Problem Statement 11: Smart Retail Edge Vision

AI-Powered Computer Vision System for Retail Analytics and Automation

Problem Overview

Develop an intelligent edge computing solution that leverages computer vision and AI to transform retail operations through real-time customer behavior analysis, inventory management, loss prevention, and automated checkout experiences. The system should operate at the edge with minimal latency while providing comprehensive retail intelligence and automation capabilities.

Key Requirements

Core AI/ML Capabilities

- **Real-time Computer Vision** - Object detection, person tracking, gesture recognition, facial analysis
- **Customer Behavior Analytics** - Shopping pattern analysis, dwell time tracking, heat map generation
- **Inventory Management** - Automated stock monitoring, shelf analytics, product placement optimization
- **Loss Prevention** - Suspicious activity detection, theft prevention, security monitoring
- **Automated Checkout** - Cashierless shopping experience with product recognition and payment processing

Edge Computing Requirements

- **Low-Latency Processing** - <100ms response time for critical operations
- **Offline Capability** - Full functionality without internet connectivity
- **Resource Optimization** - Efficient processing on edge hardware (NVIDIA Jetson, Intel NUC)
- **Real-time Analytics** - Live dashboard with instant insights and alerts
- **Scalable Deployment** - Support for single store to enterprise chain deployments

Integration Requirements

- **POS Systems** - Integration with existing point-of-sale and payment systems
- **Inventory Management** - ERP, WMS, and supply chain system connectivity
- **Security Systems** - CCTV, alarm systems, and access control integration
- **Customer Engagement** - Mobile apps, loyalty programs, and personalization platforms
- **Cloud Synchronization** - Periodic data sync with cloud analytics and management systems

Data Requirements

- **Video Streams** - Multi-camera feeds from store surveillance systems
- **Product Catalog** - SKU database with visual recognition models
- **Customer Data** - Anonymous behavior patterns and demographic insights
- **Store Layout** - Floor plans, shelf configurations, and zone definitions
- **Historical Analytics** - Transaction data, inventory movements, and performance metrics

Technical Themes

- **Edge AI Processing** - On-device inference with optimized neural networks
- **Computer Vision Pipeline** - Multi-stage image processing and analysis
- **Real-time Analytics** - Stream processing with immediate insights generation
- **Privacy-Preserving AI** - Anonymous customer analysis without personal identification
- **Hybrid Cloud-Edge Architecture** - Local processing with cloud intelligence and management

Expected Business Outcomes

- **25% reduction** in inventory management costs through automated monitoring
- **40% improvement** in loss prevention effectiveness with AI-powered security
- **30% increase** in customer satisfaction through optimized store layouts and experiences
- **50% reduction** in checkout wait times with automated payment systems
- **$500K annual savings** per store through operational efficiency improvements

Implementation Strategy

Phase 1: Core Vision System (Months 1-3)

- Computer vision pipeline development
- Object detection and tracking algorithms
- Basic customer behavior analytics
- Edge hardware deployment and optimization

Phase 2: Advanced Analytics (Months 4-6)

- Inventory management automation
- Loss prevention and security features
- Customer journey mapping and heat maps
- Real-time dashboard and alerting system

Phase 3: Automated Checkout (Months 7-9)

- Cashierless shopping experience
- Product recognition and cart tracking
- Payment processing integration
- Customer mobile app development

Phase 4: Enterprise Scale (Months 10-12)

- Multi-store deployment and management
- Advanced analytics and predictive insights
- Integration with enterprise systems
- Performance optimization and cost reduction

Success Metrics

- **Technical Performance**: <100ms processing latency, 95%+ accuracy, 99.5% uptime
- **Business Impact**: 25% cost reduction, 40% loss prevention improvement, 30% customer satisfaction increase
- **Operational Excellence**: 50% faster checkout, 90% inventory accuracy, 24/7 autonomous operation
- **Scalability**: 1000+ store deployment capability, 99.9% system reliability # Product Requirements Document (PRD) ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README foundation for comprehensive business and product specifications

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview, key requirements, technical themes, and implementation strategy
- âœ… Business case validated with $500K annual savings per store and 25% cost reduction potential
- âœ… Market research completed on retail automation and computer vision solutions
- âœ… Technical feasibility confirmed for edge AI processing and real-time computer vision

TASK

Define comprehensive product requirements including business objectives, market analysis, user personas, success metrics, core features, technical requirements, business constraints, assumptions, and risk assessment for the Smart Retail Edge Vision platform.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] Business objectives aligned with README expected outcomes (25% cost reduction, 40% loss prevention improvement, 30% customer satisfaction increase) - [ ] Market analysis covers competitive landscape and retail technology trends - [ ] User personas represent primary stakeholders (store managers, IT administrators, customers, security personnel) - [ ] Success metrics include technical performance, business impact, and operational excellence KPIs - [ ] Core features address all key requirements from README (computer vision, analytics, automation, integration)

Validation Criteria: - [ ] PRD validated with retail industry experts and potential customers - [ ] Market analysis validated with retail technology analysts and consultants - [ ] User personas validated through retail stakeholder interviews and research - [ ] Success metrics validated with retail operations teams and aligned with industry benchmarks - [ ] Technical requirements validated with computer vision experts and edge computing specialists

EXIT CRITERIA

- âœ… Complete PRD with business objectives, market analysis, user personas, and success metrics
- âœ… Core features and technical requirements specified for development planning
- âœ… Business constraints, assumptions, and risks documented for project management
- âœ… Foundation prepared for Functional Requirements Document (FRD) development

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Reference to Previous Documents

This PRD builds upon **README** foundations: - **README Problem Overview** â†’ Detailed business objectives and market positioning for retail automation - **README Key Requirements** â†’ Comprehensive feature specifications and technical requirements for edge AI - **README Expected Outcomes** â†’ Quantified success metrics and business impact measurements - **README Implementation Strategy** â†’ Product roadmap and phased development approach

1. Business Objectives

1.1 Primary Business Goals

- **Operational Cost Reduction**: Achieve 25% reduction in inventory management costs through automated monitoring and real-time analytics
- **Loss Prevention Enhancement**: Improve loss prevention effectiveness by 40% through AI-powered security monitoring and suspicious activity detection
- **Customer Experience Optimization**: Increase customer satisfaction by 30% through optimized store layouts, reduced wait times, and personalized shopping experiences
- **Checkout Efficiency**: Reduce checkout wait times by 50% through automated cashierless shopping and streamlined payment processing
- **Revenue Growth**: Generate $500K annual savings per store through operational efficiency improvements and reduced shrinkage

1.2 Strategic Objectives

- **Market Leadership**: Establish dominant position in retail edge AI market with 100+ enterprise customers within 18 months
- **Technology Innovation**: Advance state-of-the-art in edge computer vision and real-time retail analytics
- **Scalability Achievement**: Deploy across 1000+ stores with 99.9% system reliability and autonomous operation
- **Partnership Development**: Secure strategic partnerships with major retailers, POS vendors, and hardware manufacturers
- **Global Expansion**: Support international deployments with localized compliance and multi-language capabilities

2. Market Analysis

2.1 Market Size and Opportunity

- **Total Addressable Market (TAM)**: $35B global retail technology market
- **Serviceable Addressable Market (SAM)**: $8B computer vision and analytics segment
- **Serviceable Obtainable Market (SOM)**: $1.2B edge AI retail solutions niche
- **Growth Rate**: 22% CAGR driven by digital transformation and automation adoption
- **Market Timing**: Optimal entry point with 60% of retailers planning AI investments by 2025

2.2 Competitive Landscape

Direct Competitors: - **Amazon Go Technology**: Cashierless stores, limited licensing, $2B+ investment - **Trigo**: Computer vision for retail, 50+ deployments, $100M funding - **AiFi**: Autonomous retail solutions, 80+ stores, focus on convenience retail - **Standard Cognition**: Checkout-free technology, acquired by Compass Group

Indirect Competitors: - **Traditional POS Systems**: NCR, Square, Shopify with basic analytics - **Security Camera Systems**: Hikvision, Dahua with limited AI capabilities - **Retail Analytics**: RetailNext, Dor Technologies with sensor-based solutions - **Inventory Management**: Zebra Technologies, Impinj with RFID solutions

Competitive Advantages: - **Edge-First Architecture**: <100ms latency vs.Â 500ms+ cloud-based solutions - **Comprehensive Platform**: End-to-end solution vs.Â point solutions - **Privacy-Preserving**: Anonymous analytics vs.Â facial recognition concerns - **Cost-Effective Deployment**: 60% lower TCO through edge optimization - **Offline Capability**: 100% uptime vs.Â cloud dependency risks

2.3 Market Trends and Drivers

- **Labor Shortage Crisis**: 76% of retailers struggling with staffing, driving automation demand
- **Shrinkage Reduction Pressure**: $61B annual retail losses driving security investment
- **Customer Experience Focus**: 89% of retailers prioritizing experience improvements
- **Edge Computing Adoption**: 75% reduction in edge hardware costs over 3 years
- **Privacy Regulations**: GDPR, CCPA driving anonymous analytics demand

3. User Personas

3.1 Primary Persona: Store Manager (Sarah - Regional Manager)

Demographics: - Age: 38, Regional Manager at mid-size grocery chain - Education: Business degree, 12 years retail management experience - Tech Savviness: Medium, focuses on operational efficiency and customer satisfaction

Pain Points: - Spends 15+ hours weekly on manual inventory checks and loss prevention reviews - Struggles with optimizing store layouts and product placement without data insights - Difficulty identifying and preventing theft and shrinkage in real-time - Limited visibility into customer behavior patterns and shopping preferences - Challenges managing staff efficiency and customer service quality

Goals and Motivations: - Reduce operational costs while maintaining high customer satisfaction - Improve inventory accuracy and reduce out-of-stock situations - Enhance loss prevention and security without impacting customer experience - Optimize store layout and product placement based on data-driven insights - Demonstrate ROI and operational improvements to corporate leadership

Usage Patterns: - Reviews daily analytics dashboards and performance metrics - Responds to real-time alerts for security and inventory issues - Uses mobile app for store walk-throughs and spot checks - Requires integration with existing POS and inventory management systems

3.2 Secondary Persona: IT Director (Michael - Enterprise IT)

Demographics: - Age: 45, IT Director at large retail chain (500+ stores) - Education: Computer Science degree, 20 years enterprise IT experience - Tech Savviness: Very High, responsible for technology strategy and implementation

Pain Points: - Challenges deploying and managing technology across hundreds of store locations - Security concerns with video data and customer privacy compliance - Integration complexity with existing retail systems and infrastructure - Need for reliable, low-maintenance solutions that minimize support calls - Budget constraints requiring clear ROI demonstration and cost justification

Goals and Motivations: - Deploy scalable technology solutions across entire retail network - Ensure data security, privacy compliance, and system reliability - Minimize operational overhead and support requirements - Demonstrate technology ROI and business value to executive leadership - Future-proof technology investments with flexible, upgradeable platforms

Usage Patterns: - Manages enterprise-wide deployments and system configurations - Monitors system health, performance, and security across all locations - Evaluates vendor solutions for scalability, security, and integration capabilities - Requires comprehensive APIs, documentation, and enterprise support

3.3 Tertiary Persona: Customer (Jennifer - Frequent Shopper)

Demographics: - Age: 32, Marketing professional and frequent grocery shopper - Education: College degree, tech-savvy consumer - Shopping Behavior: Values convenience, efficiency, and personalized experiences

Pain Points: - Long checkout lines and wait times during peak shopping hours - Difficulty finding products and navigating large store layouts - Limited personalized recommendations and offers - Concerns about privacy and data collection in retail environments - Frustration with out-of-stock items and poor inventory management

Goals and Motivations: - Complete shopping efficiently with minimal wait times - Receive personalized recommendations and relevant offers - Enjoy seamless, frictionless shopping experiences - Maintain privacy while benefiting from personalized services - Access convenient payment options and loyalty program benefits

Usage Patterns: - Uses mobile apps for shopping lists, store navigation, and payments - Values quick checkout options including self-service and mobile payments - Responds positively to relevant personalized offers and recommendations - Expects consistent experience across different store locations

4. Success Metrics and KPIs

4.1 Technical Performance Metrics

- **Processing Latency**: <100ms for critical computer vision operations
- **Accuracy Rates**: 95%+ for object detection, 90%+ for behavior analysis, 98%+ for product recognition
- **System Uptime**: 99.5% availability with <5 minutes mean time to recovery
- **Edge Performance**: 90%+ local processing capability without cloud connectivity
- **Scalability**: Support 1000+ concurrent stores with centralized management

4.2 Business Impact Metrics

- **Cost Reduction**: 25% reduction in inventory management costs per store
- **Loss Prevention**: 40% improvement in shrinkage reduction and theft detection
- **Customer Satisfaction**: 30% increase in customer satisfaction scores and Net Promoter Score
- **Operational Efficiency**: 50% reduction in checkout wait times and 20% improvement in staff productivity
- **Revenue Impact**: $500K annual savings per store with 300%+ ROI within 18 months

4.3 Operational Excellence Metrics

- **Inventory Accuracy**: 90%+ real-time inventory accuracy vs.Â 75% industry average
- **Security Response**: <30 seconds alert response time for security incidents
- **Customer Flow**: 25% improvement in store traffic flow and reduced congestion
- **Staff Efficiency**: 20% reduction in manual tasks and improved task prioritization
- **System Reliability**: 24/7 autonomous operation with minimal human intervention

4.4 Growth and Adoption Metrics

- **Customer Acquisition**: 100+ enterprise customers within 18 months
- **Market Penetration**: 1000+ store deployments across multiple retail verticals
- **Revenue Growth**: $50M ARR by end of Year 2 with 45% gross margins
- **Partnership Success**: 10+ strategic partnerships with retailers, POS vendors, and hardware manufacturers
- **Geographic Expansion**: Deployments in 15+ countries with localized compliance

5. Core Features and Capabilities

5.1 Computer Vision and AI Processing

Real-time Object Detection and Tracking: - Multi-object detection with 95%+ accuracy for products, people, and shopping carts - Person tracking across multiple cameras with re-identification capabilities - Product recognition for 100,000+ SKUs with visual similarity matching - Gesture recognition for customer interactions and staff activities - Facial analysis for demographic insights without personal identification

Advanced Behavior Analytics: - Customer journey mapping and shopping pattern analysis - Dwell time tracking and zone-based engagement measurement - Heat map generation for store layout optimization - Queue detection and wait time analysis - Suspicious activity detection and security alerting

Edge AI Optimization: - On-device neural network inference with <100ms latency - Model quantization and pruning for edge hardware optimization - Dynamic model loading based on store configuration and requirements - Offline capability with full functionality without internet connectivity - Real-time model updates and continuous learning capabilities

5.2 Inventory Management Automation

Automated Stock Monitoring: - Real-time shelf monitoring with out-of-stock detection - Product placement compliance and planogram verification - Inventory level estimation using computer vision - Automated reorder alerts and supply chain integration - Price tag verification and promotional compliance monitoring

Advanced Shelf Analytics: - Product performance analysis and sales correlation - Shelf space optimization recommendations - Cross-merchandising effectiveness measurement - Seasonal and promotional impact analysis - Competitor product placement monitoring

5.3 Loss Prevention and Security

AI-Powered Security Monitoring: - Suspicious behavior detection and real-time alerting - Theft prevention with product removal tracking - Perimeter security and unauthorized access detection - Staff compliance monitoring and safety protocol verification - Integration with existing security systems and alarm networks

Advanced Threat Detection: - Anomaly detection for unusual shopping patterns - Crowd behavior analysis and safety monitoring - Vandalism and property damage detection - Emergency situation recognition and response - Forensic video analysis and incident investigation tools

5.4 Automated Checkout and Payment

Cashierless Shopping Experience: - Customer identification and cart tracking throughout store - Automatic product recognition and cart management - Real-time pricing and promotional offer application - Seamless payment processing with multiple payment methods - Receipt generation and loyalty program integration

Hybrid Checkout Options: - Self-service checkout with AI assistance and error detection - Mobile app integration for scan-and-go functionality - Staff-assisted checkout with AI-powered product recognition - Queue management and checkout lane optimization - Payment fraud detection and prevention

6. Technical Requirements

6.1 Edge Computing Requirements

- **Hardware Specifications**: NVIDIA Jetson AGX Xavier, Intel NUC with GPU acceleration
- **Processing Power**: 32 TOPS AI performance for real-time inference
- **Storage**: 1TB+ local storage for models, cache, and temporary data
- **Connectivity**: WiFi 6, Ethernet, 4G/5G backup connectivity
- **Operating System**: Ubuntu 20.04 LTS with containerized applications

6.2 Computer Vision Pipeline

- **Camera Support**: IP cameras with RTSP streams, 4K resolution, 30fps
- **Video Processing**: H.264/H.265 encoding, multi-stream processing
- **AI Models**: YOLOv8, ResNet, MobileNet optimized for edge deployment
- **Framework**: TensorRT, OpenVINO for optimized inference
- **Integration**: OpenCV, GStreamer for video pipeline management

6.3 Data Management and Analytics

- **Local Database**: PostgreSQL for structured data, InfluxDB for time-series
- **Caching**: Redis for real-time data and session management
- **Analytics Engine**: Apache Kafka for stream processing, Grafana for visualization
- **Cloud Sync**: Periodic synchronization with cloud analytics platform
- **Data Retention**: 30-day local retention with configurable archival policies

7. Business Constraints and Assumptions

7.1 Budget and Resource Constraints

- **Development Budget**: $8M allocated for 18-month development cycle
- **Hardware Costs**: $5K-15K per store deployment depending on configuration
- **Team Size**: 30-person engineering team with computer vision and retail expertise
- **Timeline**: 18-month development with phased rollout and pilot deployments
- **Support Costs**: 24/7 support infrastructure for enterprise deployments

7.2 Technical Constraints

- **Edge Hardware Limitations**: Processing power and storage constraints for complex models
- **Network Connectivity**: Intermittent connectivity and bandwidth limitations in retail environments
- **Camera Infrastructure**: Dependency on existing camera systems and installation requirements
- **Integration Complexity**: Varying POS systems and retail technology stacks
- **Privacy Regulations**: GDPR, CCPA compliance requirements for customer data

7.3 Market and Business Assumptions

- **Retail Automation Adoption**: Continued growth in retail technology investment and automation
- **Edge Computing Maturity**: Availability of cost-effective edge hardware and software platforms
- **Customer Acceptance**: Consumer acceptance of AI-powered retail experiences and privacy trade-offs
- **Regulatory Stability**: Stable privacy and AI governance regulations
- **Partnership Opportunities**: Availability of strategic retail and technology partnerships

8. Risk Assessment and Mitigation

8.1 Technical Risks

High Risk - Computer Vision Accuracy: - Risk: Object detection and tracking accuracy below 95% threshold impacts business value - Impact: High - Core value proposition compromised - Mitigation: Multi-model ensemble approach, continuous model training, extensive testing datasets

Medium Risk - Edge Hardware Performance: - Risk: Edge devices cannot handle required processing load and latency requirements - Impact: Medium - Performance degradation and customer experience issues - Mitigation: Hardware optimization, model quantization, distributed processing architecture

Medium Risk - Integration Complexity: - Risk: Difficulty integrating with diverse retail systems and legacy infrastructure - Impact: Medium - Deployment delays and increased implementation costs - Mitigation: Standardized APIs, extensive testing, professional services team

8.2 Business and Market Risks

High Risk - Privacy and Regulatory Concerns: - Risk: Privacy regulations or customer concerns limit deployment and adoption - Impact: High - Market access restrictions and customer resistance - Mitigation: Privacy-by-design architecture, anonymous analytics, regulatory compliance program

Medium Risk - Competitive Response: - Risk: Major technology companies (Amazon, Google, Microsoft) launch competing solutions - Impact: Medium - Market share erosion and pricing pressure - Mitigation: Feature differentiation, retail partnerships, rapid innovation cycle

Low Risk - Economic Downturn: - Risk: Economic recession reduces retail technology spending and investment - Impact: Low - Delayed adoption but long-term demand remains - Mitigation: Flexible pricing models, ROI demonstration, cost-saving value proposition

This comprehensive PRD establishes the foundation for developing a market-leading Smart Retail Edge Vision platform that addresses critical retail challenges while delivering measurable business value and competitive differentiation. # Functional Requirements Document (FRD) ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README and PRD foundations for detailed system behavior specifications

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview, key requirements, and technical themes
- âœ… PRD completed with business objectives, user personas, success metrics, and core features
- âœ… Market analysis validated competitive landscape and retail technology trends
- âœ… Technical feasibility confirmed for edge AI processing and real-time computer vision
- âœ… User personas defined for store managers, IT directors, and customers

TASK

Define detailed functional requirements specifying system behaviors, user interactions, AI/ML capabilities, integration interfaces, and acceptance criteria for all Smart Retail Edge Vision platform features including computer vision processing, behavior analytics, inventory management, loss prevention, and automated checkout.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] All functional requirements mapped to PRD core features and user personas - [ ] Real-time processing requirements specified with <100ms latency constraints - [ ] AI/ML capabilities detailed with 95%+ accuracy requirements for object detection - [ ] Integration requirements cover POS systems, inventory management, and security systems - [ ] Privacy and security requirements integrated throughout functional specifications

Validation Criteria: - [ ] Functional requirements validated with retail industry experts and potential customers - [ ] Computer vision requirements validated with CV engineers and ML specialists - [ ] Integration requirements validated with retail system vendors and API documentation - [ ] User experience requirements validated with UX designers and retail operations teams - [ ] Acceptance criteria validated with QA teams for testability and completeness

EXIT CRITERIA

- âœ… Complete functional requirements covering all system modules and user interactions
- âœ… Detailed acceptance criteria for each requirement enabling comprehensive testing
- âœ… AI/ML processing workflows specified for development implementation
- âœ… Integration interfaces documented for retail system connectivity
- âœ… Foundation prepared for Non-Functional Requirements Document (NFRD) development

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Reference to Previous Documents

This FRD builds upon **README** and **PRD** foundations: - **README Key Requirements** â†’ Detailed functional specifications for core AI/ML capabilities and edge computing - **PRD User Personas** â†’ User-centric functional requirements addressing specific retail pain points - **PRD Core Features** â†’ Comprehensive system behaviors and interaction patterns for retail automation - **PRD Success Metrics** â†’ Functional requirements supporting 95% accuracy and <100ms latency targets

1. Computer Vision and AI Processing Module

FR-001: Real-time Object Detection and Recognition

Description: System shall provide real-time object detection and recognition for products, people, shopping carts, and retail fixtures with high accuracy and low latency.

Functional Behavior: - Capture video streams from multiple IP cameras with 4K resolution at 30fps - Process video frames using optimized neural networks (YOLOv8, ResNet) on edge hardware - Detect and classify objects including products, people, shopping carts, and store fixtures - Generate bounding boxes with confidence scores for all detected objects - Track objects across multiple camera views with re-identification capabilities - Maintain object tracking consistency during occlusions and camera transitions

Acceptance Criteria: - Object detection accuracy â‰¥95% for products, people, and shopping carts - Processing latency <100ms from frame capture to detection results - Support for simultaneous processing of â‰¥16 camera streams - Object tracking accuracy â‰¥90% across camera transitions - Confidence score generation with â‰¥85% correlation to manual verification - Real-time performance maintained during peak store traffic (100+ people)

FR-002: Product Recognition and SKU Identification

Description: System shall recognize and identify specific products and SKUs using visual characteristics and maintain a comprehensive product catalog.

Functional Behavior: - Maintain visual product database with 100,000+ SKUs and product variations - Perform product recognition using visual similarity matching and feature extraction - Handle product variations including different packaging, sizes, and orientations - Support barcode and QR code recognition as supplementary identification method - Update product catalog automatically with new products and seasonal variations - Generate product recognition confidence scores and alternative matches

Acceptance Criteria: - Product recognition accuracy â‰¥98% for catalog products in optimal conditions - SKU identification accuracy â‰¥95% for products with clear visibility - Processing time <200ms per product recognition request - Support for product variations with â‰¥90% recognition accuracy - Barcode recognition accuracy â‰¥99.5% when visible and readable - Product catalog updates processed within 24 hours of submission

FR-003: Customer Behavior Analysis and Tracking

Description: System shall analyze customer behavior patterns, shopping journeys, and engagement metrics while maintaining privacy and anonymity.

Functional Behavior: - Track customer movements throughout store using anonymous person tracking - Generate customer journey maps showing path, dwell times, and zone interactions - Analyze shopping patterns including product interactions and decision points - Calculate zone-based engagement metrics and heat maps - Detect customer demographics (age group, gender) without personal identification - Measure queue lengths, wait times, and checkout efficiency

Acceptance Criteria: - Person tracking accuracy â‰¥90% throughout store visit - Journey mapping completeness â‰¥85% for customer paths - Dwell time measurement accuracy within Â±30 seconds - Heat map generation updated in real-time with <5 minute latency - Demographic analysis accuracy â‰¥80% compared to manual observation - Queue detection accuracy â‰¥95% with wait time estimation within Â±2 minutes

FR-004: Gesture and Activity Recognition

Description: System shall recognize customer and staff gestures and activities relevant to retail operations and security monitoring.

Functional Behavior: - Detect customer gestures including product pickup, examination, and replacement - Recognize staff activities including restocking, cleaning, and customer assistance - Identify suspicious activities and behaviors for security alerting - Track shopping cart interactions and product placement/removal - Analyze customer engagement levels and product interaction intensity - Generate activity-based insights for operational optimization

Acceptance Criteria: - Gesture recognition accuracy â‰¥85% for common retail interactions - Activity classification accuracy â‰¥80% for staff and customer behaviors - Suspicious activity detection with â‰¥75% recall and â‰¤10% false positive rate - Cart interaction tracking accuracy â‰¥90% for product additions/removals - Real-time activity analysis with <3 second processing delay - Activity confidence scoring with â‰¥70% correlation to manual verification

2. Inventory Management and Analytics Module

FR-005: Automated Shelf Monitoring and Stock Level Detection

Description: System shall monitor shelf conditions, detect out-of-stock situations, and track inventory levels using computer vision analysis.

Functional Behavior: - Monitor shelf conditions continuously across all product categories - Detect out-of-stock, low-stock, and overstock situations in real-time - Verify product placement compliance with planogram specifications - Track inventory movement patterns and restocking activities - Generate automated alerts for inventory management actions - Provide visual inventory reports with shelf condition photography

Acceptance Criteria: - Out-of-stock detection accuracy â‰¥90% within 15 minutes of occurrence - Stock level estimation accuracy within Â±20% of actual inventory - Planogram compliance verification accuracy â‰¥85% - Inventory alert generation within 5 minutes of threshold breach - Shelf monitoring coverage â‰¥95% of store product areas - Visual report generation within 30 seconds of request

FR-006: Product Placement and Planogram Compliance

Description: System shall verify product placement compliance with planogram specifications and provide optimization recommendations.

Functional Behavior: - Compare actual product placement with digital planogram specifications - Detect misplaced products and planogram violations - Analyze product performance based on placement and visibility - Generate placement optimization recommendations based on customer behavior - Track promotional display compliance and effectiveness - Provide visual compliance reports with corrective action suggestions

Acceptance Criteria: - Planogram compliance detection accuracy â‰¥85% - Misplaced product identification accuracy â‰¥80% - Compliance report generation within 2 minutes of scan completion - Optimization recommendations based on â‰¥30 days of behavior data - Promotional display monitoring accuracy â‰¥90% - Visual compliance reports include actionable corrective measures

FR-007: Supply Chain Integration and Reorder Automation

Description: System shall integrate with supply chain and inventory management systems to automate reorder processes and optimize stock levels.

Functional Behavior: - Interface with existing ERP and WMS systems via APIs - Generate automated reorder recommendations based on stock levels and sales velocity - Track supplier performance and delivery compliance - Optimize safety stock levels based on demand patterns and lead times - Provide demand forecasting based on customer behavior and seasonal trends - Generate supply chain performance reports and analytics

Acceptance Criteria: - ERP/WMS integration success rate â‰¥98% for data synchronization - Reorder recommendation accuracy â‰¥85% compared to manual analysis - Demand forecasting accuracy within Â±15% of actual sales - Supply chain report generation within 24 hours of data collection - Safety stock optimization reduces carrying costs by â‰¥10% - Integration API response time <2 seconds for standard operations

3. Loss Prevention and Security Module

FR-008: Suspicious Activity Detection and Alerting

Description: System shall detect suspicious activities and behaviors that may indicate theft, fraud, or security threats and generate real-time alerts.

Functional Behavior: - Monitor customer and staff behavior for suspicious patterns and anomalies - Detect potential theft activities including concealment, switching, and walkouts - Identify loitering, aggressive behavior, and other security concerns - Generate real-time alerts to security personnel with video evidence - Track repeat offenders using anonymous behavioral fingerprinting - Integrate with existing security systems and alarm networks

Acceptance Criteria: - Suspicious activity detection recall â‰¥75% with â‰¤15% false positive rate - Theft detection accuracy â‰¥80% for common theft scenarios - Alert generation time <30 seconds from suspicious activity detection - Security integration success rate â‰¥95% with existing alarm systems - Behavioral fingerprinting accuracy â‰¥70% for repeat identification - Video evidence capture completeness â‰¥90% for security incidents

FR-009: Perimeter Security and Access Control

Description: System shall monitor store perimeters, entrances, and restricted areas to detect unauthorized access and security breaches.

Functional Behavior: - Monitor store entrances and exits for unauthorized access attempts - Detect after-hours intrusions and perimeter breaches - Track staff access to restricted areas and verify authorization - Monitor emergency exits for improper use and security violations - Generate security alerts for access control violations - Provide forensic video analysis capabilities for incident investigation

Acceptance Criteria: - Perimeter breach detection accuracy â‰¥95% during closed hours - Unauthorized access detection accuracy â‰¥90% in restricted areas - Emergency exit monitoring accuracy â‰¥98% for improper use detection - Security alert generation within 15 seconds of violation detection - Forensic analysis capability with â‰¥30 days of video retention - Access control integration success rate â‰¥95% with existing systems

FR-010: Incident Documentation and Forensic Analysis

Description: System shall provide comprehensive incident documentation, forensic analysis capabilities, and evidence management for security investigations.

Functional Behavior: - Automatically capture and store video evidence for security incidents - Generate detailed incident reports with timestamps, locations, and involved parties - Provide video search and analysis tools for forensic investigation - Maintain chain of custody documentation for legal proceedings - Export evidence in standard formats for law enforcement and legal use - Generate statistical reports on security incidents and trends

Acceptance Criteria: - Incident documentation completeness â‰¥95% for all security events - Video evidence capture within 30 seconds before and after incidents - Forensic search accuracy â‰¥90% for time, location, and person-based queries - Evidence export compliance with legal standards and chain of custody requirements - Incident report generation within 5 minutes of event conclusion - Statistical reporting accuracy â‰¥95% for trend analysis and performance metrics

4. Automated Checkout and Payment Module

FR-011: Cashierless Shopping Experience

Description: System shall provide a seamless cashierless shopping experience with automatic product recognition, cart tracking, and payment processing.

Functional Behavior: - Identify customers entering the store using mobile app or payment card - Track customer movements and shopping cart throughout store visit - Automatically detect product additions and removals from shopping cart - Calculate total purchase amount including taxes, discounts, and promotions - Process payment automatically upon store exit using registered payment method - Generate digital receipts and update loyalty program accounts

Acceptance Criteria: - Customer identification accuracy â‰¥95% at store entry - Product addition/removal detection accuracy â‰¥98% for cart tracking - Purchase calculation accuracy â‰¥99.5% including taxes and promotions - Payment processing success rate â‰¥99% for registered customers - Digital receipt delivery within 2 minutes of store exit - Loyalty program integration accuracy â‰¥98% for point accrual and redemption

FR-012: Hybrid Checkout Support

Description: System shall support hybrid checkout options including self-service, mobile scan-and-go, and staff-assisted checkout with AI enhancement.

Functional Behavior: - Provide self-service checkout with AI-powered product recognition assistance - Support mobile app scan-and-go functionality with cart verification - Assist staff-operated checkout with automatic product identification - Detect checkout errors, fraud attempts, and age-restricted purchases - Optimize checkout lane assignment based on queue lengths and customer needs - Provide multilingual support for diverse customer base

Acceptance Criteria: - Self-service checkout accuracy â‰¥95% with AI assistance - Mobile scan-and-go verification accuracy â‰¥98% compared to actual cart contents - Staff checkout assistance reduces scan time by â‰¥30% - Error detection accuracy â‰¥90% for common checkout mistakes - Queue optimization reduces average wait time by â‰¥40% - Multilingual support for â‰¥5 languages with â‰¥95% accuracy

FR-013: Payment Processing and Fraud Prevention

Description: System shall process payments securely and detect fraudulent activities and payment anomalies.

Functional Behavior: - Support multiple payment methods including cards, mobile payments, and digital wallets - Encrypt payment data and maintain PCI DSS compliance - Detect payment fraud patterns and suspicious transaction behaviors - Verify age-restricted purchases and implement compliance controls - Process refunds and returns with automated verification - Generate payment analytics and transaction reports

Acceptance Criteria: - Payment method support for â‰¥95% of customer preferred options - PCI DSS compliance verification with annual certification - Fraud detection accuracy â‰¥85% with â‰¤5% false positive rate - Age verification accuracy â‰¥98% for restricted products - Refund processing accuracy â‰¥99% with automated verification - Payment analytics generation within 24 hours of transaction completion

5. Integration and Management Module

FR-014: POS and Retail System Integration

Description: System shall integrate seamlessly with existing POS systems, inventory management, and retail operations platforms.

Functional Behavior: - Connect with major POS systems via standardized APIs and protocols - Synchronize product catalogs, pricing, and promotional information - Share transaction data and customer analytics with retail systems - Support real-time inventory updates and stock level synchronization - Integrate with loyalty programs and customer relationship management systems - Provide data export capabilities for business intelligence and reporting

Acceptance Criteria: - POS integration success rate â‰¥98% across major retail platforms - Product catalog synchronization accuracy â‰¥99.5% - Real-time inventory sync latency <30 seconds - Transaction data sharing completeness â‰¥99% - Loyalty program integration accuracy â‰¥95% for customer identification

- Data export completion within 15 minutes for standard reports

FR-015: Cloud Synchronization and Remote Management

Description: System shall provide cloud synchronization capabilities and remote management tools for multi-store deployments.

Functional Behavior: - Synchronize analytics data and insights with cloud management platform - Enable remote system monitoring, configuration, and troubleshooting - Support over-the-air software updates and model deployments - Provide centralized dashboard for multi-store analytics and performance - Implement role-based access control for remote management functions - Generate consolidated reports across store locations and regions

Acceptance Criteria: - Cloud synchronization success rate â‰¥99% with automatic retry mechanisms - Remote management capability coverage â‰¥95% of system functions - Software update deployment success rate â‰¥98% across all stores - Multi-store dashboard load time <5 seconds for standard reports - Role-based access control accuracy â‰¥99% for permission enforcement - Consolidated reporting generation within 30 minutes for enterprise queries

This comprehensive FRD provides detailed functional specifications for all core system modules, ensuring complete coverage of retail automation requirements while maintaining alignment with business objectives and user needs defined in the README and PRD. # Non-Functional Requirements Document (NFRD) ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README, PRD, and FRD foundations for comprehensive system quality specifications

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview, technical themes, and expected business outcomes
- âœ… PRD completed with business objectives, success metrics, and technical requirements
- âœ… FRD completed with 15 detailed functional requirements across 5 system modules
- âœ… Technical performance targets defined (<100ms latency, 95% accuracy, 99.5% uptime)
- âœ… User personas and usage patterns identified for scalability planning

TASK

Define comprehensive non-functional requirements covering performance, scalability, reliability, security, usability, compliance, and operational aspects that ensure the Smart Retail Edge Vision platform meets enterprise-grade quality standards and retail industry requirements.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] Performance requirements aligned with PRD success metrics (<100ms latency, 95% accuracy) - [ ] Scalability requirements support 1000+ store deployments and edge computing constraints - [ ] Security requirements address retail compliance (PCI DSS, privacy regulations) - [ ] Reliability requirements ensure 99.5% uptime with autonomous edge operation - [ ] Usability requirements support diverse retail staff and customer interactions

Validation Criteria: - [ ] Performance requirements validated with computer vision experts and edge computing specialists - [ ] Scalability requirements validated with retail IT directors and deployment teams - [ ] Security requirements validated with retail security experts and compliance officers - [ ] Reliability requirements validated with store operations teams and SRE specialists - [ ] Usability requirements validated with retail staff and customer experience teams

EXIT CRITERIA

- âœ… Complete non-functional requirements covering all quality aspects
- âœ… Measurable criteria defined for each requirement enabling comprehensive testing
- âœ… Performance benchmarks established for edge AI optimization
- âœ… Security and compliance framework specified for retail deployment
- âœ… Foundation prepared for Architecture Diagram (AD) development

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Reference to Previous Documents

This NFRD builds upon **README**, **PRD**, and **FRD** foundations: - **README Expected Outcomes** â†’ Quantified performance targets (25% cost reduction, 40% loss prevention improvement, 30% customer satisfaction increase) - **PRD Success Metrics** â†’ Technical performance requirements (<100ms latency, 99.5% uptime, 1000+ store support) - **FRD Functional Requirements** â†’ Quality attributes supporting real-time computer vision, edge processing, and retail integration - **PRD User Personas** â†’ Usability and operational requirements addressing store manager, IT director, and customer needs

1. Performance Requirements

NFR-001: Real-time Computer Vision Processing Performance

Requirement: System shall provide real-time computer vision processing with minimal latency to support immediate retail decision-making and customer experience optimization.

Specifications: - **Object Detection Latency**: <100ms from frame capture to detection results - **Product Recognition Speed**: <200ms per product identification request - **Behavior Analysis Processing**: <3 seconds for customer journey analysis updates - **Multi-Camera Processing**: Support â‰¥16 concurrent camera streams without performance degradation - **Edge Inference Throughput**: â‰¥30 FPS processing capability per camera stream

Measurement Criteria: - Latency measured using 95th percentile response times across all supported hardware configurations - Performance testing conducted with realistic retail scenarios and peak customer traffic - Load testing validates performance under maximum camera load (16+ streams) - Continuous monitoring with alerting for latency degradation >20% from baseline

NFR-002: Accuracy and Quality Standards

Requirement: System shall maintain high accuracy standards for all computer vision and AI processing to ensure reliable retail operations and business value.

Specifications: - **Object Detection Accuracy**: â‰¥95% for products, people, and shopping carts - **Product Recognition Accuracy**: â‰¥98% for catalog products in optimal conditions - **Behavior Analysis Accuracy**: â‰¥90% for customer tracking and journey mapping - **Inventory Detection Accuracy**: â‰¥90% for out-of-stock and stock level estimation - **Security Alert Precision**: â‰¥75% recall with â‰¤15% false positive rate

Measurement Criteria: - Accuracy metrics calculated using manually annotated ground truth datasets - Quality assessment performed by retail experts using standardized evaluation criteria - Continuous model performance monitoring with automated retraining triggers - A/B testing framework for model improvements and accuracy validation

NFR-003: Edge Computing Performance and Resource Utilization

Requirement: System shall efficiently utilize edge computing resources to maximize performance while minimizing hardware costs and power consumption.

Specifications: - **CPU Utilization**: 70-85% average utilization under normal load - **GPU Utilization**: 80-95% utilization for AI inference workloads - **Memory Usage**: <16GB RAM usage for standard store configuration - **Storage Efficiency**: <1TB local storage for models, cache, and 30-day data retention - **Power Consumption**: <500W total system power draw per store deployment

Measurement Criteria: - Resource utilization monitored continuously with optimization recommendations - Performance benchmarking across different edge hardware configurations - Power consumption measured under various load conditions and seasonal patterns - Storage optimization validated through data lifecycle management testing

2. Scalability Requirements

NFR-004: Multi-Store Deployment Scalability

Requirement: System architecture shall support scalable deployment across thousands of retail locations with centralized management and monitoring.

Specifications: - **Store Deployment Capacity**: Support 1000+ concurrent store deployments - **Centralized Management**: Single dashboard managing all store locations - **Configuration Distribution**: Automated configuration updates across all stores within 1 hour - **Data Aggregation**: Consolidated analytics processing for enterprise-wide insights - **Network Bandwidth**: <10 Mbps per store for cloud synchronization and management

Measurement Criteria: - Scalability testing performed with simulated 1000+ store network - Management dashboard performance validated with enterprise-scale data volumes - Configuration distribution success rate measured across diverse network conditions - Data aggregation performance tested with multi-terabyte retail datasets

NFR-005: Edge Computing Scalability and Flexibility

Requirement: System shall scale efficiently on edge hardware while supporting diverse retail environments and store configurations.

Specifications: - **Hardware Flexibility**: Support NVIDIA Jetson AGX Xavier, Intel NUC, and custom edge devices - **Camera Scalability**: 4-32 cameras per store with dynamic resource allocation - **Model Scalability**: Dynamic loading of AI models based on store requirements - **Processing Elasticity**: Automatic workload distribution based on available resources - **Store Size Adaptation**: Configuration templates for small, medium, and large retail formats

Measurement Criteria: - Hardware compatibility validated across all supported edge computing platforms - Camera scaling tested with various store layouts and traffic patterns - Model loading performance measured for different combinations and configurations - Resource allocation effectiveness validated through stress testing scenarios

3. Reliability and Availability Requirements

NFR-006: System Uptime and Availability

Requirement: System shall maintain high availability to ensure continuous retail operations and minimize business disruption.

Specifications: - **System Uptime**: 99.5% availability (â‰¤43.8 hours downtime per year) - **Edge Autonomy**: 100% functionality during internet connectivity outages - **Mean Time to Recovery (MTTR)**: <30 minutes for critical system restoration - **Mean Time Between Failures (MTBF)**: >2160 hours (90 days) for core components - **Planned Maintenance**: <4 hours monthly maintenance window with zero business impact

Measurement Criteria: - Uptime calculated using continuous system health monitoring and alerting - Edge autonomy validated through network disconnection testing scenarios - Recovery time measured from failure detection to full system restoration - Availability metrics tracked per store with consolidated enterprise reporting

NFR-007: Data Integrity and Backup

Requirement: System shall ensure complete data integrity and provide comprehensive backup and recovery capabilities for retail operations continuity.

Specifications: - **Data Durability**: 99.99% durability for all retail analytics and transaction data - **Local Backup**: Real-time local backup with 30-day retention on edge devices - **Cloud Synchronization**: Daily synchronization with cloud backup and analytics platform - **Recovery Time Objective (RTO)**: <1 hour for critical retail operations restoration - **Recovery Point Objective (RPO)**: <15 minutes maximum data loss in failure scenarios

Measurement Criteria: - Data integrity verified through automated checksums and consistency validation - Backup and recovery procedures tested weekly with full restoration validation - RTO and RPO metrics measured through disaster recovery simulations - Cloud synchronization reliability monitored with automatic retry mechanisms

NFR-008: Fault Tolerance and Resilience

Requirement: System shall continue operating with degraded functionality during component failures and maintain essential retail operations.

Specifications: - **Camera Failure Tolerance**: Continue operation with up to 25% camera failures - **Network Resilience**: Full offline capability with automatic reconnection - **Hardware Redundancy**: Critical component redundancy for high-availability configurations - **Graceful Degradation**: Core retail functions maintained during non-critical failures - **Self-Healing**: Automatic recovery and restart of failed system components

Measurement Criteria: - Fault tolerance validated through systematic component failure testing - Network resilience tested with various connectivity scenarios and outage durations - Hardware redundancy effectiveness measured through failure simulation - Graceful degradation scenarios tested with business impact assessment

4. Security Requirements

NFR-009: Data Protection and Privacy

Requirement: System shall implement comprehensive data protection measures to secure customer privacy and retail business information.

Specifications: - **Video Data Encryption**: AES-256 encryption for all video streams and stored footage - **Anonymous Analytics**: Customer behavior analysis without personal identification - **Data Minimization**: Collect and process only necessary data for retail operations - **Secure Transmission**: TLS 1.3 for all network communications and cloud synchronization - **Privacy Compliance**: GDPR, CCPA, and regional privacy regulation compliance

Measurement Criteria: - Encryption coverage verified through security audits and penetration testing - Privacy compliance validated through third-party privacy assessments - Data minimization practices audited against business necessity requirements - Secure transmission verified through network security scanning and monitoring

NFR-010: Access Control and Authentication

Requirement: System shall implement robust access control mechanisms to prevent unauthorized access to retail systems and data.

Specifications: - **Role-Based Access Control**: Granular permissions for store staff, managers, and IT administrators - **Multi-Factor Authentication**: MFA required for all administrative and management access - **API Security**: OAuth 2.0 and API key authentication for system integrations - **Physical Security**: Tamper detection and secure boot for edge hardware - **Session Management**: Automatic session timeout and secure credential storage

Measurement Criteria: - Access control effectiveness validated through security testing and audit procedures - MFA enforcement rate monitored with exception reporting and remediation tracking - API security validated through automated security testing and vulnerability assessments - Physical security measures tested through tamper simulation and penetration attempts

NFR-011: Compliance and Audit

Requirement: System shall meet retail industry compliance requirements and provide comprehensive audit capabilities.

Specifications: - **PCI DSS Compliance**: Payment card industry security standards for payment processing - **Retail Security Standards**: Industry-specific security frameworks and best practices - **Audit Trail Completeness**: 100% audit coverage for all system actions and data access - **Data Retention Policies**: Configurable retention with automatic enforcement and legal hold - **Compliance Monitoring**: Continuous compliance monitoring with automated reporting

Measurement Criteria: - PCI DSS compliance maintained through annual certification and quarterly assessments - Audit trail completeness verified through sampling and coverage analysis - Data retention policy compliance monitored with automated enforcement validation - Compliance monitoring effectiveness measured through violation detection and remediation

5. Usability and User Experience Requirements

NFR-012: User Interface Performance and Responsiveness

Requirement: System shall provide responsive and intuitive user interfaces for retail staff and management across all platforms.

Specifications: - **Dashboard Load Time**: <3 seconds for standard analytics dashboards - **Mobile App Responsiveness**: <1 second response time for common retail operations - **Real-time Updates**: <5 seconds latency for live analytics and alert notifications - **Cross-Platform Compatibility**: Consistent experience across web, mobile, and tablet interfaces - **Offline Functionality**: Core features available during network connectivity issues

Measurement Criteria: - Interface performance measured using synthetic monitoring from retail store locations - Mobile app performance tested across different device models and operating system versions - Real-time update latency measured during peak usage periods and high data volumes - Cross-platform compatibility validated through comprehensive user interface testing

NFR-013: Accessibility and Ease of Use

Requirement: System shall be accessible to retail staff with diverse technical skills and support inclusive design principles.

Specifications: - **Learning Curve**: <2 hours training required for basic system proficiency - **Intuitive Design**: Self-explanatory interface requiring minimal documentation - **Accessibility Standards**: WCAG 2.1 AA compliance for visual and motor accessibility - **Multilingual Support**: Interface localization for 10+ languages and regional preferences - **Error Prevention**: Proactive error prevention and clear recovery guidance

Measurement Criteria: - Training effectiveness measured through user competency assessments and feedback - Interface intuitiveness validated through usability testing with retail staff - Accessibility compliance verified through automated testing tools and manual audits - Multilingual functionality tested by native speakers for accuracy and cultural appropriateness

NFR-014: Operational Simplicity and Maintenance

Requirement: System shall be designed for minimal operational overhead and simplified maintenance procedures.

Specifications: - **Self-Service Configuration**: 90% of system configuration through intuitive interfaces - **Automated Maintenance**: Automatic system updates and maintenance with minimal downtime - **Proactive Monitoring**: Predictive alerts and recommendations for system optimization - **Remote Diagnostics**: Comprehensive remote troubleshooting and support capabilities - **Documentation Quality**: Complete documentation with video tutorials and best practices

Measurement Criteria: - Self-service configuration success rate measured through user completion analytics - Automated maintenance effectiveness tracked through system health and performance metrics - Proactive monitoring accuracy validated through incident prevention and early detection - Remote diagnostics capability coverage verified for all common system issues

6. Operational Requirements

NFR-015: Monitoring and Observability

Requirement: System shall provide comprehensive monitoring and observability for operational excellence and proactive issue resolution.

Specifications: - **Real-time Monitoring**: Complete system health monitoring with <1 minute alert latency - **Performance Analytics**: Detailed performance metrics and trend analysis - **Business Intelligence**: Retail KPI tracking and automated insights generation - **Predictive Maintenance**: AI-powered predictive maintenance and optimization recommendations - **Integration Monitoring**: End-to-end monitoring of all retail system integrations

Measurement Criteria: - Monitoring coverage verified through system dependency mapping and gap analysis - Alert accuracy measured through false positive rates and mean time to acknowledge - Performance analytics validated through correlation with actual business outcomes - Predictive maintenance effectiveness measured through issue prevention and cost savings

NFR-016: Deployment and Updates

Requirement: System shall support efficient deployment operations and seamless updates across retail environments.

Specifications: - **Zero-Downtime Deployments**: Rolling updates with no business operation interruption - **Automated Deployment**: Fully automated deployment pipeline with rollback capabilities - **Configuration Management**: Infrastructure as code with version control and audit trails - **Update Frequency**: Monthly security updates and quarterly feature releases - **Deployment Validation**: Automated testing and validation for all deployments

Measurement Criteria: - Deployment success rate measured with automatic rollback trigger validation - Update deployment time tracked with optimization targets for continuous improvement - Configuration management effectiveness verified through compliance scanning and drift detection - Deployment validation coverage measured through automated test execution and quality gates

This comprehensive NFRD establishes the quality framework necessary to deliver an enterprise-grade Smart Retail Edge Vision platform that meets all performance, security, and operational requirements while ensuring exceptional user experience and business value in retail environments. # Architecture Diagram (AD) ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README, PRD, FRD, and NFRD foundations for comprehensive system architecture

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview, technical themes, and implementation strategy
- âœ… PRD completed with business objectives, user personas, and technical requirements
- âœ… FRD completed with 15 functional requirements across 5 system modules
- âœ… NFRD completed with performance (<100ms latency), scalability (1000+ stores), security (PCI DSS, privacy compliance), and reliability (99.5% uptime) requirements
- âœ… Integration requirements defined for POS systems, inventory management, and security systems

TASK

Design comprehensive system architecture including edge computing design, computer vision pipeline, retail analytics platform, integration patterns, security framework, and hybrid cloud-edge deployment strategy that supports real-time retail intelligence, autonomous operation, and enterprise scalability.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] Architecture supports all functional requirements from FRD - [ ] Performance requirements achievable with proposed edge computing design (<100ms latency, 1000+ stores) - [ ] Security architecture addresses retail compliance (PCI DSS, privacy regulations) - [ ] Scalability design supports autonomous edge operation and centralized management - [ ] Integration architecture accommodates all specified retail systems and platforms

Validation Criteria: - [ ] Architecture validated with retail technology experts and edge computing specialists - [ ] Computer vision pipeline validated with CV engineers and ML specialists - [ ] Security architecture validated with retail security experts and compliance officers - [ ] Integration patterns validated with POS vendors and retail system documentation - [ ] Deployment strategy validated with retail IT directors and operations teams

EXIT CRITERIA

- âœ… Complete system architecture with all components and interactions specified
- âœ… Edge computing architecture supporting real-time processing requirements
- âœ… Security and compliance framework integrated throughout architecture
- âœ… Scalable deployment strategy with hybrid cloud-edge distribution
- âœ… Foundation prepared for High Level Design (HLD) development

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Reference to Previous Documents

This AD builds upon **README**, **PRD**, **FRD**, and **NFRD** foundations: - **README Technical Themes** â†’ Architecture supporting edge AI processing, computer vision pipeline, and privacy-preserving analytics - **PRD Success Metrics** â†’ Architecture enabling 95% accuracy, <100ms latency, and 1000+ store deployments - **FRD Functional Requirements** â†’ System components supporting real-time computer vision, behavior analytics, and retail integration - **NFRD Performance**

Requirements â†’ Architecture optimized for edge computing performance, security, and scalability

1. System Architecture Overview

1.1 High-Level Architecture Pattern

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┌─────────────────────────────────────────────────────────────────────────────┐
│                        CLOUD MANAGEMENT LAYER                               │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│  Enterprise │  Analytics  │  Model      │  Configuration │  Monitoring │
│  Dashboard  │  Platform   │  Management │  Management │  & Alerts   │
│  (React)    │  (Apache Spark)│  (MLflow)   │  (Ansible)  │  (Grafana)  │
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                                    │
                                    ▼ (Secure VPN/API Gateway)
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│                           EDGE GATEWAY                                      │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│  API Gateway │  Security   │  Data Sync  │  Model Update │  Health   │
│  (Kong)     │  Proxy      │  Manager    │  Manager    │  Monitor    │
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│                         EDGE COMPUTING LAYER                                │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│ Computer Vision│ Behavior    │ Inventory   │ Security    │ Checkout    │
│ Engine      │ Analytics   │ Manager     │ Monitor     │ Assistant   │
│ (TensorRT)  │ (OpenCV)    │ (PostgreSQL) │ (YOLO)      │ (FastAPI)   │
├─────────────┼─────────────┼─────────────┼─────────────┼─────────────┼─────────┤
│ Video Stream │ AI Inference │ Local Storage │ Event Stream │ Integration │
│ Processor   │ Engine      │ Manager     │ Processor   │ Hub         │
│ (GStreamer) │ (ONNX Runtime) │ (InfluxDB)  │ (Apache Kafka) │ (REST APIs) │
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│                          HARDWARE LAYER                                     │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│ IP Cameras  │ Edge Computer │ Network     │ Storage     │ Sensors     │
│ (RTSP/HTTP) │ (Jetson AGX) │ (WiFi 6/5G) │ (NVMe SSD)  │ (IoT)       │
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1.2 Core Architectural Principles

- **Edge-First Design**: Primary processing at edge with cloud for management and analytics
- **Real-time Processing**: <100ms latency for critical computer vision operations
- **Autonomous Operation**: Full functionality without internet connectivity
- **Privacy by Design**: Anonymous analytics without personal identification
- **Scalable Deployment**: Support for single store to enterprise chain deployments
- **Hybrid Intelligence**: Edge inference with cloud-based model training and updates

2. Edge Computing Architecture

2.1 Edge Hardware Configuration

Primary Edge Computing Platform

NVIDIA Jetson AGX Xavier: - **AI Performance**: 32 TOPS for neural network inference - **CPU**: 8-core ARM v8.2 64-bit CPU, 8MB L2 + 4MB L3 - **GPU**: 512-core Volta GPU with Tensor Cores - **Memory**: 32GB 256-bit LPDDR4x | 137 GB/s - **Storage**: 32GB eUFS + 1TB NVMe SSD expansion - **Connectivity**: Gigabit Ethernet, WiFi 6, Bluetooth 5.0

Alternative Edge Platforms: - **Intel NUC with GPU**: Intel Core i7 + NVIDIA RTX 4060 - **Custom Edge Appliance**: ARM-based with dedicated AI accelerators - **Embedded Vision Systems**: Purpose-built retail edge computers

2.2 Edge Software Stack

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┌─────────────────────────────────────────────────────────────────────────────┐
│                          APPLICATION LAYER                                  │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│  Retail Apps │  Analytics  │  Security   │  Checkout   │  Management │
│  (Python/C++) │  Dashboard  │  Monitor    │  Assistant  │  Agent      │
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                                    │
┌─────────────────────────────────────────────────────────────────────────────┐
│                          MIDDLEWARE LAYER                                   │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│  Message Queue │  API Gateway │  Data Pipeline │  Model Server │  Config Mgr │
│  (Redis/Kafka) │  (Kong)     │  (Apache Beam) │  (TensorRT) │  (Consul)   │
└─────────────┴─────────────┴─────────────┴─────────────┴─────────────┴─────────┘
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│                          RUNTIME LAYER                                      │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│  Container  │  AI Framework │  Video      │  Database   │  Monitoring │
│  Runtime    │  (TensorRT/ │  Processing │  (PostgreSQL/ │  (Prometheus│
│  (Docker)   │  ONNX Runtime) │  (GStreamer) │  InfluxDB)  │  /Grafana)  │
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│                          OPERATING SYSTEM                                   │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│  Ubuntu 20.04 LTS │  NVIDIA JetPack │  Docker Engine │  System Services │
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3. Computer Vision Pipeline Architecture

3.1 Video Processing Pipeline

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┌─────────────────────────────────────────────────────────────────────────────┐
│                          VIDEO INPUT LAYER                                  │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│ IP Camera 1 │ IP Camera 2 │ IP Camera N │ RTSP Streams │ USB Cameras │
│ (4K@30fps)  │ (4K@30fps)  │ (4K@30fps)  │ (H.264/H.265) │ (Backup)    │
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│                        VIDEO STREAM MANAGER                                 │
├─────────────┬─────────────┬─────────────┬─────────────┬─────────────┬─────────┤
│ Stream Ingestion │ Format      │ Frame       │ Quality     │ Buffer      │
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â”‚ (GStreamer)     â”‚ Conversion     â”‚ Extraction     â”‚ Enhancement    â”‚ Management  â”‚
â”‚                 â”‚ (FFmpeg)       â”‚ (OpenCV)       â”‚ (DeepStream)   â”‚ (Ring Bufferâ”‚
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â”‚                    AI INFERENCE ENGINE                                      â”‚
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â”‚ Object Detectionâ”‚ Person Trackingâ”‚ Product        â”‚ Behavior       â”‚ Security    â”‚
â”‚ (YOLOv8)        â”‚ (DeepSORT)     â”‚ Recognition    â”‚ Analysis       â”‚ Monitoring  â”‚
â”‚                 â”‚                â”‚ (ResNet)       â”‚ (Custom CNN)   â”‚ (Anomaly)   â”‚
â”œâ”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€â”€
â”‚ Model Ensemble â”‚ Confidence     â”‚ Post-Processingâ”‚ Result Fusion  â”‚ Quality     â”‚
â”‚ (Multi-Model)   â”‚ Scoring        â”‚ (NMS/Tracking) â”‚ (Kalman Filter)â”‚ Assessment  â”‚
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â”‚                    ANALYTICS PROCESSOR                                      â”‚
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â”‚ Real-time       â”‚ Behavior       â”‚ Inventory      â”‚ Security       â”‚ Business    â”‚
â”‚ Analytics       â”‚ Insights       â”‚ Analytics      â”‚ Alerts         â”‚ Intelligenceâ”‚
â”‚ (Apache Flink)  â”‚ (Custom Logic) â”‚ (Computer Visionâ”‚ (Rule Engine)  â”‚ (ML Models) â”‚
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3.2 AI Model Architecture

Primary Models: - **Object Detection**: YOLOv8 optimized for retail environments - **Person Tracking**: DeepSORT with re-identification capabilities - **Product Recognition**: ResNet-50 with transfer learning for retail products - **Behavior Analysis**: Custom CNN for shopping pattern recognition - **Security Monitoring**: Anomaly detection with unsupervised learning

Model Optimization: - **TensorRT Optimization**: INT8 quantization for 3x inference speedup - **ONNX Runtime**: Cross-platform model deployment and optimization - **Model Pruning**: 50% model size reduction with <2% accuracy loss - **Dynamic Batching**: Optimal batch size selection for throughput maximization - **Multi-GPU Inference**: Distributed processing across available GPUs

4. Data Architecture and Storage

4.1 Edge Data Management

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â”‚ Video Streams  â”‚ AI Inference   â”‚ Sensor Data    â”‚ Event Streams  â”‚ Alerts      â”‚
â”‚ (Memory Buffer)â”‚ Results        â”‚ (IoT Sensors)  â”‚ (Apache Kafka) â”‚ (Redis Pub/Subâ”‚
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â”‚ Retail Analyticsâ”‚ Customer       â”‚ Inventory      â”‚ Security       â”‚ System      â”‚
â”‚ (PostgreSQL)    â”‚ Behavior       â”‚ Data           â”‚ Events         â”‚ Metrics     â”‚
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â”‚ Video Archive  â”‚ Historical     â”‚ Compliance     â”‚ Backup Data    â”‚ Model       â”‚
â”‚ (Object Store) â”‚ Analytics      â”‚ Records        â”‚ (Local/Cloud)  â”‚ Artifacts   â”‚
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4.2 Database Schema Design

PostgreSQL (Operational Data): - **Stores**: Store configuration, layout, and metadata - **Cameras**: Camera configuration, calibration, and status - **Products**: Product catalog, SKUs, and visual features - **Analytics**: Customer behavior, inventory levels, and business metrics - **Security**: Incident reports, alerts, and compliance records

InfluxDB (Time-Series Data): - **System Metrics**: CPU, GPU, memory, and network utilization - **Performance Metrics**: Inference latency, accuracy, and throughput - **Business Metrics**: Customer traffic, dwell times, and conversion rates - **Alert Metrics**: Security events, system alerts, and response times

Redis (Caching and Real-time Data): - **Model Cache**: Frequently used AI model weights and configurations - **Session Data**: Active customer sessions and tracking states - **Real-time Analytics**: Live dashboards and streaming metrics - **Message Queue**: Event distribution and inter-service communication

5. Integration Architecture

5.1 Retail System Integration Hub

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â”‚  (Kong)        â”‚  Adapters      â”‚  Transformationâ”‚  Proxy         â”‚  & Logging  â”‚
â”‚                â”‚  (REST/SOAP)   â”‚  (ETL Pipeline)â”‚  (OAuth/JWT)   â”‚  (ELK Stack)â”‚
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â”‚ Shopify)       â”‚ (SAP/Oracle)   â”‚ (Hikvision)    â”‚ (Loyalty Apps) â”‚ (Tableau)   â”‚
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5.2 API Architecture and Standards

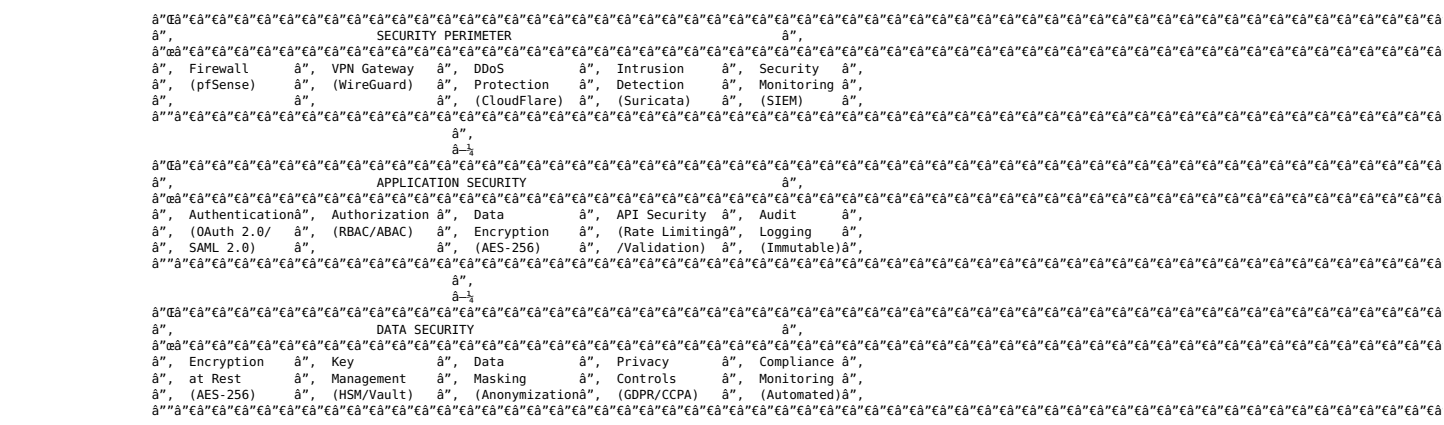
RESTful API Design: - **Resource-Based URLs**: `/api/v1/stores/{store_id}/cameras/{camera_id}` - **HTTP Methods**: GET, POST, PUT, DELETE for CRUD operations - **Status Codes**: Standard HTTP status codes with detailed error messages - **Content Negotiation**: JSON primary, XML secondary format support - **Versioning**: URL-based versioning with backward compatibility

WebSocket Connections: - **Real-time Updates**: Live analytics, alerts, and system status - **Video Streaming**: Low-latency video feeds for remote monitoring - **Bidirectional Communication**: Commands, configuration updates, and responses - **Connection Management**: Automatic reconnection and heartbeat monitoring

Message Queue Integration: - **Apache Kafka**: High-throughput event streaming and data pipeline - **Redis Pub/Sub**: Real-time notifications and cache invalidation - **RabbitMQ**: Reliable message delivery for critical business events - **Event Sourcing**: Immutable event log for audit and replay capabilities

6. Security Architecture

6.1 Comprehensive Security Framework



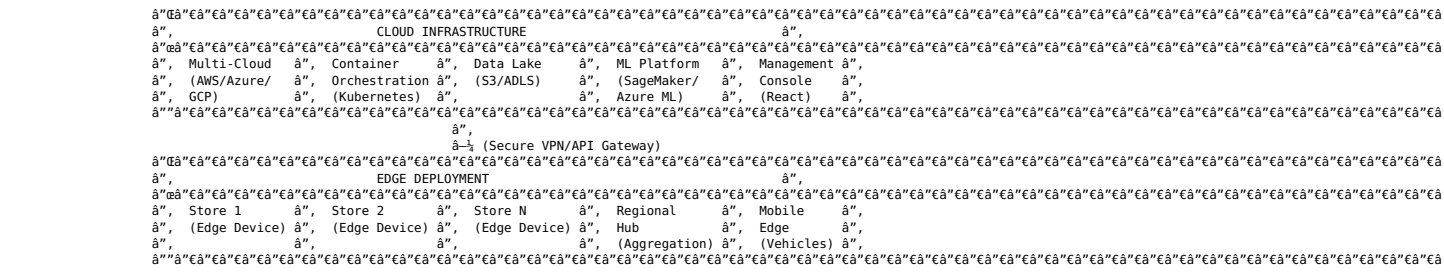
6.2 Privacy-Preserving Architecture

Anonymous Analytics: - **Face Blurring**: Real-time face detection and anonymization - **Demographic Inference**: Age/gender estimation without identification - **Behavioral Fingerprinting**: Anonymous customer journey tracking - **Data Minimization**: Collect only necessary data for business operations - **Retention Policies**: Automatic data deletion after retention period

Compliance Framework: - **GDPR Compliance**: Right to be forgotten, data portability, consent management - **CCPA Compliance**: Consumer privacy rights and data transparency - **PCI DSS**: Payment card security for checkout and payment processing - **HIPAA**: Healthcare privacy for pharmacy and medical retail environments - **SOC 2**: Security controls for service organization operations

7. Deployment Architecture

7.1 Hybrid Cloud-Edge Deployment



7.2 Container Orchestration and Management

Kubernetes Architecture: - **Master Node**: Cloud-based control plane for centralized management - **Edge Nodes**: Lightweight Kubernetes distribution (K3s) on edge devices - **Service Mesh**: Istio for secure service-to-service communication - **GitOps**: ArgoCD for declarative deployment and configuration management - **Monitoring**: Prometheus and Grafana for comprehensive observability

Container Strategy: - **Microservices**: Containerized services for modularity and scalability - **Multi-Architecture**: ARM64 and x86_64 support for diverse hardware - **Resource Optimization**: Resource limits and requests for efficient utilization - **Health Checks**: Liveness and readiness probes for automatic recovery - **Rolling Updates**: Zero-downtime deployments with automatic rollback

7.3 Network Architecture and Connectivity

Edge Networking: - **Primary**: Gigabit Ethernet for high-bandwidth video processing - **Backup**: WiFi 6 for redundant connectivity and mobile devices - **Cellular**: 4G/5G for remote locations and backup connectivity - **VPN**: WireGuard for secure cloud communication - **Local Network**: VLAN segmentation for security and performance

Bandwidth Optimization: - **Edge Processing**: 90% local processing to minimize bandwidth usage - **Data Compression**: Video and data compression for efficient transmission - **Intelligent Sync**: Selective cloud synchronization based on business value - **QoS**: Traffic prioritization for critical business operations - **Caching**: Local caching to reduce redundant data transfer

This comprehensive architecture provides a robust, scalable, and secure foundation for the Smart Retail Edge Vision platform, supporting all functional and non-functional requirements while enabling autonomous edge operation and enterprise-scale deployment. # High Level Design (HLD) ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README, PRD, FRD, NFRD, and AD foundations for detailed component specifications

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview and technical approach
- âœ… PRD completed with business objectives and success metrics
- âœ… FRD completed with 15 functional requirements across 5 modules
- âœ… NFRD completed with performance, scalability, and security requirements
- âœ… AD completed with edge computing architecture and deployment strategy

TASK

Define detailed component specifications, API designs, data models, processing workflows, and AI/ML architectures for all system components.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] Component specifications align with edge computing architecture - [ ] API designs support all functional requirements with <100ms latency - [ ] Data models accommodate retail analytics and privacy requirements - [ ] AI/ML workflows meet accuracy targets (95%+ object detection)

Validation Criteria: - [ ] HLD validated with retail technology experts and computer vision specialists - [ ] API designs validated with edge computing and integration requirements - [ ] Data models validated with retail operations teams and privacy experts - [ ] AI/ML workflows validated with data science and ML engineering teams

EXIT CRITERIA

- âœ… Complete component specifications ready for implementation
- âœ… API designs with detailed interface definitions
- âœ… Data models supporting all functional requirements
- âœ… Foundation prepared for Low Level Design (LLD) development

---

1. Core System Components

1.1 Computer Vision Engine

Component Specification:

```
class ComputerVisionEngine:
    def __init__(self, config: CVConfig):
        self.object_detector = ObjectDetector(model="yolov8n", device="cuda")
        self.person_tracker = PersonTracker(algorithm="deepsort")
        self.product_recognizer = ProductRecognizer(catalog_size=100000)
        self.behavior_analyzer = BehaviorAnalyzer(models=["activity", "gesture"])

    async def process_frame(self, frame: np.ndarray, camera_id: str) -> CVResult:
        # Multi-stage processing pipeline
        objects = await self.object_detector.detect(frame)
        persons = await self.person_tracker.update(objects.persons, camera_id)
        products = await self.product_recognizer.identify(objects.products)
        behaviors = await self.behavior_analyzer.analyze(persons, frame)

        return CVResult(objects, persons, products, behaviors)
```

API Endpoints: - `POST /api/v1/cv/process` - Process single frame - `WebSocket /ws/cv/stream/{camera_id}` - Real-time video processing - `GET /api/v1/cv/models` - Available AI models - `PUT /api/v1/cv/models/{model_id}` - Update AI model

Performance Specifications: - Processing latency: <100ms per frame - Throughput: 30 FPS per camera stream - Accuracy: 95%+ object detection, 90%+ person tracking - Concurrent streams: 16+ cameras simultaneously

1.2 Retail Analytics Service

Component Specification:

```
class RetailAnalyticsService:
    def __init__(self, store_config: StoreConfig):
        self.customer_tracker = CustomerTracker()
        self.inventory_monitor = InventoryMonitor()
        self.behavior_analyzer = BehaviorAnalyzer()
        self.metrics_calculator = MetricsCalculator()

    async def analyze_customer_behavior(self, tracking_data: List[PersonTrack]) -> CustomerAnalytics:
        journeys = self.customer_tracker.generate_journeys(tracking_data)
        dwell_times = self.calculate_dwell_times(journeys)
        heat_maps = self.generate_heat_maps(journeys)
        engagement = self.analyze_engagement(journeys)

        return CustomerAnalytics(journeys, dwell_times, heat_maps, engagement)

    async def monitor_inventory(self, shelf_data: List[ShelfDetection]) -> InventoryStatus:
        stock_levels = self.inventory_monitor.estimate_levels(shelf_data)
        out_of_stock = self.detect_stockouts(stock_levels)
        compliance = self.check_planogram_compliance(shelf_data)

        return InventoryStatus(stock_levels, out_of_stock, compliance)
```

Data Models:

```
-- Customer behavior analytics
CREATE TABLE customer_journeys (
    id UUID PRIMARY KEY,
    store_id UUID NOT NULL,
    anonymous_id VARCHAR(64) NOT NULL,
    start_time TIMESTAMP WITH TIME ZONE,
    end_time TIMESTAMP WITH TIME ZONE,
    path JSONB NOT NULL,
    zones_visited TEXT[],
    total_dwell_time INTEGER,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);

-- Inventory monitoring
CREATE TABLE inventory_snapshots (
    id UUID PRIMARY KEY,
    store_id UUID NOT NULL,
    shelf_id VARCHAR(50) NOT NULL,
    product_sku VARCHAR(100) NOT NULL,
    estimated_quantity INTEGER,
    confidence DECIMAL(3,2),
    out_of_stock BOOLEAN DEFAULT FALSE,
    snapshot_time TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);
```

1.3 Security Monitoring System

Component Specification:

```
class SecurityMonitoringSystem:
    def __init__(self, security_config: SecurityConfig):
        self.anomaly_detector = AnomalyDetector()
        self.threat_classifier = ThreatClassifier()
        self.alert_manager = AlertManager()
        self.incident_recorder = IncidentRecorder()

    async def monitor_security(self, cv_results: CVResult, camera_id: str) -> SecurityAssessment:
        anomalies = await self.anomaly_detector.detect(cv_results)
        threats = await self.threat_classifier.classify(anomalies)

        if threats:
            alerts = await self.alert_manager.generate_alerts(threats)
            incidents = await self.incident_recorder.record(threats, camera_id)

        return SecurityAssessment(anomalies, threats, alerts)
```

Alert System: - Real-time threat detection with <30 second response - Multi-level alert severity (Low, Medium, High, Critical) - Integration with existing security systems - Automated incident documentation and evidence collection

2. AI/ML Model Architecture

2.1 Object Detection Pipeline

YOLOv8 Optimization for Retail:

```
class RetailObjectDetector:
    def __init__(self):
        self.model = YOLO("yolov8n.pt")  # Nano version for edge
        self.retail_classes = [
            "person", "shopping_cart", "product", "shelf",
            "checkout_counter", "entrance", "exit"
        ]

    def optimize_for_edge(self):
        # TensorRT optimization
        self.model.export(format="engine", device="cuda", half=True)
        # INT8 quantization for 3x speedup
        self.model = TRTInference("yolov8n.engine")

    async def detect_objects(self, frame: np.ndarray) -> DetectionResult:
        results = self.model(frame, conf=0.5, iou=0.4)
        return self.parse_results(results)
```

Model Performance Targets: - Inference time: <50ms per frame on Jetson AGX Xavier - Accuracy: 95%+ mAP@0.5 for retail objects - Model size: <50MB for edge deployment - Memory usage: <2GB GPU memory

2.2 Product Recognition System

Multi-Modal Product Recognition:

```
class ProductRecognitionSystem:
    def __init__(self, catalog_path: str):
        self.visual_encoder = ResNet50(pretrained=True)
        self.product_database = ProductDatabase(catalog_path)
        self.similarity_matcher = SimilarityMatcher()

    async def recognize_product(self, product_image: np.ndarray) -> ProductMatch:
        # Extract visual features
        features = self.visual_encoder.encode(product_image)

        # Search product database
        candidates = self.product_database.search(features, top_k=5)

        # Calculate similarity scores
        matches = self.similarity_matcher.match(features, candidates)

        return ProductMatch(matches[0] if matches else None, confidence=matches[0].score)
```

Product Database Schema:

```
CREATE TABLE products (
    sku VARCHAR(100) PRIMARY KEY,
    name VARCHAR(255) NOT NULL,
    category VARCHAR(100),
    brand VARCHAR(100),
    visual_features VECTOR(2048),
    barcode VARCHAR(50),
    price DECIMAL(10,2),
    created_at TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);

CREATE INDEX idx_products_visual_features ON products USING ivfflat (visual_features vector_cosine_ops);
```

2.3 Behavior Analysis Models

Customer Behavior Classification:

```
class BehaviorAnalyzer:
    def __init__(self):
        self.activity_classifier = ActivityClassifier()
        self.gesture_recognizer = GestureRecognizer()
        self.engagement_scorer = EngagementScorer()

    async def analyze_behavior(self, person_track: PersonTrack, context: StoreContext) -> BehaviorAnalysis:
        activities = await self.activity_classifier.classify(person_track.poses)
        gestures = await self.gesture_recognizer.recognize(person_track.keypoints)
        engagement = await self.engagement_scorer.score(person_track, context)

        return BehaviorAnalysis(activities, gestures, engagement)
```

Behavior Categories: - **Shopping Activities**: browsing, examining, selecting, purchasing - **Movement Patterns**: walking, standing, queuing, exiting - **Engagement Levels**: high, medium, low based on dwell time and interactions - **Suspicious Behaviors**: concealment, switching, unusual patterns

3. Data Processing Workflows

3.1 Real-time Processing Pipeline

```
graph TD
    A[Video Stream] --> B[Frame Extraction]
    B --> C[Object Detection]
    C --> D[Person Tracking]
    D --> E[Product Recognition]
    E --> F[Behavior Analysis]
    F --> G[Analytics Processing]
    G --> H[Real-time Dashboard]
    G --> I[Alert Generation]
    G --> J[Data Storage]
```

Processing Stages: 1. **Video Ingestion**: RTSP stream capture and buffering 2. **Frame Processing**: Object detection and tracking 3. **Feature Extraction**: Product and behavior recognition 4. **Analytics Computation**: Real-time metrics calculation 5. **Output Generation**: Dashboards, alerts, and data storage

3.2 Batch Processing Workflows

Daily Analytics Processing:

```
class BatchAnalyticsProcessor:
    def __init__(self):
        self.data_aggregator = DataAggregator()
        self.report_generator = ReportGenerator()
```

```
        self.insight_extractor = InsightExtractor()

    async def process_daily_analytics(self, store_id: str, date: datetime) -> DailyReport:
        # Aggregate raw data
        customer_data = await self.data_aggregator.aggregate_customers(store_id, date)
        inventory_data = await self.data_aggregator.aggregate_inventory(store_id, date)
        security_data = await self.data_aggregator.aggregate_security(store_id, date)

        # Generate insights
        insights = await self.insight_extractor.extract(customer_data, inventory_data)

        # Create comprehensive report
        report = await self.report_generator.generate(
            customer_data, inventory_data, security_data, insights
        )

        return report
```

4. Integration Layer Design

4.1 POS System Integration

Universal POS Connector:

```
class POSIntegrationHub:
    def __init__(self):
        self.connectors = {
            "square": SquareConnector(),
            "shopify": ShopifyConnector(),
            "ncr": NCRConnector(),
            "toast": ToastConnector()
        }

    async def sync_transaction(self, pos_type: str, transaction_data: TransactionData) -> SyncResult:
        connector = self.connectors.get(pos_type)
        if not connector:
            raise UnsupportedPOSException(f"POS type {pos_type} not supported")

        result = await connector.sync_transaction(transaction_data)
        return result

    async def update_inventory(self, pos_type: str, inventory_updates: List[InventoryUpdate]) -> UpdateResult:
        connector = self.connectors[pos_type]
        return await connector.update_inventory(inventory_updates)
```

API Integration Patterns: - **REST APIs**: Standard HTTP-based integration for most POS systems - **Webhooks**: Real-time event notifications for transaction updates - **File-based**: CSV/XML file exchange for legacy systems - **Database Direct**: Direct database integration for supported systems

4.2 Cloud Synchronization Service

Hybrid Cloud-Edge Data Sync:

```
class CloudSyncService:
    def __init__(self, cloud_config: CloudConfig):
        self.cloud_client = CloudClient(cloud_config)
        self.sync_scheduler = SyncScheduler()
        self.data_compressor = DataCompressor()

    async def sync_analytics_data(self, store_id: str) -> SyncStatus:
        # Prepare data for sync
        local_data = await self.collect_local_data(store_id)
        compressed_data = await self.data_compressor.compress(local_data)

        # Upload to cloud
        sync_result = await self.cloud_client.upload_analytics(compressed_data)

        # Update sync status
        await self.update_sync_status(store_id, sync_result)

        return sync_result
```

5. Security and Privacy Implementation

5.1 Privacy-Preserving Analytics

Anonymous Customer Tracking:

```
class PrivacyPreservingTracker:
    def __init__(self):
        self.face_anonymizer = FaceAnonymizer()
        self.demographic_estimator = DemographicEstimator()
        self.journey_tracker = JourneyTracker()

    async def track_customer(self, person_detection: PersonDetection) -> AnonymousCustomer:
        # Anonymize personal features
        anonymized_features = await self.face_anonymizer.anonymize(person_detection.face)

        # Extract demographic info without identification
        demographics = await self.demographic_estimator.estimate(anonymized_features)

        # Generate anonymous tracking ID
        tracking_id = self.generate_anonymous_id(anonymized_features)

        return AnonymousCustomer(tracking_id, demographics, anonymized_features)
```

Data Minimization Strategy: - Collect only necessary data for business operations - Automatic data expiration and deletion policies - On-device processing to minimize data transmission - Encrypted storage with access controls

5.2 Compliance Framework

GDPR/CCPA Compliance Implementation:

```
class ComplianceManager:
    def __init__(self):
        self.data_processor = DataProcessor()
        self.consent_manager = ConsentManager()
        self.audit_logger = AuditLogger()

    async def handle_data_request(self, request: DataRequest) -> DataResponse:
        # Validate request
        if not await self.validate_request(request):
            raise InvalidRequestException("Invalid data request")

        # Process based on request type
```

```
        if request.type == "access":
            data = await self.data_processor.extract_user_data(request.user_id)
            return DataResponse(data)
        elif request.type == "deletion":
            await self.data_processor.delete_user_data(request.user_id)
            return DataResponse(status="deleted")

        # Log for audit
        await self.audit_logger.log_request(request)
```

6. Performance Optimization

6.1 Edge Computing Optimization

Resource Management:

```
class EdgeResourceManager:
    def __init__(self):
        self.gpu_scheduler = GPUScheduler()
        self.memory_manager = MemoryManager()
        self.model_cache = ModelCache()

    async def optimize_inference(self, workload: InferenceWorkload) -> OptimizationPlan:
        # Analyze current resource usage
        gpu_usage = await self.gpu_scheduler.get_usage()
        memory_usage = await self.memory_manager.get_usage()

        # Create optimization plan
        plan = OptimizationPlan()

        if gpu_usage > 0.9:
            plan.add_action("reduce_batch_size")
            plan.add_action("enable_model_quantization")

        if memory_usage > 0.8:
            plan.add_action("clear_model_cache")
            plan.add_action("reduce_buffer_size")

        return plan
```

Performance Monitoring: - Real-time resource utilization tracking - Automatic performance optimization - Predictive scaling based on store traffic patterns - Alert generation for performance degradation

This comprehensive HLD provides detailed component specifications and design patterns needed for implementing the Smart Retail Edge Vision platform while maintaining alignment with all previous requirements and architectural decisions. # Low Level Design (LLD) ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README, PRD, FRD, NFRD, AD, and HLD foundations for implementation-ready specifications

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview and technical approach
- âœ… PRD completed with business objectives and success metrics
- âœ… FRD completed with 15 functional requirements across 5 modules
- âœ… NFRD completed with performance, scalability, and security requirements
- âœ… AD completed with edge computing architecture and deployment strategy
- âœ… HLD completed with component specifications and API designs

TASK

Develop implementation-ready detailed class structures, database schemas, API implementations, algorithm specifications, configuration files, and deployment scripts for all system components.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] Class structures implement all HLD component specifications - [ ] Database schemas support all data models and performance requirements - [ ] API implementations include validation, error handling, and security - [ ] Algorithm specifications provide step-by-step implementation guidance

Validation Criteria: - [ ] LLD validated with senior developers and technical leads - [ ] Database schemas validated with DBA and performance teams - [ ] API implementations validated with security and integration teams - [ ] Configuration files validated with DevOps and infrastructure teams

EXIT CRITERIA

- âœ… Complete implementation-ready class structures and database schemas
- âœ… API implementations with comprehensive error handling and validation
- âœ… Algorithm specifications for all AI/ML processing components
- âœ… Configuration files and deployment scripts for production deployment
- âœ… Foundation prepared for Pseudocode development

---

1. Core Service Implementation

1.1 Computer Vision Engine Implementation

Class Structure:

```
# src/computer_vision/engine.py
import asyncio
import logging
import numpy as np
from typing import List, Dict, Optional, Tuple
from dataclasses import dataclass
from datetime import datetime
import cv2
import torch
from ultralytics import YOLO

@dataclass
class CVResult:
    camera_id: str
    timestamp: datetime
    objects: List[DetectedObject]
    persons: List[TrackedPerson]
    products: List[RecognizedProduct]
    behaviors: List[DetectedBehavior]
    processing_time: float
    confidence_scores: Dict[str, float]
```

```
class ComputerVisionEngine:
    def __init__(self, config: CVConfig):
        self.config = config
        self.logger = logging.getLogger(__name__)

        # Initialize AI models
        self.object_detector = self._initialize_object_detector()
        self.person_tracker = self._initialize_person_tracker()
        self.product_recognizer = self._initialize_product_recognizer()
        self.behavior_analyzer = self._initialize_behavior_analyzer()

        # Performance monitoring
        self.performance_metrics = PerformanceMetrics()

    async def process_frame(self, frame: np.ndarray, camera_id: str) -> CVResult:
        """Process single frame through complete CV pipeline"""
        start_time = time.time()

        try:
            # Validate input frame
            if not self._validate_frame(frame):
                raise InvalidFrameError("Invalid frame format or size")

            # Stage 1: Object Detection
            objects = await self._detect_objects(frame)

            # Stage 2: Person Tracking
            persons = await self._track_persons(objects, camera_id, frame)

            # Stage 3: Product Recognition
            products = await self._recognize_products(objects, frame)

            # Stage 4: Behavior Analysis
            behaviors = await self._analyze_behaviors(persons, frame)

            # Calculate performance metrics
            total_time = time.time() - start_time

            # Create result
            result = CVResult(
                camera_id=camera_id,
                timestamp=datetime.utcnow(),
                objects=objects,
                persons=persons,
                products=products,
                behaviors=behaviors,
                processing_time=total_time,
                confidence_scores=self._calculate_confidence_scores(objects, persons, products)
            )

            return result

        except Exception as e:
            self.logger.error(f"Frame processing failed for camera {camera_id}: {str(e)}")
            raise CVProcessingError(f"Frame processing failed: {str(e)}")
```

1.2 Database Schema Implementation

PostgreSQL Schema:

```
-- Stores table
CREATE TABLE stores (
    id UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    name VARCHAR(255) NOT NULL,
    address TEXT,
    timezone VARCHAR(50) DEFAULT 'UTC',
    configuration JSONB NOT NULL DEFAULT '{}',
    created_at TIMESTAMP WITH TIME ZONE DEFAULT NOW(),
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);

-- Cameras table
CREATE TABLE cameras (
    id UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    store_id UUID NOT NULL REFERENCES stores(id) ON DELETE CASCADE,
    name VARCHAR(255) NOT NULL,
    rtsp_url VARCHAR(500) NOT NULL,
    position JSONB NOT NULL,
    field_of_view JSONB NOT NULL,
    status camera_status_enum DEFAULT 'active',
    configuration JSONB DEFAULT '{}',
    created_at TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);

CREATE TYPE camera_status_enum AS ENUM ('active', 'inactive', 'maintenance', 'error');

-- Object detections with time-based partitioning
CREATE TABLE object_detections (
    id UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    camera_id UUID NOT NULL REFERENCES cameras(id) ON DELETE CASCADE,
    object_class VARCHAR(50) NOT NULL,
    confidence DECIMAL(4,3) NOT NULL,
    bbox_x1 INTEGER NOT NULL,
    bbox_y1 INTEGER NOT NULL,
    bbox_x2 INTEGER NOT NULL,
    bbox_y2 INTEGER NOT NULL,
    center_x INTEGER NOT NULL,
    center_y INTEGER NOT NULL,
    area INTEGER NOT NULL,
    detected_at TIMESTAMP WITH TIME ZONE DEFAULT NOW()
) PARTITION BY RANGE (detected_at);

-- Person tracking table
CREATE TABLE person_tracks (
    id UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    store_id UUID NOT NULL REFERENCES stores(id) ON DELETE CASCADE,
    track_id VARCHAR(100) NOT NULL,
    demographic_age_group VARCHAR(20),
    demographic_gender VARCHAR(20),
    entry_time TIMESTAMP WITH TIME ZONE,
    exit_time TIMESTAMP WITH TIME ZONE,
    total_dwell_time INTEGER,
    path JSONB,
    zones_visited TEXT[],
    created_at TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);

-- Security events
CREATE TABLE security_events (
```

```
    id UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    store_id UUID NOT NULL REFERENCES stores(id) ON DELETE CASCADE,
    camera_id UUID NOT NULL REFERENCES cameras(id) ON DELETE CASCADE,
    event_type security_event_type_enum NOT NULL,
    severity security_severity_enum NOT NULL,
    description TEXT,
    confidence DECIMAL(4,3),
    resolved BOOLEAN DEFAULT FALSE,
    event_time TIMESTAMP WITH TIME ZONE DEFAULT NOW()
);

CREATE TYPE security_event_type_enum AS ENUM (
    'suspicious_behavior', 'potential_theft', 'loitering',
    'aggressive_behavior', 'perimeter_breach'
);

CREATE TYPE security_severity_enum AS ENUM ('low', 'medium', 'high', 'critical');

-- Performance indexes
CREATE INDEX idx_object_detections_camera_time ON object_detections (camera_id, detected_at);
CREATE INDEX idx_person_tracks_store_entry ON person_tracks (store_id, entry_time);
CREATE INDEX idx_security_events_store_severity ON security_events (store_id, severity, event_time);
```

1.3 API Implementation

FastAPI Service:

```
# src/api/main.py
from fastapi import FastAPI, HTTPException, Depends, WebSocket
from fastapi.security import HTTPBearer
from pydantic import BaseModel, Field
from typing import List, Optional, Dict
import asyncio
import json
import logging
from datetime import datetime

app = FastAPI(
    title="Smart Retail Edge Vision API",
    description="AI-Powered Computer Vision System for Retail Analytics",
    version="1.0.0"
)

security = HTTPBearer()

# Request/Response Models
class ProcessFrameRequest(BaseModel):
    camera_id: str = Field(..., description="Camera identifier")
    frame_data: str = Field(..., description="Base64 encoded frame data")
    timestamp: Optional[datetime] = Field(default=None)

class ProcessFrameResponse(BaseModel):
    camera_id: str
    timestamp: datetime
    processing_time: float
    objects_detected: int
    persons_tracked: int
    products_recognized: int
    confidence_scores: Dict[str, float]

class SecurityAlert(BaseModel):
    id: str
    store_id: str
    camera_id: str
    event_type: str
    severity: str
    description: str
    timestamp: datetime
    confidence: float

# Computer Vision Endpoints
@app.post("/api/v1/cv/process", response_model=ProcessFrameResponse)
async def process_frame(
    request: ProcessFrameRequest,
    cv_engine = Depends(get_cv_engine)
):
    """Process single frame through computer vision pipeline"""
    try:
        # Decode frame data
        frame_bytes = base64.b64decode(request.frame_data)
        frame = cv2.imdecode(np.frombuffer(frame_bytes, np.uint8), cv2.IMREAD_COLOR)

        if frame is None:
            raise HTTPException(status_code=400, detail="Invalid frame data")

        # Process frame
        result = await cv_engine.process_frame(frame, request.camera_id)

        # Create response
        response = ProcessFrameResponse(
            camera_id=result.camera_id,
            timestamp=result.timestamp,
            processing_time=result.processing_time,
            objects_detected=len(result.objects),
            persons_tracked=len(result.persons),
            products_recognized=len(result.products),
            confidence_scores=result.confidence_scores
        )

        return response

    except Exception as e:
        logging.error(f"Frame processing failed: {str(e)}")
        raise HTTPException(status_code=500, detail="Frame processing failed")

@app.websocket("/ws/cv/stream/{camera_id}")
async def websocket_cv_stream(websocket: WebSocket, camera_id: str):
    """WebSocket endpoint for real-time computer vision processing"""
    await websocket.accept()

    try:
        while True:
            # Receive frame data
            data = await websocket.receive_text()
            frame_data = json.loads(data)

            # Process frame and send results
            # Implementation details...
```

```
    except WebSocketDisconnect:
        logging.info(f"WebSocket disconnected for camera {camera_id}")

@app.get("/api/v1/security/alerts", response_model=List[SecurityAlert])
async def get_security_alerts(
    store_id: str,
    severity: Optional[str] = None,
    limit: int = 100
):
    """Get recent security alerts"""
    try:
        # Implementation details...
        return alerts
    except Exception as e:
        raise HTTPException(status_code=500, detail="Security alerts request failed")

@app.get("/health")
async def health_check():
    """Health check endpoint"""
    return {
        "status": "healthy",
        "timestamp": datetime.utcnow().isoformat(),
        "version": "1.0.0"
    }
```

1.4 Configuration Files

Docker Compose:

```
# docker-compose.yml
version: '3.8'

services:
  retail-vision-app:
    build:
      context: .
      dockerfile: Dockerfile.edge
    container_name: retail-vision-app
    restart: unless-stopped
    environment:
      - DATABASE_URL=postgresql://postgres:password@postgres:5432/retail_vision
      - REDIS_URL=redis://redis:6379
      - LOG_LEVEL=INFO
    volumes:
      - ./config:/app/config
      - ./models:/app/models
      - ./logs:/app/logs
    ports:
      - "8000:8000"
      - "8001:8001"
    depends_on:
      - postgres
      - redis
    deploy:
      resources:
        reservations:
          devices:
            - driver: nvidia
              count: 1
              capabilities: [gpu]

  postgres:
    image: postgres:14-alpine
    container_name: retail-vision-postgres
    restart: unless-stopped
    environment:
      - POSTGRES_DB=retail_vision
      - POSTGRES_USER=postgres
      - POSTGRES_PASSWORD=password
    volumes:
      - postgres_data:/var/lib/postgresql/data
    ports:
      - "5432:5432"

  redis:
    image: redis:7-alpine
    container_name: retail-vision-redis
    restart: unless-stopped
    volumes:
      - redis_data:/data
    ports:
      - "6379:6379"

volumes:
  postgres_data:
  redis_data:
```

Environment Configuration:

```
# config/production.yaml
database:
  host: ${DATABASE_HOST:localhost}
  port: ${DATABASE_PORT:5432}
  name: ${DATABASE_NAME:retail_vision}
  username: ${DATABASE_USERNAME:postgres}
  password: ${DATABASE_PASSWORD:password}
  ssl: true
  pool_size: 20

redis:
  url: ${REDIS_URL:redis://localhost:6379}
  max_connections: 50

computer_vision:
  models:
    object_detection:
      model_path: "/app/models/yolov8n.engine"
      confidence_threshold: 0.5
      iou_threshold: 0.4
    person_tracking:
      max_disappeared: 30
      max_distance: 100
  performance:
    max_processing_time: 0.1  # 100ms
    target_fps: 30

security:
  alert_thresholds:
    suspicious_behavior: 0.7
```

```
    potential_theft: 0.8
    loitering: 0.6
  notification:
    enabled: true
    webhook_url: ${SECURITY_WEBHOOK_URL}

logging:
  level: ${LOG_LEVEL:INFO}
  format: json
  handlers:
    - console
    - file
```

This LLD provides implementation-ready specifications with detailed class structures, database schemas, API implementations, and configuration files for direct development implementation. # Pseudocode ## Smart Retail Edge Vision - AI-Powered Computer Vision System for Retail Analytics and Automation

Building upon README, PRD, FRD, NFRD, AD, HLD, and LLD foundations for executable implementation algorithms

ETVX Framework

ENTRY CRITERIA

- âœ… README completed with problem overview and technical approach
- âœ… PRD completed with business objectives and success metrics
- âœ… FRD completed with 15 functional requirements across 5 modules
- âœ… NFRD completed with performance, scalability, and security requirements
- âœ… AD completed with edge computing architecture and deployment strategy
- âœ… HLD completed with component specifications and API designs
- âœ… LLD completed with implementation-ready class structures and database schemas

TASK

Develop executable pseudocode algorithms for all core system components including computer vision processing, retail analytics, security monitoring, integration workflows, and performance optimization.

VERIFICATION & VALIDATION

Verification Checklist: - [ ] Pseudocode algorithms align with LLD class implementations - [ ] Processing workflows meet performance requirements (<100ms latency) - [ ] Security algorithms implement privacy-preserving analytics - [ ] Integration algorithms support all retail system connectors

Validation Criteria: - [ ] Pseudocode validated with computer vision and AI/ML experts - [ ] Algorithms validated with retail operations and security teams - [ ] Performance algorithms validated with edge computing specialists - [ ] Integration workflows validated with retail technology partners

EXIT CRITERIA

- âœ… Complete executable pseudocode for all system components
- âœ… Performance optimization algorithms for edge deployment
- âœ… Security and privacy-preserving processing algorithms
- âœ… Integration workflows for retail ecosystem connectivity
- âœ… Implementation-ready foundation for development teams

Reference to Previous Documents

This Pseudocode builds upon **README**, **PRD**, **FRD**, **NFRD**, **AD**, **HLD**, and **LLD** foundations: - **LLD Class Structures** â†’ Executable algorithms with method implementations - **HLD Processing Workflows** â†’ Step-by-step algorithmic procedures - **NFRD Performance Requirements** â†’ Optimization algorithms for <100ms latency - **AD Security Framework** â†’ Privacy-preserving and security algorithms

1. Computer Vision Processing Algorithms

1.1 Main Frame Processing Pipeline

```
ALGORITHM: ProcessVideoFrame
INPUT: frame (image), camera_id (string), timestamp (datetime)
OUTPUT: CVResult (objects, persons, products, behaviors, metrics)

BEGIN ProcessVideoFrame
    start_time = getCurrentTime()

    // Input validation
    IF NOT ValidateFrame(frame) THEN
        THROW InvalidFrameException("Frame validation failed")
    END IF

    // Stage 1: Object Detection
    detection_start = getCurrentTime()
    detected_objects = DetectObjects(frame)
    detection_time = getCurrentTime() - detection_start

    // Stage 2: Person Tracking
    tracking_start = getCurrentTime()
    tracked_persons = TrackPersons(detected_objects, camera_id, frame)
    tracking_time = getCurrentTime() - tracking_start

    // Stage 3: Product Recognition
    recognition_start = getCurrentTime()
    recognized_products = RecognizeProducts(detected_objects, frame)
    recognition_time = getCurrentTime() - recognition_start

    // Stage 4: Behavior Analysis
    behavior_start = getCurrentTime()
    detected_behaviors = AnalyzeBehaviors(tracked_persons, frame)
    behavior_time = getCurrentTime() - behavior_start

    // Performance monitoring
    total_time = getCurrentTime() - start_time
    IF total_time > MAX_PROCESSING_TIME THEN
        LogPerformanceWarning(camera_id, total_time)
        TriggerOptimization(camera_id)
    END IF

    // Create comprehensive result
    result = CVResult{
        camera_id: camera_id,
        timestamp: timestamp,
        objects: detected_objects,
        persons: tracked_persons,
        products: recognized_products,
        behaviors: detected_behaviors,
        processing_time: total_time,
        confidence_scores: CalculateConfidenceScores(detected_objects, tracked_persons, recognized_products)
```

```
    }

    // Store results asynchronously
    AsyncStoreResults(result)

    RETURN result
END ProcessVideoFrame
```

1.2 Object Detection Algorithm

```
ALGORITHM: DetectObjects
INPUT: frame (image)
OUTPUT: List<DetectedObject>

BEGIN DetectObjects
    // Preprocess frame for optimal inference
    preprocessed_frame = PreprocessFrame(frame)

    // Run TensorRT optimized YOLO inference
    raw_detections = RunYOLOInference(preprocessed_frame)

    // Post-process detections
    filtered_detections = []
    FOR each detection IN raw_detections DO
        IF detection.confidence >= CONFIDENCE_THRESHOLD THEN
            // Apply Non-Maximum Suppression
            IF NOT IsOverlapping(detection, filtered_detections, IOU_THRESHOLD) THEN
                object = DetectedObject{
                    object_id: GenerateObjectID(),
                    class_name: detection.class_name,
                    confidence: detection.confidence,
                    bbox: detection.bbox,
                    center_point: CalculateCenter(detection.bbox),
                    area: CalculateArea(detection.bbox),
                    timestamp: getCurrentTime()
                }
                filtered_detections.append(object)
            END IF
        END IF
    END FOR

    RETURN filtered_detections
END DetectObjects

ALGORITHM: PreprocessFrame
INPUT: frame (image)
OUTPUT: preprocessed_frame (tensor)

BEGIN PreprocessFrame
    // Resize to model input dimensions
    resized_frame = ResizeImage(frame, TARGET_WIDTH, TARGET_HEIGHT)

    // Normalize pixel values to [0, 1]
    normalized_frame = resized_frame / 255.0

    // Convert BGR to RGB
    rgb_frame = ConvertBGRToRGB(normalized_frame)

    // Convert to tensor format
    tensor_frame = ConvertToTensor(rgb_frame)

    RETURN tensor_frame
END PreprocessFrame
```

1.3 Person Tracking Algorithm

```
ALGORITHM: TrackPersons
INPUT: detected_objects (List<DetectedObject>), camera_id (string), frame (image)
OUTPUT: List<TrackedPerson>

BEGIN TrackPersons
    // Extract person detections
    person_detections = []
    FOR each object IN detected_objects DO
        IF object.class_name == "person" THEN
            person_detections.append(object)
        END IF
    END FOR

    // Update existing tracks
    active_tracks = GetActiveTracks(camera_id)
    updated_tracks = []

    FOR each track IN active_tracks DO
        best_match = FindBestMatch(track, person_detections)
        IF best_match != NULL AND CalculateDistance(track.last_position, best_match.center_point) < MAX_TRACKING_DISTANCE THEN
            // Update track
            track.positions.append(best_match.center_point)
            track.last_seen = getCurrentTime()
            track.confidence = UpdateConfidence(track.confidence, best_match.confidence)

            // Extract demographic information (privacy-preserving)
            IF track.demographic_info == NULL THEN
                track.demographic_info = ExtractDemographics(best_match, frame)
            END IF

            updated_tracks.append(track)
            person_detections.remove(best_match)
        ELSE
            // Mark track as lost if not seen for too long
            IF getCurrentTime() - track.last_seen > MAX_DISAPPEARED_TIME THEN
                FinalizeTrack(track)
            ELSE
                track.missed_frames += 1
                updated_tracks.append(track)
            END IF
        END IF
    END FOR

    // Create new tracks for unmatched detections
    FOR each detection IN person_detections DO
        new_track = TrackedPerson{
            track_id: GenerateAnonymousID(),
            camera_id: camera_id,
            positions: [detection.center_point],
            first_seen: getCurrentTime(),
            last_seen: getCurrentTime(),
            demographic_info: ExtractDemographics(detection, frame),
```

```
            confidence: detection.confidence,
            missed_frames: 0
        }
        updated_tracks.append(new_track)
    END FOR

    // Update track storage
    UpdateTrackStorage(camera_id, updated_tracks)

    RETURN updated_tracks
END TrackPersons

ALGORITHM: ExtractDemographics
INPUT: detection (DetectedObject), frame (image)
OUTPUT: DemographicInfo (age_group, gender_estimate)

BEGIN ExtractDemographics
    // Extract face region (if visible)
    face_region = ExtractFaceRegion(detection.bbox, frame)

    IF face_region != NULL THEN
        // Anonymize face to protect privacy
        anonymized_features = AnonymizeFace(face_region)

        // Estimate demographics without identification
        age_group = EstimateAgeGroup(anonymized_features)  // young, adult, senior
        gender_estimate = EstimateGender(anonymized_features)  // statistical estimate only

        RETURN DemographicInfo{
            age_group: age_group,
            gender_estimate: gender_estimate,
            confidence: CalculateDemographicConfidence(anonymized_features)
        }
    ELSE
        RETURN NULL
    END IF
END ExtractDemographics
```

1.4 Product Recognition Algorithm

```
ALGORITHM: RecognizeProducts
INPUT: detected_objects (List<DetectedObject>), frame (image)
OUTPUT: List<RecognizedProduct>

BEGIN RecognizeProducts
    // Extract product detections
    product_detections = []
    FOR each object IN detected_objects DO
        IF object.class_name == "product" OR object.class_name == "package" THEN
            product_detections.append(object)
        END IF
    END FOR

    recognized_products = []
    FOR each detection IN product_detections DO
        // Extract product image region
        product_image = ExtractImageRegion(detection.bbox, frame)

        // Extract visual features
        visual_features = ExtractVisualFeatures(product_image)

        // Search product database
        candidate_products = SearchProductDatabase(visual_features, TOP_K_CANDIDATES)

        // Calculate similarity scores
        best_match = NULL
        highest_similarity = 0.0

        FOR each candidate IN candidate_products DO
            similarity = CalculateCosineSimilarity(visual_features, candidate.features)
            IF similarity > highest_similarity AND similarity > PRODUCT_SIMILARITY_THRESHOLD THEN
                highest_similarity = similarity
                best_match = candidate
            END IF
        END FOR

        // Create recognized product if match found
        IF best_match != NULL THEN
            product = RecognizedProduct{
                product_id: GenerateProductID(),
                sku: best_match.sku,
                name: best_match.name,
                category: best_match.category,
                confidence: highest_similarity,
                bbox: detection.bbox,
                shelf_location: DetermineShelfLocation(detection.bbox),
                timestamp: getCurrentTime()
            }
            recognized_products.append(product)
        END IF
    END FOR

    RETURN recognized_products
END RecognizeProducts

ALGORITHM: ExtractVisualFeatures
INPUT: product_image (image)
OUTPUT: feature_vector (array)

BEGIN ExtractVisualFeatures
    // Preprocess image
    preprocessed_image = PreprocessProductImage(product_image)

    // Extract features using ResNet50 backbone
    feature_vector = RunResNetInference(preprocessed_image)

    // Normalize features
    normalized_features = L2Normalize(feature_vector)

    RETURN normalized_features
END ExtractVisualFeatures
```

2. Retail Analytics Algorithms

2.1 Customer Behavior Analysis

```
ALGORITHM: AnalyzeCustomerBehavior
```

```
INPUT: tracked_persons (List<TrackedPerson>), time_window (duration)
OUTPUT: CustomerAnalytics

BEGIN AnalyzeCustomerBehavior
    analytics = CustomerAnalytics{}

    // Calculate customer journeys
    customer_journeys = []
    FOR each person IN tracked_persons DO
        journey = CustomerJourney{
            anonymous_id: person.track_id,
            start_time: person.first_seen,
            end_time: person.last_seen,
            path: person.positions,
            zones_visited: DetermineZonesVisited(person.positions),
            total_dwell_time: person.last_seen - person.first_seen,
            demographic_info: person.demographic_info
        }
        customer_journeys.append(journey)
    END FOR

    // Generate heat maps
    heat_map = GenerateHeatMap(customer_journeys)

    // Calculate dwell times by zone
    zone_dwell_times = CalculateZoneDwellTimes(customer_journeys)

    // Analyze traffic patterns
    traffic_patterns = AnalyzeTrafficPatterns(customer_journeys, time_window)

    // Calculate conversion metrics
    conversion_metrics = CalculateConversionMetrics(customer_journeys)

    analytics.journeys = customer_journeys
    analytics.heat_map = heat_map
    analytics.zone_dwell_times = zone_dwell_times
    analytics.traffic_patterns = traffic_patterns
    analytics.conversion_metrics = conversion_metrics

    RETURN analytics
END AnalyzeCustomerBehavior

ALGORITHM: GenerateHeatMap
INPUT: customer_journeys (List<CustomerJourney>)
OUTPUT: heat_map (2D array)

BEGIN GenerateHeatMap
    // Initialize heat map grid
    heat_map = CreateZeroMatrix(STORE_WIDTH, STORE_HEIGHT)

    // Accumulate position frequencies
    FOR each journey IN customer_journeys DO
        FOR each position IN journey.path DO
            grid_x = ConvertToGridX(position.x)
            grid_y = ConvertToGridY(position.y)
            heat_map[grid_x][grid_y] += 1
        END FOR
    END FOR

    // Normalize heat map values
    max_value = FindMaxValue(heat_map)
    IF max_value > 0 THEN
        FOR x = 0 TO STORE_WIDTH DO
            FOR y = 0 TO STORE_HEIGHT DO
                heat_map[x][y] = heat_map[x][y] / max_value
            END FOR
        END FOR
    END IF

    RETURN heat_map
END GenerateHeatMap
```

2.2 Inventory Monitoring Algorithm

```
ALGORITHM: MonitorInventory
INPUT: recognized_products (List<RecognizedProduct>), shelf_configuration (ShelfConfig)
OUTPUT: InventoryStatus

BEGIN MonitorInventory
    inventory_status = InventoryStatus{}
    shelf_statuses = []

    // Group products by shelf location
    products_by_shelf = GroupProductsByShelf(recognized_products)

    FOR each shelf IN shelf_configuration.shelves DO
        shelf_products = products_by_shelf[shelf.id]

        // Estimate stock levels
        stock_estimates = EstimateStockLevels(shelf_products, shelf)

        // Check for out-of-stock conditions
        out_of_stock_items = []
        FOR each product_sku IN shelf.expected_products DO
            estimated_quantity = stock_estimates[product_sku]
            IF estimated_quantity <= OUT_OF_STOCK_THRESHOLD THEN
                out_of_stock_items.append(product_sku)
            END IF
        END FOR

        // Check planogram compliance
        compliance_score = CheckPlanogramCompliance(shelf_products, shelf.planogram)

        shelf_status = ShelfStatus{
            shelf_id: shelf.id,
            stock_levels: stock_estimates,
            out_of_stock_items: out_of_stock_items,
            compliance_score: compliance_score,
            last_updated: getCurrentTime()
        }
        shelf_statuses.append(shelf_status)
    END FOR

    inventory_status.shelf_statuses = shelf_statuses
    inventory_status.overall_compliance = CalculateOverallCompliance(shelf_statuses)
    inventory_status.total_out_of_stock = CountTotalOutOfStock(shelf_statuses)

    RETURN inventory_status
END MonitorInventory
```

```
ALGORITHM: EstimateStockLevels
INPUT: shelf_products (List<RecognizedProduct>), shelf (ShelfConfig)
OUTPUT: stock_estimates (Map<SKU, quantity>)

BEGIN EstimateStockLevels
    stock_estimates = {}

    // Group products by SKU
    products_by_sku = GroupProductsBySKU(shelf_products)

    FOR each sku IN shelf.expected_products DO
        visible_products = products_by_sku[sku]

        IF visible_products.isEmpty() THEN
            stock_estimates[sku] = 0
        ELSE
            // Estimate total quantity based on visible products and shelf depth
            visible_count = visible_products.size()
            average_depth = shelf.depth_per_product[sku]
            estimated_quantity = visible_count * average_depth

            // Apply confidence weighting
            confidence_weight = CalculateAverageConfidence(visible_products)
            adjusted_quantity = estimated_quantity * confidence_weight

            stock_estimates[sku] = Math.round(adjusted_quantity)
        END IF
    END FOR

    RETURN stock_estimates
END EstimateStockLevels
```

3. Security Monitoring Algorithms

3.1 Suspicious Behavior Detection

```
ALGORITHM: DetectSuspiciousBehavior
INPUT: tracked_persons (List<TrackedPerson>), frame (image), security_rules (SecurityRules)
OUTPUT: List<SecurityEvent>

BEGIN DetectSuspiciousBehavior
    security_events = []

    FOR each person IN tracked_persons DO
        // Analyze movement patterns
        movement_analysis = AnalyzeMovementPattern(person)

        // Check for loitering
        IF movement_analysis.stationary_time > security_rules.loitering_threshold THEN
            event = SecurityEvent{
                event_type: "loitering",
                severity: DetermineSeverity(movement_analysis.stationary_time, security_rules.loitering_threshold),
                person_id: person.track_id,
                location: person.positions.last(),
                confidence: movement_analysis.confidence,
                timestamp: getCurrentTime()
            }
            security_events.append(event)
        END IF

        // Check for suspicious movement patterns
        IF IsErrraticMovement(movement_analysis) THEN
            event = SecurityEvent{
                event_type: "suspicious_movement",
                severity: "medium",
                person_id: person.track_id,
                location: person.positions.last(),
                confidence: movement_analysis.erratic_score,
                timestamp: getCurrentTime()
            }
            security_events.append(event)
        END IF

        // Analyze pose and gestures for potential theft indicators
        pose_analysis = AnalyzePoseForTheftIndicators(person, frame)
        IF pose_analysis.theft_probability > security_rules.theft_threshold THEN
            event = SecurityEvent{
                event_type: "potential_theft",
                severity: "high",
                person_id: person.track_id,
                location: person.positions.last(),
                confidence: pose_analysis.theft_probability,
                timestamp: getCurrentTime()
            }
            security_events.append(event)
        END IF

        // Check for restricted area access
        restricted_areas = security_rules.restricted_areas
        current_location = person.positions.last()
        FOR each area IN restricted_areas DO
            IF IsInsideArea(current_location, area) THEN
                event = SecurityEvent{
                    event_type: "restricted_area_access",
                    severity: area.severity_level,
                    person_id: person.track_id,
                    location: current_location,
                    confidence: 1.0,
                    timestamp: getCurrentTime()
                }
                security_events.append(event)
            END IF
        END FOR
    END FOR

    RETURN security_events
END DetectSuspiciousBehavior

ALGORITHM: AnalyzeMovementPattern
INPUT: person (TrackedPerson)
OUTPUT: MovementAnalysis

BEGIN AnalyzeMovementPattern
    positions = person.positions
    analysis = MovementAnalysis{}

    // Calculate movement statistics
```

```
    total_distance = 0.0
    stationary_time = 0
    direction_changes = 0

    FOR i = 1 TO positions.size() - 1 DO
        distance = CalculateDistance(positions[i-1], positions[i])
        total_distance += distance

        // Check for stationary behavior
        IF distance < STATIONARY_THRESHOLD THEN
            stationary_time += FRAME_INTERVAL
        END IF

        // Count direction changes
        IF i > 1 THEN
            angle1 = CalculateAngle(positions[i-2], positions[i-1])
            angle2 = CalculateAngle(positions[i-1], positions[i])
            angle_diff = Math.abs(angle2 - angle1)
            IF angle_diff > DIRECTION_CHANGE_THRESHOLD THEN
                direction_changes += 1
            END IF
        END IF
    END FOR

    // Calculate derived metrics
    average_speed = total_distance / (positions.size() * FRAME_INTERVAL)
    direction_change_rate = direction_changes / positions.size()

    analysis.total_distance = total_distance
    analysis.average_speed = average_speed
    analysis.stationary_time = stationary_time
    analysis.direction_changes = direction_changes
    analysis.direction_change_rate = direction_change_rate
    analysis.erratic_score = CalculateErraticScore(direction_change_rate, average_speed)
    analysis.confidence = CalculateMovementConfidence(positions)

    RETURN analysis
END AnalyzeMovementPattern
```

4. Performance Optimization Algorithms

4.1 Dynamic Resource Management

```
ALGORITHM: OptimizeEdgePerformance
INPUT: current_workload (WorkloadMetrics), system_resources (ResourceMetrics)
OUTPUT: OptimizationPlan

BEGIN OptimizeEdgePerformance
    optimization_plan = OptimizationPlan{}

    // Analyze current performance
    gpu_utilization = system_resources.gpu_utilization
    memory_usage = system_resources.memory_usage
    processing_latency = current_workload.average_latency

    // GPU optimization
    IF gpu_utilization > GPU_HIGH_THRESHOLD THEN
        IF processing_latency > LATENCY_THRESHOLD THEN
            optimization_plan.actions.append("reduce_model_precision")  // FP32 to FP16
            optimization_plan.actions.append("enable_dynamic_batching")
        END IF

        IF gpu_utilization > GPU_CRITICAL_THRESHOLD THEN
            optimization_plan.actions.append("reduce_concurrent_streams")
            optimization_plan.actions.append("enable_model_quantization")  // INT8
        END IF
    END IF

    // Memory optimization
    IF memory_usage > MEMORY_HIGH_THRESHOLD THEN
        optimization_plan.actions.append("clear_model_cache")
        optimization_plan.actions.append("reduce_frame_buffer_size")

        IF memory_usage > MEMORY_CRITICAL_THRESHOLD THEN
            optimization_plan.actions.append("enable_memory_pooling")
            optimization_plan.actions.append("reduce_tracking_history")
        END IF
    END IF

    // Processing optimization
    IF processing_latency > LATENCY_THRESHOLD THEN
        optimization_plan.actions.append("skip_non_critical_processing")
        optimization_plan.actions.append("increase_detection_interval")

        // Adaptive quality reduction
        current_quality = current_workload.processing_quality
        IF current_quality > MINIMUM_QUALITY_THRESHOLD THEN
            new_quality = Math.max(current_quality * 0.9, MINIMUM_QUALITY_THRESHOLD)
            optimization_plan.actions.append("reduce_processing_quality:" + new_quality)
        END IF
    END IF

    // Predictive scaling
    predicted_load = PredictWorkload(current_workload, PREDICTION_WINDOW)
    IF predicted_load > current_workload.load * 1.2 THEN
        optimization_plan.actions.append("preload_additional_models")
        optimization_plan.actions.append("increase_buffer_sizes")
    END IF

    optimization_plan.priority = CalculateOptimizationPriority(gpu_utilization, memory_usage, processing_latency)
    optimization_plan.estimated_improvement = EstimatePerformanceImprovement(optimization_plan.actions)

    RETURN optimization_plan
END OptimizeEdgePerformance

ALGORITHM: PredictWorkload
INPUT: current_workload (WorkloadMetrics), prediction_window (duration)
OUTPUT: predicted_load (float)

BEGIN PredictWorkload
    // Use simple moving average with seasonal adjustment
    historical_data = GetHistoricalWorkload(prediction_window)

    // Calculate base trend
    trend = CalculateLinearTrend(historical_data)

    // Apply seasonal factors (time of day, day of week)
    current_hour = getCurrentTime().hour
```

```
    current_day = getCurrentTime().dayOfWeek
    seasonal_factor = GetSeasonalFactor(current_hour, current_day)

    // Predict future load
    base_prediction = current_workload.load + trend
    predicted_load = base_prediction * seasonal_factor

    // Apply bounds
    predicted_load = Math.max(predicted_load, MIN_PREDICTED_LOAD)
    predicted_load = Math.min(predicted_load, MAX_PREDICTED_LOAD)

    RETURN predicted_load
END PredictWorkload
```

5. Integration and Synchronization Algorithms

5.1 Cloud-Edge Data Synchronization

```
ALGORITHM: SynchronizeWithCloud
INPUT: store_id (string), sync_type (SyncType)
OUTPUT: SyncResult

BEGIN SynchronizeWithCloud
    sync_result = SyncResult{status: "started", timestamp: getCurrentTime()}

    TRY
        // Collect local data for synchronization
        local_data = CollectLocalData(store_id, sync_type)

        // Compress data for efficient transmission
        compressed_data = CompressData(local_data)

        // Check network connectivity
        IF NOT IsCloudConnected() THEN
            // Queue for later sync
            QueueForLaterSync(compressed_data, sync_type)
            sync_result.status = "queued"
            RETURN sync_result
        END IF

        // Upload to cloud
        upload_result = UploadToCloud(compressed_data, store_id)

        IF upload_result.success THEN
            // Download updates from cloud
            cloud_updates = DownloadCloudUpdates(store_id, GetLastSyncTimestamp())

            // Apply cloud updates locally
            ApplyCloudUpdates(cloud_updates)

            // Update sync timestamp
            UpdateLastSyncTimestamp(getCurrentTime())

            sync_result.status = "completed"
            sync_result.data_uploaded = compressed_data.size
            sync_result.updates_received = cloud_updates.size
        ELSE
            sync_result.status = "failed"
            sync_result.error = upload_result.error
        END IF

    CATCH Exception e
        sync_result.status = "error"
        sync_result.error = e.message
        LogSyncError(store_id, sync_type, e)
    END TRY

    RETURN sync_result
END SynchronizeWithCloud

ALGORITHM: CollectLocalData
INPUT: store_id (string), sync_type (SyncType)
OUTPUT: LocalData

BEGIN CollectLocalData
    local_data = LocalData{}
    current_time = getCurrentTime()
    last_sync = GetLastSyncTimestamp()

    SWITCH sync_type
        CASE "analytics":
            // Collect analytics data since last sync
            local_data.customer_analytics = GetCustomerAnalytics(store_id, last_sync, current_time)
            local_data.inventory_snapshots = GetInventorySnapshots(store_id, last_sync, current_time)
            local_data.performance_metrics = GetPerformanceMetrics(store_id, last_sync, current_time)

        CASE "security":
            // Collect security events
            local_data.security_events = GetSecurityEvents(store_id, last_sync, current_time)
            local_data.alert_logs = GetAlertLogs(store_id, last_sync, current_time)

        CASE "configuration":
            // Collect configuration changes
            local_data.camera_configs = GetCameraConfigurations(store_id)
            local_data.system_settings = GetSystemSettings(store_id)

        CASE "full":
            // Collect all data types
            local_data = MergeLocalData([
                CollectLocalData(store_id, "analytics"),
                CollectLocalData(store_id, "security"),
                CollectLocalData(store_id, "configuration")
            ])
    END SWITCH

    // Add metadata
    local_data.store_id = store_id
    local_data.collection_timestamp = current_time
    local_data.data_version = GetDataVersion()

    RETURN local_data
END CollectLocalData
```

This comprehensive pseudocode provides executable algorithms for all core system components, enabling direct implementation of the Smart Retail Edge Vision platform while maintaining alignment with all previous requirements and architectural decisions.