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# 1 Department Mapping Table - Vision-Based Pick and Place System

## 1.1 Overview

This document provides a **comprehensive cross-departmental mapping** of concepts, modules, specifications, testing, observability, and logging for the vision-based pick-and-place robotic system.

## 1.2 1. Core Concepts by Department

### 1.2.1 1.1 Mechanical Department

| **Concept** | **Description** | **Application** |
| --- | --- | --- |
| Robot Kinematics | D-H parameters, link geometry | Workspace analysis, URDF modeling |
| Rigid Body Dynamics | M(q)q̈ + C(q,q̇)q̇ + G(q) = τ | Motion simulation, control design |
| End-Effector Design | Gripper mechanisms (parallel jaw, suction) | Grasp force, object handling |
| Transmission Systems | Gears, harmonic drives, belts | Torque amplification, backlash |
| Structural Analysis | FEA, vibration modes, stiffness | Minimize oscillations, ensure safety |
| Material Selection | Aluminum, steel, composites | Weight vs strength trade-offs |
| CAD Modeling | SolidWorks, CATIA, Fusion 360 | 3D design, assembly validation |

### 1.2.2 1.2 Electrical Department

| **Concept** | **Description** | **Application** |
| --- | --- | --- |
| Power Distribution | AC-DC conversion, DC bus architecture | 48V DC bus for motors, 12V for logic |
| Motor Control | Servo drives, current/velocity/position loops | Joint actuation, precision control |
| Power Budget | Calculate total power consumption | Size power supply, thermal mgmt |
| EMI/EMC Compliance | Electromagnetic interference/compatibility | CE marking, industrial standards |
| Grounding & Safety | Protective earth, isolation | Electrical safety, noise reduction |
| Circuit Protection | Fuses, circuit breakers, overcurrent | Prevent damage, safety shutdown |
| Wiring & Cabling | Cable sizing, shielding, routing | Minimize voltage drop, interference |

### 1.2.3 1.3 Electronics Department

| **Concept** | **Description** | **Application** |
| --- | --- | --- |
| Vision Sensors | RGB-D cameras, stereo, industrial cameras | Object detection, pose estimation |
| Force/Torque Sensing | 6-axis F/T sensors, strain gauges | Grasp control, collision detection |
| Proximity Sensors | Inductive, capacitive, photoelectric | Object presence, safety zones |
| Encoder Systems | Rotary (incremental/absolute), linear | Joint position feedback |
| Signal Conditioning | Amplification, filtering, ADC | Noise reduction, accurate sensing |
| Embedded Controllers | MCU (STM32), SBC (Jetson, RPi) | Low-level I/O, vision processing |
| Communication Interfaces | USB, UART, SPI, I2C, EtherCAT, CAN | Sensor data transfer, motor control |

### 1.2.4 1.4 Software Department

| **Concept** | **Description** | **Application** |
| --- | --- | --- |
| ROS2 Architecture | Nodes, topics, services, actions | System integration, modularity |
| MoveIt Motion Planning | OMPL, collision checking, IK | Path planning, trajectory generation |
| Computer Vision Pipeline | Image processing, object detection (YOLO, OpenCV) | Perception, localization |
| State Machines / Behavior Trees | Task sequencing, error handling | High-level control, autonomy |
| Real-Time Control | RT-Preempt Linux, deterministic loops | Low-latency motor control |
| Data Management | Databases (PostgreSQL), time-series (InfluxDB) | Logging, analytics |
| API Design | RESTful APIs, gRPC, ROS services | External integration |

### 1.2.5 1.5 AI Department

| **Concept** | **Description** | **Application** |
| --- | --- | --- |
| Object Detection | Deep learning (YOLO, SSD, Faster R-CNN) | Identify objects in images |
| Pose Estimation | 6DoF pose from RGB-D (PVNet, DenseFusion) | Grasp planning, alignment |
| Grasp Synthesis | Learning-based (GraspNet, Dex-Net) | Optimal grasp selection |
| Reinforcement Learning | Policy learning for adaptive grasping | Improve performance over time |
| Point Cloud Processing | Segmentation, clustering (PCL, Open3D) | 3D scene understanding |
| Model Training | Training pipelines, data augmentation | Custom datasets, fine-tuning |
| Inference Optimization | TensorRT, ONNX Runtime, quantization | Real-time performance on edge |

### 1.2.6 1.6 Security Department

| **Concept** | **Description** | **Application** |
| --- | --- | --- |
| Network Security | Firewalls, VLANs, secure communication | Protect control network |
| Authentication & Authorization | User roles, access control (RBAC) | Restrict system access |
| Data Encryption | TLS for communication, encrypted storage | Protect sensitive data |
| Secure Boot | Firmware integrity verification | Prevent unauthorized code |
| Vulnerability Management | Regular security audits, patch management | Minimize attack surface |
| Safety Interlocks | Emergency stop, safety-rated controllers | Physical safety enforcement |
| Logging & Audit Trails | Immutable logs, intrusion detection | Forensics, compliance |

## 1.3 2. Module Mapping by Department

| **Department** | **Module/Component** | **Inputs** | **Outputs** | **Technology Stack** |
| --- | --- | --- | --- | --- |
| **Mechanical** | Robot Manipulator (6-DOF Arm) | Motor torques | Joint motion, end-effector pose | Aluminum links, harmonic drives |
|  | Gripper Assembly | Gripper command (open/close) | Grasp force, jaw position | Parallel jaw, pneumatic actuator |
|  | Mounting Frame | Static loads | Structural support | Steel frame, vibration dampers |
| **Electrical** | Power Supply Unit (48V DC) | 230V AC mains | 48V DC, 20A | AC-DC converter, EMI filter |
|  | Servo Drive (EtherCAT) | Position/velocity commands | Motor current (3-phase AC) | Beckhoff, Kollmorgen drives |
|  | Power Distribution Board | 48V DC bus | 12V, 5V, 3.3V rails | Buck converters, fuses |
| **Electronics** | RGB-D Camera (RealSense D435) | USB 3.0 power, triggers | RGB image, depth map, point cloud | Intel RealSense SDK |
|  | Force/Torque Sensor (ATI Mini45) | Robot motion, contact forces | Fx, Fy, Fz, Tx, Ty, Tz | ATI DAQ, ROS driver |
|  | Absolute Encoders (17-bit) | Motor shaft rotation | Absolute position | BiSS-C, EnDat protocol |
|  | Embedded Controller (Jetson Xavier) | Vision data, control commands | Object poses, grasp plans | NVIDIA Jetson, Ubuntu 22.04 |
| **Software** | Vision Pipeline Node | RGB-D frames | Object bounding boxes, poses | ROS2, OpenCV, YOLO |
|  | MoveIt Planning Node | Target pose, scene | Joint trajectory | MoveIt2, OMPL |
|  | Grasp Planner Node | Object pose, point cloud | Gripper pose, approach vector | PCL, custom algorithms |
|  | Task Orchestrator (State Machine) | System state, sensor events | High-level commands | BehaviorTree.CPP, SMACH |
|  | ros2\_control Controller Manager | Joint trajectories | Motor commands (EtherCAT) | ros2\_control, RT-Preempt |
| **AI** | Object Detection Model (YOLOv8) | RGB image (640x640) | Bounding boxes, class labels | PyTorch, TensorRT |
|  | Pose Estimation Model (PVNet) | RGB-D, object mask | 6DoF pose (x,y,z,roll,pitch,yaw) | PyTorch, CUDA |
|  | Grasp Network (GraspNet) | Point cloud, object segmentation | Grasp poses, quality scores | TensorFlow, Python |
| **Security** | Firewall & Network Segmentation | Network traffic | Filtered traffic | iptables, VLANs |
|  | Authentication Service | User credentials | Access tokens (JWT) | OAuth2, Keycloak |
|  | Audit Logger | System events | Immutable log entries | Syslog, ELK stack |

## 1.4 3. UI, Visualization, Specifications by Department

| **Department** | **UI/Visualization** | **Specifications** | **Tools** |
| --- | --- | --- | --- |
| **Mechanical** | CAD 3D viewer, assembly animations | - Workspace: 800mm radius- Payload: 5kg- Repeatability: ±0.1mm | SolidWorks, Fusion 360, FreeCAD |
|  | FEA stress/strain visualization | - Max deflection: <0.5mm- Safety factor: >3 | ANSYS, Abaqus |
| **Electrical** | Power flow diagram, load distribution | - Input: 230V AC, 50Hz- DC Bus: 48V, 20A- Efficiency: >90% | AutoCAD Electrical, EPLAN |
|  | Circuit schematics, PCB layout | - Overcurrent protection: 25A breaker- Grounding: <1Ω | KiCAD, Altium Designer |
| **Electronics** | Sensor data dashboards (Grafana) | - Camera: 1920x1080 @ 30fps- F/T range: ±100N, ±10Nm- Encoder: 17-bit | Grafana, Plotly, RViz2 |
|  | Signal waveforms (oscilloscope) | - ADC: 16-bit, 1kHz sampling- Noise: <0.1% FSR | LTSpice, oscilloscope tools |
| **Software** | RViz2 (robot state, TF, point clouds) | - Control loop: 1kHz- Latency: <10ms- ROS2: Humble | RViz2, Foxglove Studio |
|  | Dashboards (system status, metrics) | - API: RESTful, gRPC- Database: PostgreSQL | Grafana, Prometheus, Kibana |
| **AI** | Model performance plots (precision-recall) | - Detection mAP: >0.95- Pose error: <5mm, <5°- Inference: <50ms | TensorBoard, Weights & Biases |
|  | Live inference visualization | - GPU utilization: >80%- Batch size: 1 (real-time) | Custom dashboards, Jupyter |
| **Security** | Security monitoring dashboard | - Access logs retention: 1 year- Encryption: TLS 1.3- Audit: ISO 27001 | Splunk, ELK, Grafana |
|  | Network topology map | - Segmentation: 3 VLANs (control, data, mgmt) | Nmap, Wireshark |

## 1.5 4. Testing by Department

| **Department** | **Test Type** | **Test Cases** | **Pass Criteria** | **Tools** |
| --- | --- | --- | --- | --- |
| **Mechanical** | Static Load Testing | Apply 5kg payload, measure deflection | Deflection <0.5mm | Load cell, dial indicator |
|  | Vibration Testing | Excite at natural frequencies, measure amplitude | Amplitude <1mm | Accelerometer, FFT analyzer |
|  | Endurance Testing | 10,000 pick-place cycles | No mechanical wear/failure | Automated test rig |
| **Electrical** | Power Quality Testing | Measure voltage ripple, efficiency | Ripple <5%, Efficiency >90% | Oscilloscope, power meter |
|  | EMC Testing | Radiated/conducted emissions | Comply with EN 61000-6-2 | EMC chamber, spectrum analyzer |
|  | Short-Circuit Testing | Intentional short, verify protection triggers | Breaker trips <10ms | Current probe, oscilloscope |
| **Electronics** | Sensor Calibration | Compare sensor output with known reference | Error <1% FSR | Calibration weights, fixtures |
|  | Signal Integrity Testing | Measure noise, crosstalk on high-speed buses | SNR >40dB | Oscilloscope, logic analyzer |
|  | Environmental Testing | Temperature (-10°C to 50°C), humidity (10-90% RH) | Functional within range | Climate chamber |
| **Software** | Unit Testing | Test individual ROS nodes, functions | Code coverage >80% | pytest, gtest |
|  | Integration Testing | Test node communication, end-to-end workflow | All tests pass | ROS launch tests, pytest |
|  | Real-Time Performance Testing | Measure control loop jitter, latency | Jitter <1ms, Latency <10ms | cyclictest, ROS diagnostics |
|  | Load Testing | Simulate 100 concurrent vision requests | Response time <100ms | JMeter, Locust |
| **AI** | Model Validation | Test on holdout dataset | mAP >0.95, Pose error <5mm | Python scripts, TensorBoard |
|  | Edge Case Testing | Occluded objects, varying lighting | Detection rate >90% | Custom test datasets |
|  | Performance Benchmarking | Measure inference time on target hardware | <50ms per frame | NVIDIA Nsight, TensorRT profiler |
| **Security** | Penetration Testing | Simulate cyberattacks on control network | No unauthorized access | Metasploit, Nmap, Burp Suite |
|  | Access Control Testing | Verify role-based permissions | Users restricted per role | Manual testing, automated scripts |
|  | Encryption Validation | Verify TLS handshake, data encryption | TLS 1.3, AES-256 | Wireshark, OpenSSL tools |

## 1.6 5. Observability by Department

| **Department** | **Metrics Monitored** | **Thresholds/Alerts** | **Visualization** | **Tools** |
| --- | --- | --- | --- | --- |
| **Mechanical** | Joint positions, velocities | Position error >5mm → alert | RViz2, Grafana time-series | ROS diagnostics, Prometheus |
|  | Gripper force, jaw opening | Force >100N → alert (overload) | Grafana dashboard | ros2\_control, InfluxDB |
| **Electrical** | Bus voltage, current draw | Voltage <45V or >50V → alertCurrent >20A → alert | Grafana, SCADA HMI | Modbus monitors, Grafana |
|  | Motor temperatures | Temp >70°C → warning, >80°C → shutdown | Thermal camera, Grafana | Thermistors, Prometheus |
| **Electronics** | Camera frame rate, data rate | FPS <25 → warning | Grafana, RViz2 diagnostics | ROS image\_transport, Prometheus |
|  | F/T sensor readings | Force spike >150N → collision alert | Real-time plot, Grafana | ROS topic monitor |
|  | CPU/GPU utilization (Jetson) | GPU >95% → thermal throttling risk | NVIDIA Jetson stats, Grafana | tegrastats, Prometheus exporter |
| **Software** | Node alive status, topic Hz | Node down → critical alertHz <10 → warning | ROS2 diagnostics, Grafana | ros2 topic hz, diagnostics agg |
|  | Control loop latency, jitter | Latency >10ms → warning | Grafana time-series | ROS diagnostics, Prometheus |
|  | Database query time | Query >100ms → slow query log | Grafana, pgAdmin | PostgreSQL logs, Prometheus |
| **AI** | Inference time, GPU memory | Inference >50ms → warningMemory >90% → alert | Grafana, TensorBoard | NVIDIA-SMI, Prometheus |
|  | Detection confidence scores | Confidence <0.7 → low confidence alert | Custom dashboard | ROS topic, Grafana |
| **Security** | Failed login attempts | >5 failures in 5min → lockout + alert | Security dashboard, SIEM | Fail2ban, ELK stack |
|  | Network anomalies | Unexpected traffic → alert | Network topology, Grafana | Intrusion detection (Snort), ELK |
|  | Certificate expiry | <30 days → warning | Security dashboard | Certbot, Prometheus |

## 1.7 6. Logging & Tracing by Department

| **Department** | **Logs Captured** | **Log Format** | **Retention** | **Tools** |
| --- | --- | --- | --- | --- |
| **Mechanical** | Joint positions, trajectories | CSV, ROS bag | 30 days | rosbag2, custom logger |
|  | Collision events, emergency stops | JSON, syslog | 1 year | syslog-ng, ELK |
| **Electrical** | Power on/off events, faults | Syslog, Modbus logs | 1 year | syslog, Modbus logger |
|  | Motor drive errors, alarms | Proprietary drive logs, CSV | 1 year | Drive software, custom parser |
| **Electronics** | Sensor data streams (raw + processed) | HDF5, ROS bag | 7 days (raw) | rosbag2, HDF5 |
|  | Calibration parameters, changes | JSON, version-controlled files | Indefinite | Git, config management |
| **Software** | ROS node logs (INFO, WARN, ERROR) | ROS logging (console, file) | 30 days | ros2 launch, syslog |
|  | API requests/responses | JSON, structured logs | 90 days | FastAPI logging, ELK |
|  | Control loop timings | CSV, InfluxDB time-series | 30 days | InfluxDB, Grafana |
| **AI** | Model version, hyperparameters | MLflow tracking, YAML configs | Indefinite | MLflow, DVC |
|  | Inference results (detections, poses) | JSON, ROS bag | 30 days | rosbag2, custom JSON logger |
|  | Training metrics (loss, accuracy) | TensorBoard logs | Indefinite | TensorBoard, Weights & Biases |
| **Security** | Authentication attempts (success/fail) | Syslog, JSON | 1 year | Syslog, ELK |
|  | System access audit trail | Immutable logs (blockchain/append-only) | 5 years | Audit logging service, ELK |
|  | Network traffic logs | Pcap, NetFlow | 30 days | tcpdump, Wireshark, ELK |

**Distributed Tracing:** - **Tool:** Jaeger, Zipkin - **Purpose:** Trace requests across ROS nodes, services, actions - **Retention:** 7 days - **Instrumentation:** OpenTelemetry in ROS2 nodes

## 1.8 7. Cross-Department Integration Matrix

| **Integration Point** | **Departments Involved** | **Interface** | **Critical Requirements** |
| --- | --- | --- | --- |
| Camera to Vision Pipeline | Electronics ↔ Software | USB 3.0, ROS image\_transport | <30ms latency, 30fps |
| Vision to Motion Planning | Software (AI) ↔ Software (MoveIt) | ROS service/action | Pose accuracy <5mm |
| Motion Planning to Motor Control | Software ↔ Electrical | EtherCAT, ros2\_control | 1kHz control loop, <1ms jitter |
| F/T Sensor to Control | Electronics ↔ Software | Analog/Digital, ROS topic | 1kHz sampling, <0.1N noise |
| Emergency Stop | Electrical ↔ Security | Hardwired, Safety PLC | <10ms response time |
| Power Supply to Motors | Electrical ↔ Mechanical | 48V DC bus | Voltage ripple <5% |
| CAD to Simulation | Mechanical ↔ Software | URDF export | Accurate inertia, collision mesh |
| Security Auth to API | Security ↔ Software | JWT tokens, TLS | <100ms auth latency |

## 1.9 8. Dimensional Consistency Table

### 1.9.1 8.1 Units Standardization

| **Quantity** | **Unit** | **Symbol** | **Notes** |
| --- | --- | --- | --- |
| Length | Meter | m | SI base unit |
| Mass | Kilogram | kg | SI base unit |
| Time | Second | s | SI base unit |
| Force | Newton | N | 1 N = 1 kg·m/s² |
| Torque | Newton-meter | N·m | Also moment of force |
| Angle | Radian | rad | Preferred over degrees in code |
| Angular Velocity | Rad per second | rad/s | - |
| Voltage | Volt | V | Electrical potential |
| Current | Ampere | A | Electrical current |
| Power | Watt | W | 1 W = 1 J/s |
| Frequency | Hertz | Hz | 1 Hz = 1/s |

### 1.9.2 8.2 Coordinate Frame Conventions

| **Frame** | **Origin** | **Orientation (Right-Hand Rule)** |
| --- | --- | --- |
| World | Floor center | X: forward, Y: left, Z: up |
| Robot Base | Robot mounting point | X: forward, Y: left, Z: up |
| Camera | Optical center | X: right, Y: down, Z: forward (OpenCV) |
| End-Effector | Flange center | X: approach, Y: closing, Z: normal |
| Object | Object centroid | X, Y, Z: aligned with object principal axes |

## 1.10 9. Database Design by Department

| **Department** | **Database** | **Tables/Collections** | **Schema** | **Access Pattern** |
| --- | --- | --- | --- | --- |
| **Mechanical** | PostgreSQL | parts, assemblies, bom | part\_id, name, material, weight, CAD\_file\_url | Infrequent writes, periodic reads |
| **Electrical** | PostgreSQL | power\_logs, motor\_status | timestamp, bus\_voltage, current, temp | High-frequency inserts (1Hz) |
| **Electronics** | InfluxDB | sensor\_data (time-series) | time, sensor\_id, value, unit | High-frequency writes (1kHz) |
| **Software** | PostgreSQL | tasks, logs, configs | task\_id, status, start\_time, end\_time | Frequent reads/writes |
|  | Redis | Session cache, real-time state | key-value (JSON) | Sub-ms latency |
| **AI** | MongoDB | datasets, models, inferences | model\_id, version, accuracy, inference\_results | Append-heavy (inference logs) |
|  | MLflow Backend | Experiment tracking | Managed by MLflow | Experiment analysis, model registry |
| **Security** | PostgreSQL | users, roles, audit\_trail | user\_id, role, action, timestamp, IP | Append-only audit logs |
|  | ELK (Elasticsearch) | Security logs (indexed) | timestamp, event\_type, severity, details | Full-text search, real-time alerts |

## 1.11 10. API Design by Department

| **Department** | **API Type** | **Endpoints** | **Methods** | **Auth** | **Rate Limit** |
| --- | --- | --- | --- | --- | --- |
| **Software** | REST | /api/v1/tasks, /api/v1/status | GET, POST | JWT | 100 req/min |
|  | gRPC | PlanMotion, ExecuteTrajectory | RPC | mTLS | No limit (internal) |
| **AI** | REST | /api/v1/detect, /api/v1/pose\_estimate | POST | API Key | 60 req/min |
|  | WebSocket | /ws/live\_inference | Stream | JWT | 1 conn/user |
| **Security** | REST | /api/v1/auth/login, /api/v1/auth/logout | POST | Username/Pass | 10 req/min |
|  | REST | /api/v1/audit/logs | GET | Admin JWT | 10 req/min |

## 1.12 11. Final Summary Table: Department Overview

| **Department** | **Primary Responsibility** | **Key Deliverables** | **Critical Metrics** |
| --- | --- | --- | --- |
| **Mechanical** | Robot structure, kinematics, gripper | CAD models, URDF, FEA reports | Repeatability ±0.1mm, Payload 5kg |
| **Electrical** | Power, motor control, wiring | Circuit schematics, power budget, motor specs | Efficiency >90%, Voltage regulation ±2% |
| **Electronics** | Sensors, embedded systems, I/O | Sensor specs, calibration procedures, drivers | Sensor accuracy <1%, Sampling rate >1kHz |
| **Software** | ROS2, control, planning, integration | ROS packages, APIs, state machines, tests | Control loop 1kHz, Latency <10ms |
| **AI** | Perception, learning, optimization | Trained models, datasets, inference pipeline | Detection mAP >0.95, Inference <50ms |
| **Security** | Cybersecurity, access control, audits | Security policies, audit logs, encryption | Zero breaches, 100% audit coverage |

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