CleanWalker Robotics

Autonomous Quadrupedal Litter Collection

A Technical White Paper for Municipal Operations, Property Management, and Procurement Teams

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CONFIDENTIAL

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EXECUTIVE SUMMARY

Urban litter collection consumes $8–12 billion annually in the United States alone, with 55–70% of costs driven by manual labor. Current solutions—diesel sweeper trucks and manual crews—cannot access the parks, plazas, and pedestrian zones where litter is most visible and collection most labor-intensive.

CleanWalker Robotics has developed the CW-1, an autonomous quadrupedal robot for outdoor litter collection. The CW-1 combines terrain-adaptive legged locomotion, an AI perception pipeline detecting 10 litter categories in under 75 ms, and a robotic arm with class-specific grasping. Deployed as a Robot-as-a-Service fleet, the CW-1 delivers 40–60% cost reduction versus manual labor at scale while operating across grass, gravel, paths, and uneven terrain that wheeled platforms cannot traverse.

1 The Urban Litter Challenge

Scale of the Problem

Municipal cleaning is a substantial and growing fiscal burden. US municipalities spend $8–12 billion annually on street cleaning; the EU allocates a comparable EUR 9–14 billion. Individual cities bear disproportionate costs: San Francisco allocates $47.8 million annually ($59 per capita), while NYC's Department of Sanitation devotes ~$890 million to collection and street cleaning. San Francisco's budget rose 63% between 2018 and 2025, yet the city simultaneously cut 20 positions due to fiscal pressure.

$8-12B	US ANNUAL STREET CLEANING SPEND
55-70%	LABOR SHARE OF CLEANING COSTS
$85K	FULLY LOADED FTE COST (HIGH)
0	CERTIFIED OUTDOOR LITTER ROBOTS

Why Current Solutions Fail

Mechanized sweepers ($250K–$450K per unit) are confined to paved roads, generate 85–95 dB noise, and cannot selectively collect individual litter items from grass or garden beds. **Manual crews** cost $55,000–$85,000 per FTE annually, face recruitment challenges, and cover only 2–4 hectares per shift. Neither operates economically during off-peak hours, and neither generates data on litter accumulation patterns.

The Automation Gap

The autonomous cleaning robot market ($592M in 2025, projected $832M by 2034) has focused exclusively on indoor environments. All commercially certified autonomous cleaners operate in airports, malls, and warehouses on flat, predictable surfaces. No commercially available robot addresses outdoor litter collection in parks, plazas, and pedestrian zones—the segment where labor costs per hectare are highest.

2 Technical Approach

Quadrupedal Locomotion

The CW-1 uses four-legged locomotion rather than wheels or tracks. Urban parks present grass, gravel, tree roots, curbs, slopes to 15°, and narrow gaps between furniture that wheeled platforms cannot traverse. Each leg has three degrees of freedom (hip abduction, hip flexion, knee flexion) driven by quasi-direct-drive actuators providing up to 24.8 Nm peak torque. The 12-DOF system enables dynamic gait selection—trot, walk, and amble—based on real-time terrain classification. Ground clearance of ~35 cm allows stepping over low obstacles.

Locomotion control uses model predictive control (MPC) for initial deployment, with a reinforcement learning policy trained in NVIDIA Isaac Lab (4,096 parallel environments, domain randomization) as the production path for superior terrain adaptability.

AI Perception Pipeline

Three concurrent pipelines run on a single NVIDIA Jetson Orin Nano Super (67 TOPS INT8):

- **Litter Detection:** YOLO26s (TensorRT INT8) detects 10 litter categories at ~260 FPS with 5–10 ms latency. STAL (Small-Target-Aware Label Assignment) ensures detection of items as small as cigarette butts at 0.3–5 m range. Trained on 30,000+ annotated images from public and field-collected datasets.
- **Stereo Depth:** OAK-D Pro provides hardware stereo depth at 30 FPS (0.7–15 m, active IR) with zero GPU cost—runs on the camera's onboard 4 TOPS VPU. Isaac ROS ESS adds confidence-filtered depth for production.
- **Terrain Segmentation:** SegFormer-B0 (TRT FP16) classifies 8 ground surface types at 5 Hz, feeding speed and traversability costs directly into the navigation costmap.
- **SLAM & Localization:** cuVSLAM (GPU visual odometry, 30 Hz, 9% GPU) fused with RTAB-Map mapping and Livox Mid-360 LiDAR (360° × 59° FOV, IP67) via EKF sensor fusion.

> **Pipeline Performance:** The full detection-to-grasp pipeline operates within 50–75 ms end-to-end. Total GPU utilization across all concurrent models is ~52%, with 48% headroom for future capabilities. Memory usage is 3.6 GB of 8 GB available.

Grasping System

A 5-DOF robotic arm (turret, shoulder, elbow, wrist, gripper) with 50 cm reach collects detected items. GR-ConvNet v2 (1.9M params, 5–10 ms TRT INT8) generates grasp poses achieving 95.4% success rate, with class-specific strategies: enveloping grasps for bottles/cans, pinch grasps for cigarette butts, scoop grasps for flat wrappers. A wrist camera provides visual servoing for the final approach. Failed grasps (3 attempts) are logged with GPS and photo for human review.

Autonomous Navigation

ROS 2 Nav2 handles path planning and obstacle avoidance, integrated with Boustrophedon Cell Decomposition for systematic area coverage. Pedestrian-aware navigation inflates detected people into costmap zones (1.5 m adults, 2.0 m children/pets) with adaptive speed modulation: 0.5 m/s at distance, full stop below 2 m.

3 System Architecture

CW-1 Platform Specifications

PARAMETER	SPECIFICATION
Mass	15 kg (fully loaded)
Dimensions (L × W × H)	60 × 20 × 55 cm (standing)
Locomotion	12-DOF quadrupedal, 3 joints per leg
Manipulation	5-DOF arm with mechanical gripper, 50 cm reach
Compute	NVIDIA Jetson Orin Nano Super (8 GB, 67 TOPS)
Primary Camera	Luxonis OAK-D Pro (12 MP RGB, stereo depth, 9-axis IMU)
LiDAR	Livox Mid-360 (360° × 59° FOV, 70 m range, IP67)
Battery	48V 20Ah Li-ion NMC (960 Wh)
Runtime	4–5 hours per charge (terrain dependent)
Operating Speed	0.5 m/s patrol | 1.5 m/s transit
Litter Categories	10 classes (bottles, cans, butts, paper, bags, wrappers, glass, cardboard, styrofoam, general)
Detection Latency	5–10 ms (YOLO26s TensorRT INT8)
Full Pipeline Latency	50–75 ms (detection through grasp pose)
Connectivity	4G LTE (global) + WiFi
Weather Rating	IP65 (dust-tight, water jet resistant)
Noise Level	< 55 dB at 1 m
Operating Temperature	-10°C to 45°C
Charging	Autonomous contact docking, 2–4 hr charge
Collection System	Roll-dispensed bag, auto-seal, 30–50 L
Safety	Physical + wireless e-stop, independent safety MCU

Software Stack

Built on ROS 2 Humble Hawksbill (LTS through May 2027) with TensorRT-optimized neural networks, Nav2 navigation, BehaviorTree.CPP v4 state management, and a cloud-based fleet management dashboard for remote monitoring, mission assignment, telemetry, and OTA model updates.

Fleet Management

Each CW-1 reports real-time telemetry—position, battery state, collection count, litter heatmaps, system health—to a web-based dashboard. Operators define geofenced zones, schedule patrols, review analytics, and receive automated maintenance alerts. OTA updates enable continuous model improvement without physical access.

4 Operational Model

Robot-as-a-Service (RaaS)

CleanWalker deploys exclusively via a monthly subscription that includes hardware, software, remote monitoring, maintenance, and model updates. This eliminates capital expenditure, aligns cost with usage, and ensures continuous fleet improvement. The RaaS model suits municipal procurement where OPEX budgets are more flexible than CAPEX.

Deployment Process

PHASE	DURATION	ACTIVITIES
Site Assessment	2 weeks	Survey area, plan dock placement, define operating zones
Infrastructure	2 weeks	Install charging docks, outdoor power, network
Deployment	1 week	Deploy fleet, initial mapping, supervised autonomy
Operations	Ongoing	Full autonomous operation with remote monitoring

Maintenance

Quarterly gripper pad replacement, semi-annual actuator inspection, annual battery assessment. All maintenance performed on-site through modular component swap. Remote diagnostics identify issues before downtime occurs.

5 Safety & Compliance

EU Machinery Regulation 2023/1230

The CW-1 is designed for full compliance with EU Machinery Regulation 2023/1230 (effective January 20, 2027). As an autonomous machine with ML-based safety functions, it requires mandatory Notified Body CE certification under Annex I, Part A. The architecture addresses autonomous mobile machinery provisions (Section 3.5.4): supervisor function, working area safety, and movement functions with people/animal detection.

Dual-Channel Safety Architecture

- **Software layer:** Behavior tree enforces pedestrian clearance (1.5 m adults, 2.0 m children/pets), speed modulation, geofence compliance, and battery management with immediate stop on collision risk detection.
- **Hardware layer:** Independent STM32 safety MCU monitors physical e-stop, wireless kill switch (100 m range), motor overcurrent, Jetson watchdog, and tilt/rollover. Cuts motor power via hardware relay within 10 ms. Satisfies ISO 13849 Performance Level d.

Applicable Standards

STANDARD	SCOPE
EN ISO 12100:2010	Risk assessment and risk reduction
ISO 13482 (revised)	Safety for professional service robots
IEC 63327	Autonomous mobile robot safety
ISO 13849-1 / IEC 62061	Safety control systems (PL/SIL)
IEC 62443	Industrial cybersecurity
EU AI Act 2024/1689	High-risk AI system requirements

> **First-Mover Advantage:** No competitor has publicly achieved CE certification for an autonomous outdoor litter-collecting robot. CleanWalker's compliance-first architecture creates a 12–18 month regulatory moat for EU market access.

6 Economic Analysis

Total Cost of Ownership Comparison

METRIC	MANUAL LABOR (PER FTE)	CW-1 (PER UNIT, FLEET SCALE)
Annual cost	$55,000–$85,000	Contact Sales
Daily operating hours	6–8 (single shift)	16–20 (with recharge)
Area coverage per day	2–4 hectares	4–8 hectares
Night / early morning	Limited (overtime rates)	Standard (no premium)
Rain operation	Reduced staffing	Normal (IP65)
Data collection	None	Continuous heatmaps & analytics
Consistency	Variable	Algorithmic coverage

Each CW-1 provides coverage equivalent to 1.5–2.5 FTEs of manual labor. At fleet scale (100+ units), hardware cost per unit drops below $8,500 with annual operating costs of $2,500–$4,000 per unit. Total cost of ownership represents a **40-60% reduction** versus equivalent manual labor. Detailed pricing is available through CleanWalker's sales team.

1.5–2.5x
FTE OFFSET PER UNIT

40-60%
COST REDUCTION AT SCALE

16–20h
DAILY OPERATING HOURS

RaaS
ZERO CAPEX MODEL

7 Pilot Program

CleanWalker offers structured 6-month pilots deploying 5–10 units in a defined zone (park, downtown, campus, waterfront). Pilots are evaluated against agreed KPIs: collection rate, area coverage, uptime, detection accuracy, grasp success rate, and safety incidents (target: zero). The pilot timeline spans approximately 7 weeks from contract to autonomous operations.

PHASE	DURATION
Site Assessment	2 weeks
Infrastructure & Deployment	3 weeks
Autonomous Operations	5 months
Review & Expansion Planning	2 weeks

8 About CleanWalker Robotics

CleanWalker Robotics develops autonomous robotic systems for outdoor litter collection in public spaces. Founded with the mission of making cities cleaner, quieter, and more sustainable, the company combines expertise in quadrupedal robotics, computer vision, and fleet operations to address the growing gap between municipal cleanliness demands and available labor. Our technology is built on open-source foundations (ROS 2, NVIDIA Isaac) and designed for the European regulatory environment from day one.

Ready to explore autonomous litter collection?

Learn more at **cleanwalkerrobotics.com**

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