

# 03 Department Mapping Table

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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.

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### 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	$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) =$	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

Concept	Description	Application
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
<b>Mechanical</b>	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
<b>Electrical</b>	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
<b>Electronics</b>	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
	Vision Pipeline Node	RGB-D frames	Object bounding boxes, poses	ROS2, OpenCV, YOLO
<b>Software</b>	MoveIt Planning Node	Target pose, scene	Joint trajectory	MoveIt2, OMPL

Department	Module/Component	Inputs	Outputs	Technology Stack
<b>AI</b>	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
	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
	Firewall & Network Segmentation	Network traffic	Filtered traffic	iptables, VLANs
<b>Security</b>	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
<b>Mechanical</b>	CAD 3D viewer, assembly animations	- Workspace: 800mm radius- Payload: 5kg- Repeatability: $\pm 0.1\text{mm}$	SolidWorks, Fusion 360, FreeCAD
	FEA stress/strain visualization	- Max deflection: $< 0.5\text{mm}$ - Safety factor: $> 3$	ANSYS, Abaqus
<b>Electrical</b>	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: $< 1\Omega$	KiCAD, Altium Designer
<b>Electronics</b>	Sensor data dashboards (Grafana)	- Camera: 1920x1080 @ 30fps- F/T range: $\pm 100\text{N}$ , $\pm 10\text{Nm}$ - Encoder: 17-bit	Grafana, Plotly, RViz2
	Signal waveforms (oscilloscope)	- ADC: 16-bit, 1kHz sampling- Noise: $< 0.1\%$ FSR	LTSpice, oscilloscope tools
<b>Software</b>	RViz2 (robot state, TF, point clouds)	- Control loop: 1kHz- Latency: $< 10\text{ms}$ - ROS2: Humble	RViz2, Foxglove Studio
	Dashboards (system status, metrics)	- API: RESTful, gRPC- Database: PostgreSQL	Grafana, Prometheus, Kibana

Department	UI/Visualization	Specifications	Tools
<b>AI</b>	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
<b>Security</b>	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
<b>Mechanical</b>	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
<b>Electrical</b>	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
<b>Electronics</b>	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
<b>Software</b>	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	cyclicttest, ROS diagnostics

Department	Test Type	Test Cases	Pass Criteria	Tools
AI	Load Testing	Simulate 100 concurrent vision requests	Response time <100ms	JMeter, Locust
	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 → alert Current >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
Software	CPU/GPU utilization (Jetson)	GPU >95% → thermal throttling risk	NVIDIA Jetson stats, Grafana	tegrastats, Prometheus exporter
	Node alive status, topic Hz	Node down → critical alert Hz <10 → warning	ROS2 diagnostics, Grafana	ros2 topic hz, diagnostics agg

Department	Metrics Monitored	Thresholds/Alerts	Visualization	Tools
<b>AI</b>	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
	Inference time, GPU memory	Inference >50ms → warning Memory >90% → alert	Grafana, TensorBoard	NVIDIA-SMI, Prometheus
<b>Security</b>	Detection confidence scores	Confidence <0.7 → low confidence alert	Custom dashboard	ROS topic, Grafana
	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
<b>Mechanical</b>	Joint positions, trajectories	CSV, ROS bag	30 days	rosviz, custom logger
	Collision events, emergency stops	JSON, syslog	1 year	syslog-ng, ELK
<b>Electrical</b>	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
<b>Electronics</b>	Sensor data streams (raw + processed)	HDF5, ROS bag	7 days (raw)	rosviz, HDF5
	Calibration parameters, changes	JSON, version-controlled files	Indefinite	Git, config management
<b>Software</b>	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
<b>AI</b>	Control loop timings	CSV, InfluxDB time-series	30 days	InfluxDB, Grafana
	Model version, hyperparameters	MLflow tracking, YAML configs	Indefinite	MLflow, DVC



Department	Logs Captured	Log Format	Retention	Tools
Security	Inference results (detections, poses)	JSON, ROS bag	30 days	rosbag2, custom JSON logger
	Training metrics (loss, accuracy)	TensorBoard logs	Indefinite	TensorBoard, Weights & Biases
	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)		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	$1\text{ N} = 1\text{ kg} \cdot \text{m/s}^2$
Torque	Newton-meter	$\text{N} \cdot \text{m}$	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	$1\text{ W} = 1\text{ J/s}$
Frequency	Hertz	Hz	$1\text{ Hz} = 1/\text{s}$

## 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
<b>Mechanics</b>	PostgreSQL	parts, assemblies, bom	part_id, name, material, weight, CAD_file_url	Infrequent writes, periodic reads
<b>Electrical</b>	PostgreSQL	power_logs, motor_status	timestamp, bus_voltage, current, temp	High-frequency inserts (1Hz)
<b>Electronics</b>	InfluxDB	sensor_data (time-series)	time, sensor_id, value, unit	High-frequency writes (1kHz)
<b>Software</b>	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
<b>AI</b>	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
<b>Security</b>	PostgreSQL	users, roles, audit_trail	user_id, role, action, timestamp, IP	Append-only audit logs

Department	Database Tables/Collections	Schema	Access Pattern
	ELK (Elastic-search)	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/Password	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 $\pm 0.1\text{mm}$ , Payload 5kg
Electrical	Power, motor control, wiring	Circuit schematics, power budget, motor specs	Efficiency $>90\%$ , Voltage regulation $\pm 2\%$
Electronics	Sensors, embedded systems, I/O	Sensor specs, calibration procedures, drivers	Sensor accuracy $<1\%$ , Sampling rate $>1\text{kHz}$
Software	ROS2, control, planning, integration	ROS packages, APIs, state machines, tests	Control loop 1kHz, Latency $<10\text{ms}$
AI	Perception, learning, optimization	Trained models, datasets, inference pipeline	Detection mAP $>0.95$ , Inference $<50\text{ms}$
Security	Cybersecurity, access control, audits	Security policies, audit logs, encryption	Zero breaches, 100% audit coverage

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