302, 131, 328, 431, 2, 304, 305, 3, 40, 4, 135]

- RaspberryPi [41, 45, 430, 46, 59, 73, 244, 251, 441, 254, 92, 453, 437, 460, 71, 459, 19, 231, 233, 155, 234, 161, 423, 32, 35]
- LattePanda [24]
- Beagle Bone Blue (BBBlue) [235]

4.2.2 Sensors (hardware) [424, 302, 131, 328, 431, 265, 134, 277, 304, 306, 3, 40, 46, 48, 379, 50, 4, 433, 5, 61, 64, 178, 422, 418, 313, 6, 211, 113, 117, 118, 259, 195, 121, 122, 198, 336, 128, 275, 276, 225, 71, 228, 22, 235, 212, 28, 161, 240]

- Kinect Sensor [278, 237, 267, 179]
- Leap Motion [43, 9, 427]
- RealSense camera sensor [43]
- Ultrasonic sensors [52, 203]
- SmartMat Digital Scale [319]

4.3 Signal Processing [302, 131, 134, 304, 306, 281, 3, 166, 421, 49, 379, 53, 4, 433, 5, 61, 178, 245, 6, 187, 190, 116, 192, 153, 240, 326, 164, 443]

- Software Defined Radio (SDR) [39]
- Blind Source Separation (BSS) [107]

4.4 Connectivity [424, 302, 134, 2, 304, 305, 3, 5, 135, 415, 313, 6, 218, 257]

4.4.1 Radio Communication Technologies

4.4.1.1 Cellular Communications

- LTE/GSM/4G/5G [131, 328, 431, 1, 306, 307, 281, 3, 4, 433, 289, 148, 159, 356, 39, 40, 47, 461, 50, 438, 65, 68, 300, 324, 72, 243, 253, 89, 92, 220, 417, 105, 419, 196]
  - Multimedia Broadcast Multicast Service (eMBMS) [449]
  - Group Communication System Enablers (GCSE) [449]
- Wi-Fi, WLAN (wireless local area network) [44, 46, 55, 59, 451, 323, 324, 422, 83, 211, 114, 117, 383, 462, 419, 195, 271, 320, 410, 337, 226]

4.4.1.2 Short-range wireless

- RFID/NFC [131, 328, 277, 291, 40, 44, 48, 217, 342, 323, 175, 208, 422, 73, 80, 83, 312, 184, 95, 98, 110, 211, 374, 195, 271, 336, 320, 337, 321, 347, 348, 314, 315, 146, 18, 234, 26, 212, 264, 326, 390, 443, 423, 33, 34]
- Bluetooth/Bluetooth Low Energy [277, 307, 281, 40, 44, 430, 48, 4, 323, 422, 78, 83, 462, 195, 271, 320, 11, 316, 33]
- ZigBee [378, 40, 44, 430, 50, 451, 64, 323, 422, 83, 212, 238, 326]
- 6LoWPAN [50, 195]
- Ultra-wideband (UWB) [277, 40, 44, 323, 83, 11, 318]

4.4.1.3 Long-range wireless

- LPWAN (Low power wide area network) [307, 4, 438]
  - LoRaWan [277, 3, 59, 438, 244, 83, 87, 102, 320, 240, 165]
  - MIoTy [207]
  - LTE-M [438]
  - NB-IoT [438, 320]

4.4.2 Optical Communication Technologies [57]

4.4.3 IoT Messaging Protocols

- Message Queuing Telemetry Transport (MQTT) [11, 289, 13, 148, 19, 231, 353, 22, 233, 25, 161, 389, 423, 241, 35, 37, 45, 46, 422, 179, 77, 368, 249, 254, 92, 460, 198, 320]
- Advanced Message Queuing Protocol (AMQP) [382, 16]

4.4.4 Application Programming Interfaces and Programming Tools

- REST API and Webhook [131, 328, 329, 431, 133, 1, 307, 37, 45, 310, 71, 179, 294, 188, 109, 18, 25]
- FIWARE NGSI API [184]
- Node-Red [422, 73, 179, 242, 244, 209, 368, 256, 187, 188, 221, 19, 387, 389, 31, 35]

4.4.5 Real-time Web Frameworks

- Socket.io [41, 139]

4.5 IoE (Internet of Everything) [463]

5. **Digital Twins** [139, 140, 24, 159, 390, 378, 359, 268, 362, 60, 401, 286, 365, 181, 287, 246, 249, 84, 111, 327, 118, 194, 126, 260, 201, 339, 130]

5.1 Computer-aided design (CAD) Software

- Dassault Catia CAD suite [232, 266, 263, 28]
- Dassault SystÃÍmesâĂŹ SolidWorks [266, 234]
- Siemens NX [156, 234, 264]

5.2 Finite Element Analysis (FEA) Software

- Xcos [158]
- CREO Simulate [155, 266]

5.3 Simulation software [327, 118]

- SimulationX [157]
- XcelgoâĂŹs Experior [439, 27]

- Tecnomatix Plant Simulation [44, 217, 23, 262, 26, 279, 264]
- FlexSim [387]
- SimPy [25]
- SIMIT simulation platform [264]
- Emulate3D [23]
- FastSuite [264]
- CIROS Studio [386]
- AutoMod [23]
- Anylogic Simulation [261]
- RF :: Suite [264]
- S7-PLCSIM Advanced [262, 264]
- Automation Studio [28]
- OpenSimulator [25]
- Dassault Dymola [232]
- DynSOx [14]
- ClearView Ammonia [15]
- COMSOL [24]
- MSC ADAMS [24]
- Ansys [24]

5.4 DTs management and Orchestration Framework

- Eclipse Ditto [16]

5.5 Digital Twin Data Modelling

- AutomationML [249, 233, 266, 456, 163]

5.6 Virtual Process Controllers (VPC) [258]

6. **Industrial Robotics** [1, 325, 226, 228, 229, 231, 235, 212, 236, 354, 237, 238, 28, 355, 240, 43, 216, 208, 248, 249, 221, 222, 121, 223, 224, 126, 126, 274, 377, 225]

6.1 Offline Robot Programming and Simulation [327, 118]

- ABB RobotStudio [221, 262, 264]
- Roboguide [264]
- Polyscope software [27]
- KUKASim [264]
- Delmia V5 Robotics [264]
- URSim [27]
- ARIA programming package [226]

6.2 Middleware

- ROS (Robot Operating System) [37, 228, 229, 318, 236, 159]

7. **Augmented Reality (AR) and Virtual Reality (VR)**

7.1 Virtual Reality [1, 394, 262, 401, 403, 179, 209, 404, 405, 256, 408]

7.1.1 VR glasses

- Oculus Rift HMD [9, 396, 427]
- HTC Vive [397]

7.2 Augmented Reality [329, 343, 392, 212, 217, 401, 402, 179, 270, 121, 408, 126, 322, 276, 411]

7.2.1 AR glasses

- Microsoft HoloLens [9, 147, 391, 227, 148, 149, 228, 229, 344, 21, 151, 395, 353, 22, 412]
- Vuzix Smart Glasses [227, 316]

- Magic Leap [391]
- Glass-up F4 [20]
- LindeGO smart glasses [394]
- Epson Moverio BT-35E [317]
- Meta 2 AR glasses [231]

7.2.2 AR Software Development Kits

- Soldamatic Simulator [9, 394]
- HoloToolkit (HTK) [147, 344]
- Google Project Tango Development Kit [17]
- ARKit framework [17, 18]
- Vuforia Engine [401, 17, 227, 229, 150, 230, 410, 412]
- Pixyz Software [227]
- ARCore [393, 318, 399]
- Wikitude Studio [19]
- Maxst [317]
- EasyAR [317]
- Mixed Reality Toolkit (MRTK) [395]

7.3 AR and VR Software development, Platforms and Technologies [414, 127, 409, 129]

- Unity [147, 391, 17, 227, 393, 228, 229, 344, 150, 230, 151, 395, 231, 353, 396, 397, 427, 398, 232, 233, 262, 263, 399, 400, 401, 406, 410, 412]
- Blender [228, 262]
- Motion Capture (MoCap) [267, 278, 392, 280]
- WebXR [9]

8. **Additive manufacturing** [298, 173, 207, 21, 236, 121, 346, 428, 290, 429, 350]

8.1 3D Printers

- DR10 [152]
- Craftbot plus [345]

8.2 3D Printing Technologies

- Fused Deposition Modeling (FDM) [420]
- Selective Laser Sintering (SLS) [420]
- Selective Laser Melting (SLM) [410]
- Polyjet Modeling (PJM) [420]
- Fused Filament Fabrication [410, 349]

9. **Cybersecurity Technologies** [459, 456, 443, 83, 462, 464, 126]

9.1 Security Virtualization

9.1.1 Virtual Machine Monitor (VMM) [452]

9.2 Data Protection

9.2.1 Secure Communication Protocols [453]

- MACsec [457, 454]

9.2.2 Key Management System (KMS) [430]

9.2.3 Public Key Infrastructure (PKI) [39, 368]

9.2.4 Encryption [39, 457, 430, 451, 452, 441, 279, 150, 409]

9.2.5 Tokenization [451]

9.2.6 Blockchain [305, 291, 331, 332, 310, 74, 292, 333, 334, 88, 444, 465, 335, 466, 33, 34, 450]

- Hyperledger Fabric [330, 467]
- Ethereum virtual machine [330, 466, 163]

9.3 Identity and Access Management

9.3.1 Protocols

- Lightweight Directory Access Protocol (LDAP) [460]

9.3.2 User Management

- Passwords [452, 453, 459]

9.3.3 Authentication [39, 457, 451, 453, 150]

9.3.4 Authorization [39, 457, 451]

9.4 Security Operations

9.4.1 Change Management

- Asset Management [455]

9.4.2 Threat Detection and Analysis

- Threat Intelligence
  - Honeypot Networks [430]
- Advanced Malware Detection [452]

9.5 Foundational Security

9.5.1 Network Security

- Firewall [457, 453]
  - Port Knocking Method [459]
- Intrusion Detection Systems/Intrusion Prevention Systems (IDS/IPS) [430, 440, 451, 458, 468]
- Network Access Control [451, 452, 455]
- Virtual Private Networks (VPN) [451, 150, 122]
- DDoS Mitigation [457, 451]

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