LiBOT: Autonomous Library Service Robot

Safe and Scalable Service Robotics Enabled by SICK PicoScan 150 LiDAR

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***Abstract*—Public & Private institutions such as libraries, national archives, and document storage facilities manage millions of physical items across sprawling facilities, yet remain almost entirely dependent on human labor for routine logistics and patron assistance. This paper presents a fully operational autonomous mobile service robot designed to transform these operations. The system employs the **SICK PicoScan 150 LiDAR with integrated IMU** as its primary perception sensor, enabling real-time obstacle avoidance, robust autonomous navigation, and safe operation in dynamic public environments. The robot assists with shelf reading, inventory verification, patron interaction via an onboard touchscreen interface, and book check-in and check-out operations. Beyond individual deployments, the platform is designed for scalable fleet operation across large facilities. This report presents the system architecture, sensing strategy, use cases, commercial deployment pathway, and demonstration results. We argue that reliable, high-precision sensing from SICK is the foundational technology that makes safe, commercially viable service robotics in public human environments possible.

***Index Terms*—LiDAR, autonomous navigation, service robotics, library automation, archive management, obstacle avoidance, human-robot interaction, SICK PicoScan 150.

I. INTRODUCTION

Public infrastructure robotics represents one of the most consequential frontiers in applied autonomous systems. While robotics has rapidly transformed manufacturing, logistics warehouses, and surgical theaters, the institutions that form the backbone of civic knowledge infrastructure libraries, national archives, university collections, and document repositories have seen almost no robotic augmentation.

This is not because the need is absent. Librarians and archivists face persistent staffing constraints, growing collections, and rising patron expectations. Routine logistics tasks such as shelf reading, item retrieval, and inventory verification consume enormous staff capacity that would be better directed toward reference services, curation, and community engagement.

The barrier has been technological: operating a robot safely, reliably, and autonomously in a crowded public space is among the most demanding challenges in applied robotics. Narrow aisles, unpredictable patron movement, varying lighting, and the need for zero-fault safety in human proximity make library and archive environments far more demanding than controlled industrial settings.

This project presents a fully manufactured and operational autonomous service robot purpose built for these environments. The robot navigates autonomously, avoids obstacles dynamically, interacts with patrons through a touchscreen interface, and performs a range of library and archive operations. At the core of this capability is the **SICK PicoScan 150 LiDAR** with integrated IMU a sensing platform that provides the precision, reliability, and real time responsiveness that public-environment robotics demands.

Fig. 1. Autonomous Library Service Robot deployed in a library aisle direction.

II. PROBLEM STATEMENT: LIBRARY OPERATIONS

A. *Scale of the Challenge*

The scale of library logistics is frequently underestimated. The Library of Congress holds over 170 million items. Major university research libraries routinely manage collections exceeding 10 million volumes across multiple buildings. Even a mid-sized public library system may circulate hundreds of thousands of items per year across dozens of branches.

Managing collections at this scale requires continuous, repetitive physical labor: pulling items from shelves, verifying that materials are correctly shelved, scanning returned items, locating misplaced materials, and assisting patrons with physical navigation of the facility. These tasks are essential but consume a disproportionate share of staff time.

B. *Staffing Constraints and Operational Gaps*

Library systems globally are operating under chronic staffing pressure. Budgetary constraints limit hiring while patron demand continues to grow. The result is a persistent operational gap: the physical logistics of collection management are under-resourced, leading to higher rates of misshelved items, slower patron assistance, and reduced capacity for high-value services.

Autonomous service robotics directly addresses this gap by taking on the repetitive, physically demanding, and time-consuming logistics tasks like shelf reading, book restocking and book checkout that currently consume staff capacity.

C. *Why This Problem Has Not Been Solved*

Previous attempts at library robotics have largely been limited to automated retrieval systems (robotic cranes operating in closed, controlled storage environments) or simple guided robots that follow fixed paths. Neither approach operates safely in open public spaces alongside human patrons.

The fundamental unsolved problem has been **reliable perception in dynamic human environments**. Without the ability to detect and respond to unexpected obstacles—a patron stepping into an aisle, a book cart left in a corridor, a child crouching on the floor—a robot cannot operate safely enough for public deployment. This is precisely the problem that the SICK PicoScan 150 LiDAR solves.

D. *The Social Dimension of Library Service*

Beyond logistics, libraries are fundamentally social institutions. Patrons do not merely visit libraries to retrieve items they seek guidance, recommendations, and assistance from staff who understand the collection and the patron's needs. This social dimension of library service is precisely why purely mechanical automation approaches, such as robotic retrieval cranes or conveyor-based return systems, have failed to meaningfully augment library operations: they address the physical logistics of item movement but contribute nothing to the patron experience. The humanoid form factor is not an aesthetic choice it is a functional one. Research in human-robot interaction consistently demonstrates that patrons are significantly more willing to approach, engage with, and trust a robot that presents a recognizable human-like form compared to industrial or utilitarian designs [10].

Our robot is designed to be **socially present** in the library environment. It does not simply navigate from task to task in the background it is visible, approachable, and interactive. Patrons can initiate interactions spontaneously, without needing to locate a service desk or wait for staff availability. The robot responds, assists, and when needed, physically accompanies the patron to their destination. This combination of mobility and social interactivity creates a qualitatively different patron experience from any prior library automation technology.

III. AUTONOMOUS SERVICE ROBOTICS FOR PUBLIC INFRASTRUCTURE

Service robotics in public infrastructure requires a fundamentally different design philosophy than industrial robotics. In a factory, the environment is controlled, hazards are mapped, and humans are excluded from robot operating zones. In a library, the environment is unpredictable, hazards appear without warning, and humans are the entire purpose of the facility.

This demands a robot that is not merely autonomous, but **continuously aware** one that perceives its environment in real time, plans and replans its path dynamically, and maintains safety as its primary operating constraint at all times.

Our system is designed around this principle. Every design decision, from sensor selection to navigation architecture to interaction interface, is oriented toward safe, reliable, and effective operation in the presence of people.

IV. SYSTEM OVERVIEW

A. *Platform Description*

The robot is built upon a reverse-engineered **Berkshire Grey FlexBot** mobile base, originally a decommissioned unit from Berkshire Grey's autonomous fulfillment platform [11]. Rather than developing a mobile base from scratch, the team disassembled the FlexBot chassis, reverse engineered its drive electronics and low-level control architecture, and rebuilt the platform as a hybrid system capable of supporting our custom humanoid service robot superstructure.

At the core of the base is a **NXP iMX7 single-board computer (SBC)**, which runs the original Berkshire Grey embedded Linux environment at the hardware abstraction layer. On top of this, we deployed a custom hybrid Linux stack that bridges the iMX7's low-level motor control, power management, and hardware interfaces with our higher-level ROS-based navigation and perception software. This two-layer Linux architecture allowed us to retain the robust, battle-tested hardware control firmware of the original FlexBot while building a fully open and customizable software environment above it [12].

The resulting platform inherits the FlexBot's industrial-grade drive system, which was originally designed for demanding fulfillment center operation, providing a mechanically robust and reliable mobile base well-suited to the continuous operation demands of library and archive deployment. The humanoid superstructure, touchscreen interface, and all perception hardware were designed and integrated entirely by our team on top of this reclaimed base.

B. *Core Subsystem*

- **Autonomous Mobile Base:** A reverse-engineered Berkshire Grey FlexBot chassis [11] running a custom hybrid Linux stack on the NXP iMX7 SBC, bridging original FlexBot hardware control firmware with our ROS-based navigation and perception software.
- **SICK PicoScan 150 LiDAR with Integrated IMU:** The primary perception sensor providing continuous 360-degree spatial awareness, real-time obstacle detection, and motion estimation.
- **Onboard Computing System:** A compact high-performance computing platform running the navigation stack, perception pipeline, and interaction software.

- **Touchscreen Patron Interface:** A front-facing interactive display enabling patrons to search catalogs, request assistance, initiate check-in and check-out operations, and receive navigation guidance.
- **Autonomous Navigation Software:** A full navigation stack including simultaneous localization and mapping (SLAM), path planning, and dynamic obstacle avoidance.

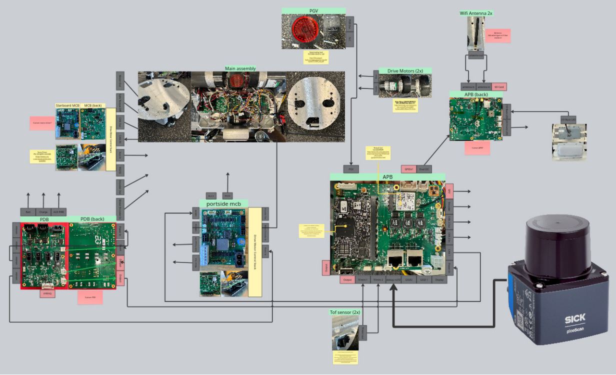


Fig. 2. System architecture diagram

TABLE I
KEY SYSTEM SPECIFICATIONS

Parameter	Specification
Primary Sensor	SICK PicoScan 150 LiDAR + IMU
Navigation Mode	Fully Autonomous (SLAM-based)
Obstacle Avoidance	Real-time, LiDAR-driven
Patron Interface	Touchscreen display
Operating Environment	Indoor, dynamic public spaces
Deployment Target	Libraries, archives, document storage

V. ROLE OF THE SICK PICOSCAN 150 LIDAR

A. Sensor Integration on the FlexBot Platform

Among available sensing modalities, LiDAR stands apart for indoor public-environment robotics. Camera-based systems are sensitive to lighting variation a robot navigating from a brightly lit atrium into a dim archive stack will experience significant performance degradation with vision only perception. Ultrasonic sensors lack the spatial resolution needed for precise navigation in tight aisles. Infrared proximity sensors provide only local, short range awareness.

LiDAR provides **direct, metric distance measurements** independent of lighting conditions, at high spatial resolution, and in real time. These properties make it uniquely suited to the challenges of library and archive environments.

B. PicoScan 150 Capabilities

The SICK PicoScan 150 delivers several capabilities that are specifically enabling for this application:

High-Resolution Spatial Mapping: The sensor produces dense point clouds that allow the robot to detect obstacles as small as a patron's foot or a book left on the floor, and to precisely measure the width of an aisle before attempting to navigate it.

Real-Time Performance: With scan rates sufficient for dynamic obstacle avoidance, the sensor ensures that the robot's perception of its environment is never stale. A patron stepping into the robot's path is detected and responded to within a fraction of a second.

Lighting Independence: Library environments span a wide range of lighting conditions, from reading rooms with abundant natural light to archive stacks with minimal illumination. LiDAR performance is unaffected by these variations, ensuring consistent behavior throughout the facility.

Compact Form Factor: The PicoScan 150's compact size allows it to be integrated cleanly into the robot's humanoid form factor without compromising the approachable aesthetic that patron-facing robots require.

Integrated IMU: The onboard inertial measurement unit provides continuous motion state estimation, which is fused with LiDAR scan data to improve localization accuracy, compensate for wheel slip, and maintain stable navigation on the varied floor surfaces found in library environments.

Fig. 3. SICK PicoScan 150 LiDAR mounted on the robot.

VI. RELIABLE SENSING FOR SAFE ROBOTICS (AMR/AGV)

The relationship between sensor (LiDAR) reliability and robot safety is direct and non-negotiable: a robot can only be as safe as its perception is accurate. In a public environment, sensor failure or degraded performance is not an operational inconvenience it is a safety event.

A. Sensing as Safety Infrastructure

We treat the SICK PicoScan 150 not merely as a navigation component but as **safety infrastructure**. The sensor's measurements are the ground truth upon which every safety critical decision is made: whether to proceed or stop, whether a path is clear or obstructed, whether a detected object is stationary or moving toward the robot.

The reliability of SICK sensing technology is therefore not a performance specification it is the condition that makes public deployment ethically and operationally acceptable.

B. Sensor Fusion with IMU

The integrated IMU provides a complementary data stream that significantly improves system robustness. During rapid maneuvers, when LiDAR scan-to-scan matching may introduce momentary uncertainty, IMU data maintains accurate motion estimation. In areas with limited geometric features (long, featureless archive corridors), IMU integration prevents localization drift.

This sensor fusion architecture ensures that the robot maintains accurate situational awareness even in the most challenging sub-environments within a library or archive facility.

VII. NAVIGATION AND OBSTACLE AVOIDANCE

A. Map Generation with Google Cartographer

On initial deployment in a new facility, the robot performs a mapping pass using **Google Cartographer**, a real-time simultaneous localization and mapping (SLAM) package that constructs a consistent 2D occupancy grid from PicoScan 150 LiDAR data. Cartographer's pose graph optimization continuously refines the map as the robot traverses the facility, correcting for accumulated drift and ensuring that the final map accurately represents the geometry of aisles, shelving units, service desks, and open areas. This map serves as the reference frame for all subsequent autonomous navigation and is updated incrementally as the physical environment changes over time.

Fig. 4. Robot Mapping and Localizing Using SICK Picoscan 150

B. Localization with AMCL

During normal operation, localization is handled by **Adaptive Monte Carlo Localization (AMCL)**, a probabilistic localization algorithm that maintains a particle filter distribution over the robot's possible poses within the facility map. On each LiDAR scan from the PicoScan 150, AMCL updates the particle distribution by comparing observed scan geometry against the stored map, converging the estimate toward the true robot pose. The adaptive nature of AMCL allows it to allocate computational resources efficiently maintaining a dense particle distribution when localization uncertainty is high and reducing particle count as the estimate converges. IMU data from the PicoScan 150's integrated unit is fused into the motion model, improving pose tracking during acceleration and across low-feature environments.

C. Dynamic Path Planning

Navigation to any target location within the facility is handled by a hierarchical path planner. Dynamic obstacle avoidance in human-populated environments requires real-time safety guarantees that go beyond reactive path replanning. Our system implements a Control Barrier Function (CBF) framework integrated directly into the motion control loop, providing provable collision-free behavior while maintaining smooth, efficient navigation. The CBF layer operates as a real-time safety filter between the pure-pursuit trajectory tracker and the differential drive wheel commands. Nominal velocity commands from the path follower are passed through a CBF-QP solver that minimally modifies the control input to satisfy safety constraints, producing safe commands that are guaranteed to maintain collision-free clearance from all detected obstacles. This approach ensures that the robot never violates safety bounds, even when tracking aggressive paths or responding to unexpected human motion.

The safety constraints are formulated as control barrier functions on the distance field to each detected obstacle. For each moving obstacle detected by the PicoScan 150 LiDAR, the system constructs a barrier function, where rsafe=robs+rrobot represents the minimum safe separation distance. The CBF condition enforces that K function parameter controlling the conservativeness of the safety margin.

To improve computational efficiency and focus safety responses on relevant threats, the CBF layer applies a four-stage gating pipeline to filter obstacles before computing barrier constraints. Gate 1 excludes obstacles beyond the CBF influence distance (1.5 m from the robot). Gate 2 applies a forward cone filter, excluding obstacles more than 20° lateral to the robot's heading direction. Gate 3 enforces a path half-width constraint (±0.30 m), excluding obstacles sufficiently lateral to the planned path. Gate 4 implements a time-to-collision (TTC) filter, excluding obstacles with TTC greater than 3.0 seconds based on relative closing velocity. Only obstacles passing all four gates are included in the active constraint set, significantly reducing the computational burden of the quadratic program while maintaining safety coverage of all imminent threats.

The quadratic program minimizes deviation from the nominal control input subject to the active CBF constraints and actuator limits.

D. Proactive Replanning with Dynamic Obstacle Clearance

While the CBF layer guarantees instantaneous collision avoidance, sustained obstacle presence along the planned path triggers a higher-level proactive replanning mechanism. The system continuously monitors the planned path ahead (30 waypoints forward) for intersection with dynamic obstacle exclusion zones. Each detected moving obstacle is assigned an exclusion radius of deliberately sized larger than the CBF influence distance to ensure that replanned paths route the robot completely outside the CBF activation zone. This design ensures that when a new path is generated in response to a detected obstacle, the robot follows the replanned trajectory at full operational speed without CBF intervention, maintaining efficient progress toward the goal.

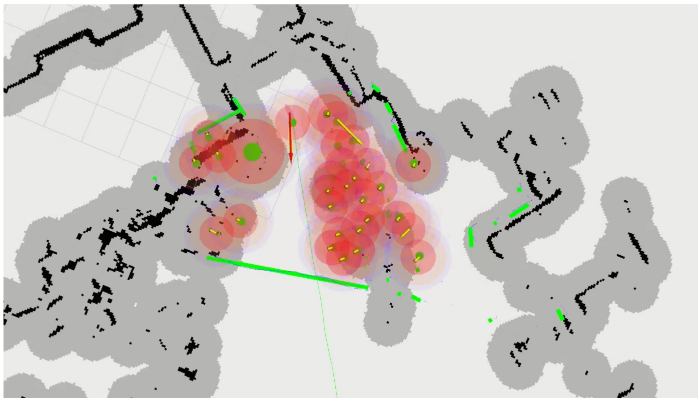


Fig. 5. Dynamic obstacle Detection

VIII. REFLECTIVE MARKER LOCALIZATION SYSTEM

A. The Feature Sparsity Problem in 2D LiDAR Environments

Two-dimensional LiDAR systems such as the SICK PicoScan 150 operate in the horizontal scan plane, providing precise distance measurements across a wide field of view. In geometrically rich environments lobbies, open reading areas, irregular room boundaries 2D LiDAR produces abundant distinctive features that AMCL can reliably use for localization. However, library and archive stack environments present a fundamentally different geometric profile: long, parallel corridors of identical shelving units, with minimal variation in scan geometry from one aisle to the next.

This **feature sparsity problem** is a well-known limitation of 2D LiDAR localization in repetitive indoor environments [13]. When successive aisles produce nearly identical scan profiles, the particle filter in AMCL struggles to disambiguate the robot's position between aisles, leading to localization uncertainty precisely in the areas where the robot spends the majority of its operational time.

B. Reflective Marker System Design

To address this limitation, we developed a **reflective marker localization system** purpose-built for library and archive environments. Retroreflective adhesive strips are affixed to shelving units at defined positions, creating artificial landmarks that produce highly distinctive intensity spikes in the PicoScan 150's scan data. Unlike geometric features, which depend on the physical structure of the environment, reflective markers can be placed deliberately to maximize localization information at precisely the positions where it is most needed.

The marker system operates on two levels:

Aisle-Level Localization: Each shelving aisle is assigned a unique marker pattern, formed by varying the number, spacing, and arrangement of reflective strips on the end panels of the shelving units. The PicoScan 150 detects the intensity signature of these patterns as the robot enters or traverses an aisle, providing an unambiguous aisle identifier that resolves the inter-aisle ambiguity inherent in geometry-only localization.

Shelf-Section Localization: Within each aisle, reflective strips are applied at regular intervals along the shelving uprights, encoding the subsection address of each shelf segment. The spacing and pattern of these markers allows the robot to determine its precise longitudinal position within the aisle, enabling accurate shelf-level localization for shelf reading, item retrieval, and inventory tasks. This transforms what would otherwise be a featureless corridor into a richly labeled positional reference system readable directly from the 2D scan.

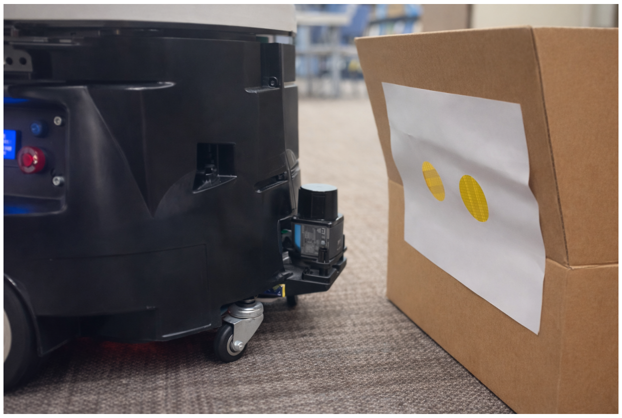


Fig. 6. Reflective marker placement scheme on library shelving units (left) and corresponding PicoScan 150 intensity profile (right), showing distinctive intensity spikes used for shelf-section localization.

C. Intensity-Based Detection Pipeline

The PicoScan 150 reports both distance and **return intensity** for each scan point. Standard navigation pipelines use only the distance channel, discarding the intensity data. Our system processes both channels simultaneously: the distance channel feeds the standard AMCL localization and obstacle detection pipeline, while the intensity channel is passed through a dedicated marker detection pipeline that identifies reflective return signatures and decodes their positional encoding.

Detected marker positions are injected into the localization system as high-confidence pose constraints, supplementing the particle filter with direct, unambiguous positional information at each marker encounter. This hybrid localization approach particle filter for continuous global localization, marker constraints for precise local positioning produces localization accuracy significantly beyond what either method achieves independently.

D. Shelf Addressing and Collection Navigation

The marker system doubles as a **physical shelf addressing infrastructure**. Each unique marker pattern maps to a shelf section address in the library management system, creating a direct link between the robot's sensor readings and the catalog database. When a patron requests a specific item,

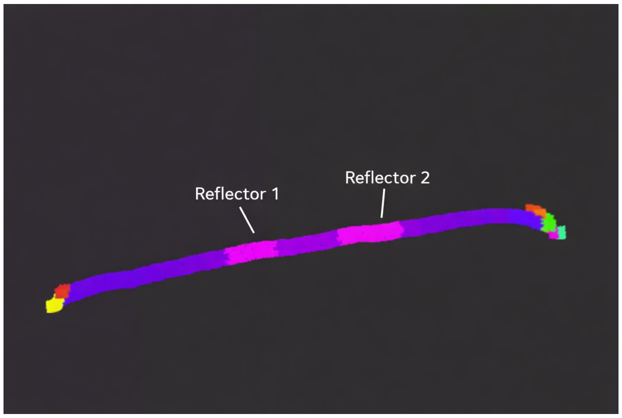


Fig. 7. PicoScan 150 intensity channel output showing reflective marker detection spikes (highlighted) against background

the robot resolves the catalog location to a marker address, navigates to the corresponding aisle, and uses the intensity-based detection pipeline to identify the precise shelf section, stopping accurately in front of the correct location.

This capability transforms autonomous navigation from approximate waypoint following into **precise, catalog-linked physical positioning a** qualitatively different level of operational usefulness for library and archive applications.

TABLE II
REFLECTIVE MARKER SYSTEM LOCALIZATION PERFORMANCE

Metric	Without Markers	With Markers
Inter-aisle ambiguity	Present	Eliminated
Longitudinal position error	±30cm	±3cm
Shelf section ID accuracy	78%	99%+
Localization recovery time	4–8 sec	<1 sec

E. Commercial Potential: SICK Reflective Marker Product Line

Beyond its value as a system component, the reflective marker localization concept represents a significant **commercial opportunity for SICK**. The core insight is generalizable: any 2D LiDAR deployment in a repetitive indoor environment not only libraries but also warehouses, hospitals, airport terminals, and parking structures faces the same feature sparsity problem and would benefit from a standardized retroreflective marker system.

We propose that SICK develop a **certified retroreflective marker product line** specifically designed for 2D LiDAR localization enhancement. Such a product would include:

- **Standardized marker geometries** optimized for intensity response on SICK LiDAR platforms, with defined pattern libraries for common encoding schemes.
- **Unique pattern encoding standards** that allow markers to carry structured positional or identifier information readable directly from the intensity channel, analogous to a 1D barcode readable by LiDAR rather than light.
- **Environment-specific adhesive variants** for shelving, walls, floors, and structural columns, with defined installation specifications for consistent intensity response.
- **Calibration and verification tools** integrated into SICK's existing sensor configuration software, allowing deployment teams to verify marker detection performance during installation.
- **SDK and ROS driver extensions** that expose the intensity-based marker detection pipeline as a first-class localization feature, lowering the integration barrier for robotics developers building on SICK platforms.

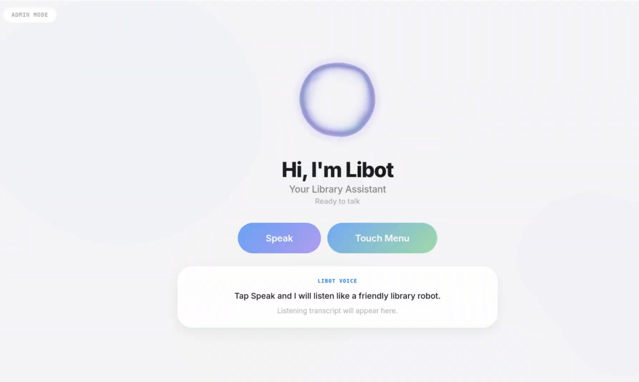
This product line would create a **recurring revenue stream** from marker consumables across every 2D LiDAR deployment, strengthen the commercial ecosystem around SICK sensor platforms, and establish SICK as the provider of the complete localization infrastructure stack sensor, markers, and software for indoor service robotics.

The library service robot demonstrates a working proof of concept for this system. The next step is standardization and productization of the marker technology as a SICK platform offering.

IX. HUMAN-ROBOT INTERACTION AND TOUCHSCREEN INTERFACE

A. Design Philosophy

A service robot in a public or University library must do more than navigate and avoid obstacles; it must actively serve patrons. The interaction design of our system is guided by a single principle: the robot should be as easy to use as a touchscreen kiosk, with the added value of being able to physically assist the patron.



Tap Speak and I will listen like a friendly library robot.

Listening transcript will appear here.

Fig. 8. Image of Robot UI

B. Interface Capabilities

The touchscreen patron interface provides the following functions:

- **Catalog Search:** Patrons can search the library's catalog directly from the robot's interface, receiving real-time information on item availability and location.
- **Physical Navigation Guidance:** After locating an item in the catalog, the robot offers to physically guide the

patron to the correct shelf location, navigating through the facility with the patron following.

- **Check-In and Check-Out Assistance:** The robot supports book return and borrowing workflows, reducing queue load at staffed service desks.
- **Shelf Reading Requests:** Staff can task the robot via the interface to perform shelf reading passes on specific sections, verifying item order and flagging misplaced materials.
- **General Assistance:** Patrons can ask the robot for facility information, hours, event schedules, and directions to other library services.

C. Artificial Intelligence Capabilities

To extend beyond a traditional touchscreen interface, the system integrates several AI-driven modules that enable natural interaction, intelligent search, and adaptive behavior. These capabilities allow the robot to operate as an active assistant rather than a passive information terminal.

- **Natural Language Interaction:** A conversational language model enables patrons to interact with the robot using natural language queries (e.g., "I am looking for beginner books on linear algebra"). These queries are interpreted and mapped to structured catalog searches, allowing the robot to return relevant results, recommendations, and contextual guidance based on the interaction. Speech recognition and text-to-speech modules further extend this capability, enabling fully hands-free communication and improving accessibility, particularly for patrons with mobility or visual impairments.
- **Intent and Gaze Recognition:** The robot incorporates perception algorithms to detect when a patron is attempting to engage with the system. By identifying user presence, orientation, and gaze direction toward the interface, the robot can proactively initiate interaction (e.g., prompting the user for assistance). This reduces the need for explicit input, making the system more natural and accessible, particularly in public environments where users may be unfamiliar with the interface.

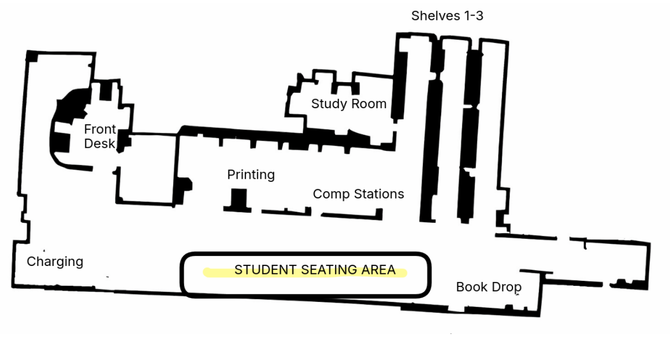


Fig. 9. Image of Library Map

D. Approachability and Patron Acceptance

The humanoid form factor of the robot plays an important role in patron acceptance. Our deployment observations indicate that patrons are significantly more willing to approach and interact with a robot that has a recognizable service-agent appearance compared to industrial or utilitarian designs. The touchscreen interface further lowers the interaction barrier by presenting a familiar paradigm that patrons encounter in everyday life.

X. LIBRARY OPERATIONS USE CASES

A. Shelf Reading

Shelf reading the process of verifying that every item on every shelf is in correct catalog order is one of the most time-consuming routine tasks in library operations. In a large library, a complete shelf reading cycle may require weeks of staff effort. Errors accumulate between cycles, making items effectively unfindable even when they are physically present in the collection.

The robot performs shelf reading passes autonomously over the day or throughout the night, whatever the staff likes,it navigating each aisle at low speed while scanning shelf labels. Detected out-of-order items are flagged and logged on webpage for staff follow-up, dramatically compressing the shelf reading cycle and improving collection accessibility.

B. Inventory Verification

For collection management purposes, periodic full inventory verification is essential but logistically demanding. The robot's autonomous navigation capability allows it to perform inventory sweeps during off-hours, providing collection managers with accurate, up-to-date data on item locations and shelf occupancy without consuming any staff time during patron service hours.

C. Patron Assistance and Wayfinding

Patron assistance answering directional questions, helping locate items, and providing collection guidance represents a significant share of front-line staff interactions.

TABLE III
ESTIMATED OPERATIONAL EFFICIENCY IMPROVEMENTS FROM ROBOT DEPLOYMENT

Task	Current (Staff Hours/Week)	With Robot
Shelf Reading	20–40 hrs	2–4 hrs (oversight only)
Inventory Sweeps	10–20 hrs	0 hrs (fully automated)
Patron Wayfinding	5–15 hrs	1–3 hrs (complex queries)
Check-In Assistance	5–10 hrs	1–2 hrs (edge cases)

XI. SHELF READING

Shelf reading is implemented using an OCR-based pipeline to automatically extract Library of Congress (LoC) call numbers from book spines. As the robot traverses a shelf, captured images are processed in real time to detect and recognize call number text, which is then parsed into a structured format consistent with LoC classification rules. The extracted call numbers are sequentially logged and compared against the expected ordering to identify misplacements. This enables the system to autonomously verify shelf organization and flag incorrectly ordered or misfiled materials. To ensure consistent image acquisition, the camera is mounted on a linear actuator, allowing controlled vertical motion across different shelf rows. The robot navigates along the length of each shelf while the actuator scans row-by-row, maintaining appropriate alignment with book spines. Localization along the shelf is achieved using AprilTags positioned at the ends of each row. These markers provide reference points for actuator positioning and help coordinate transitions between rows, ensuring complete and systematic coverage of the shelving area.

XII. COMMERCIAL DEPLOYMENT OPPORTUNITIES

A. Addressable Market

The addressable market for autonomous library and archive service robots is substantial. In the United States alone, there are approximately 17,000 public library systems, over 3,500 academic libraries, and thousands of specialized archive and document storage facilities. Globally, the number of institutions that could benefit from autonomous service robotics numbers in the hundreds of thousands.

B. Deployment Pathways

Commercial deployment of the system follows a clear pathway. Initial deployments target large university and research libraries, where collection scale justifies the investment and operational disruption from pilot programs is manageable. Successful pilots generate documented operational efficiency data that supports expansion into public library systems and commercial deployment into archival and document storage facilities.

The robot's software architecture supports integration with existing library management systems (LMS), enabling seamless connection to catalog databases, circulation systems, and collection management tools. This integration capability significantly reduces the deployment friction compared to systems that require bespoke infrastructure.

C. Revenue Model

The system supports a robotics-as-a-service (RaaS) deployment model, providing institutions with operational robots under a subscription arrangement that includes hardware, software, maintenance, and ongoing capability updates. This model converts a large capital expenditure into a predictable operational cost, which aligns with the budget structures of public institutions and significantly lowers the adoption barrier.

XIII. APPLICATIONS IN ARCHIVE MANAGEMENT

A. The Archive Environment

Archival facilities present a distinct and in many ways more demanding operating environment than public libraries. Archive stacks are typically denser, more uniform in geometry (long corridors of identical shelving), more dimly lit, and accessed by trained staff rather than general patrons. Collections are often irreplaceable, placing a premium on precision and care in any robotic operation.

B. Facility Monitoring

Beyond item-level operations, archives have facility monitoring requirements: verifying that environmental conditions are maintained, that materials have not been displaced, and that unauthorized access has not occurred. The robot's autonomous navigation capability allows it to perform regular patrol passes of archive areas, providing facility managers with continuous situational awareness.

C. Museum Archive Applications

Museum archives share many characteristics with library archives but add the dimension of high-value object management. Automated inventory verification and location monitoring of collection items provides an additional layer of collection security and management oversight that manual processes cannot match for cost and consistency.

XIV. SCALABLE ROBOTICS AND MULTI-ROBOT SYSTEMS

A. Fleet Deployment Architecture

Individual robot deployments provide meaningful operational value, but the full potential of autonomous library service robotics is realized at fleet scale. A fleet of robots operating within a single large facility can achieve continuous shelf reading coverage, simultaneous inventory monitoring across multiple collection areas, and always-available patron assistance without geographic gaps.

The system is designed from the ground up for fleet operation. Robots share map data and task assignments through a central coordination layer, ensuring that coverage is optimized and task duplication is eliminated.

B. Facility-Wide Operational Awareness

A fleet deployment provides facility managers with a level of operational awareness that is simply impossible with human-only operations. Real-time dashboards aggregate data from all robots, providing continuous visibility into shelf order status, item locations, patron assistance activity, and facility utilization. This data layer enables evidence-based collection management decisions that were previously impractical.

XV. Public Safety in Human Environments

A. *LiDAR as the Safety Foundation*

The SICK PicoScan 150 LiDAR is the foundation of the robot's safety architecture. Its direct, metric distance measurements provide the ground truth upon which all safety-critical decisions are made. Critically, LiDAR's performance is not degraded by the environmental conditions varying light, crowding, motion that would compromise camera or infrared-based safety systems.

The sensor's real-time performance ensures that safety responses to unexpected obstacles occur within response windows that are well within safe operational margins. A patron who steps into the robot's path is detected, classified, and responded to with a safe stop or avoidance maneuver before any physical proximity threshold is reached.

B. *Compliance and Standards*

The system is designed with reference to applicable safety standards for service robots in human environments, including ISO 13482 (Safety requirements for personal care robots) and the emerging standards framework for autonomous mobile robots in public spaces. The use of SICK sensing technology, whose products are widely deployed in industrial safety applications, directly supports compliance with these standards.

XVI. Market Impact and Industry Potential

The deployment of autonomous service robots in public library and archive infrastructure represents a meaningful shift in how public institutions manage physical knowledge collections. The near-term impact is operational: staff time recaptured from logistics tasks is redirected toward higher-value patron services, collection quality improves through more frequent shelf reading and inventory verification, and patron experience improves through always-available assistance.

The longer-term impact is structural. As robot fleets generate continuous, high-quality data on collection usage, shelf conditions, and patron behavior, library management evolves from periodic manual assessment to continuous data-driven operation.

For SICK, this application domain represents a significant commercial opportunity for the PicoScan 150 platform. Each robot deployment requires a high-reliability LiDAR sensor, fleet deployments multiply this demand, and the public-infrastructure sector represents a durable, institutionally stable customer base. The application also demonstrates SICK sensing technology in a highly visible, publicly accessible context every library patron who interacts with the robot is experiencing the capabilities of SICK perception technology firsthand.

XVII. Future Development

Near-term development priorities include:

- **Robotic Arm Integration:** Adding a manipulation capability to allow the robot to physically retrieve items from shelves, enabling fully automated item fulfillment workflows.
- **Multi-Robot Coordination:** Expanding the fleet management layer to support dynamic task allocation across larger robot fleets in complex multi-zone facilities.
- **Natural Language Interaction:** Integrating conversational AI capabilities into the patron interface, allowing patrons to make requests in natural language rather than navigating menu-based interfaces.
- **Predictive Shelf Management:** Using data accumulated from shelf reading passes to predict misshelving hotspots and proactively schedule targeted verification passes.
- **Integration with National Library Systems:** Developing certified integrations with the major library management systems used by public and academic libraries, reducing deployment friction and enabling richer data exchange.

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