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FORCE: A Conceptual Multi-Function Robotic Platform for Construction Site Safety and Operations

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Abstract— **Construction sites are among the most hazardous and operationally complex work environments in the modern economy, presenting persistent challenges across worker safety, site organization, environmental management, and security. Injury and illness rates in the construction sector consistently rank among the highest of any industry, with workers facing chronic illness, fatigue, elevated rates of anxiety, and burnout that collectively drive absenteeism, labor shortages, and project delays. Skilled workers are routinely diverted to repetitive tasks such as cleaning, debris removal, and material transport, reducing productivity and increasing costs. During off-hours, sites remain vulnerable to theft and vandalism due to inconsistent security coverage, while the absence of real-time spatial intelligence leaves project managers unable to identify hazards early or make proactive decisions.**

Current solutions address fragments of this problem but fail to offer a comprehensive response. Static security cameras and human patrols provide inconsistent coverage at significant cost, while existing site management tools offer limited real-time spatial feedback. This fragmentation forces project managers to coordinate across disconnected systems and manual labor, leaving critical gaps in safety, efficiency, and visibility that no single existing platform resolves. This paper presents FORCE (Functional Operations Robot for Construction Environments), a conceptual semi-autonomous mobile platform designed as a systems-level response to these interconnected challenges. The proposed design integrates automated site cleaning, material transport through an internal hydraulic forklift and articulating claw, continuous 3D environment mapping, and autonomous after-hours security patrol into a single adaptable system. If successfully developed and implemented, FORCE could reduce reliance on manual labor, improve site organization, and support a shift from reactive to proactive construction site management across the full operational cycle.

Keywords: Construction robots, Mobile robots, Materials handling, Robotic mapping, Sensor fusion, LiDAR, Autonomous surveillance, Occupational safety

I. Introduction

As the global construction industry continues to expand, persistent operational and safety challenges have made the modernization of construction site management an urgent priority. The construction sector consistently ranks among the most hazardous industries worldwide, with workers routinely exposed to high temperatures, limited space, poor lighting, hazardous substances, and airborne debris generated by active worksites [1]. In South Korea, an analysis of 2020 workers' compensation data found that the occupational injury rate in construction was 1.17 per 100 workers, more than twice the 0.57 rate across all other industries combined [2]. In the United States, OSHA's 2023 injury and illness data recorded 78,641 cases within the construction sector alone, with injuries comprising 96.7% of those cases [3]. These figures reflect not only the frequency of harm but the systemic nature of a problem that has resisted resolution through conventional safety measures alone.

The physical dangers of construction work extend well beyond acute injury. Chronic conditions such as work-related musculoskeletal disorders and noise-induced hearing loss are widely documented among construction workers, with pooled musculoskeletal disorder prevalence approaching 60% [4] and hearing-loss prevalence within the sector reaching 23%, above the all-industry average [5]. Together with persistent fatigue, these conditions contribute to absenteeism, labor shortages, and project delays. The consequences of these conditions are not limited to the physical domain. Workers who perceive poor workplace safety conditions report significantly higher rates of anxiety, burnout, and depression [6], compounding the industry's productivity challenges through diminished workforce engagement and elevated turnover. Research has further established a direct relationship between safer working conditions and higher construction quality [7], suggesting that the costs of inaction are not merely humanitarian but structural, embedded in the quality and timeliness of the built environment itself.

Beyond the human toll, construction sites generate considerable environmental and organizational burden. The U.S. Environmental Protection Agency estimated that 600 million tons of construction and demolition debris were generated nationally in 2018 alone [8]. Poorly planned site layouts further amplify these effects, increasing air pollution through unnecessary equipment displacement and on-site transport, while degrading natural resources in surrounding areas [9]. During off-hours, sites remain highly vulnerable to equipment theft and vandalism, events that reduce productivity and introduce significant unplanned costs into already strained project budgets [10]. Taken together, these challenges reveal a construction industry that remains largely reactive in its approach to site management, addressing problems as they arise rather than preventing them through continuous, proactive oversight.

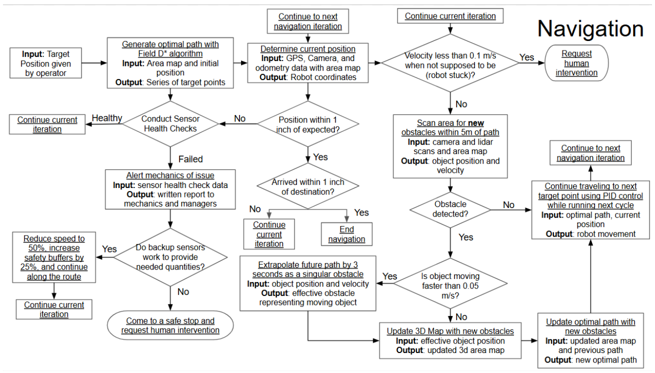
Current solutions address fragments of this problem but fall far short of a comprehensive response. Robotic platforms such as Hilti's JAIBOT perform overhead drilling with precision but require pre-mapped, structured environments and cannot operate in the dynamic terrain of an active job site. Autonomous cleaning systems like Kärcher's KIRA B50 are optimized for smooth, predictable surfaces and are ill-suited to the debris-laden floors of construction zones. Security solutions, meanwhile, rely on static cameras or costly human patrols that offer inconsistent and expensive coverage. No existing platform integrates these functions — site maintenance, material handling, environmental mapping, and security — into a unified system capable of operating continuously across shifting site conditions. This fragmentation forces project managers to coordinate across disconnected tools and manual labor, leaving critical gaps in safety, organization, and real-time site visibility.

Viewed together, the construction industry's challenges cannot be solved by narrowly specialized tools deployed in isolation. Occupational injury, chronic illness, mental health deterioration, environmental impact, and security vulnerability are not independent problems — they are interconnected symptoms of sites that lack continuous, intelligent operational support. Skilled workers are routinely diverted to repetitive tasks such as cleaning, debris removal, and material transport that could be automated, reducing both productivity and morale. Real-time visibility into site conditions remains limited, making it difficult for managers to track progress, identify hazards early, or make informed decisions before problems escalate. These limitations point to a clear need for a next-generation, systems-level approach to construction site management. FORCE—a conceptual semi-autonomous construction robot for site maintenance, material transport, security, and 3D environment mapping—is proposed as a response to that need. By unifying essential support functions within a single adaptable platform, the FORCE design could support a shift from reactive to proactive construction site management while improving efficiency, safety, and visibility across the operational cycle of a modern job site.

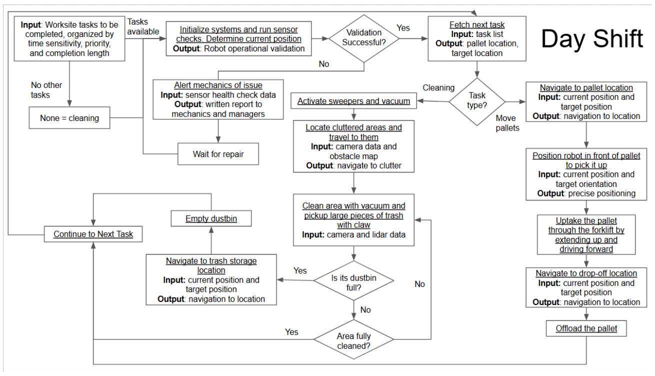
II. Methodology

The Functional Operations Robot for Construction Environments (FORCE) is proposed as a semi-autonomous mobile platform that would use hydraulic actuation, multimodal sensing, and integrated autonomous control to support construction site operations across day and night cycles. The proposed aluminum chassis would house a dual-processor control system, lithium battery pack, and hydraulic power unit coordinating an internal forklift mechanism, articulating claw, and cleaning subsystems for material transport, debris removal, and site maintenance across rugged, uneven terrain. The sensor and perception suite would incorporate LiDAR, surround cameras, GPS, and inertial measurement units to map the environment and update navigation paths in real time through a Field D* algorithm and closed-loop obstacle-avoidance logic. The proposed three-phase operational framework—Navigation, Day Shift Operations, and Night Shift Security—would enable transitions between construction support and autonomous security patrol. Together, the prioritized task hierarchy and value-based patrol logic are intended to reduce labor diversion, deter theft, and provide continuous spatial intelligence, supporting improved safety, organization, and operational visibility across the construction workflow.

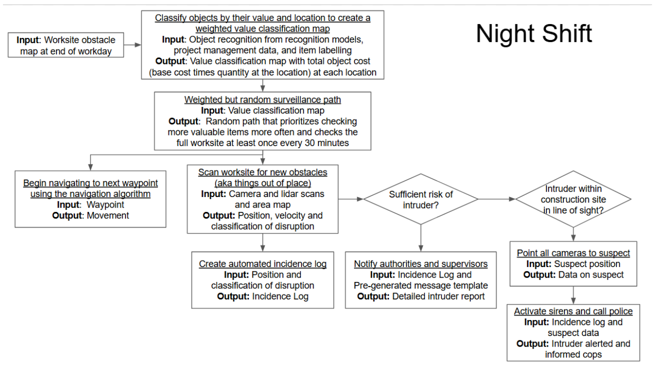
A. FORCE Deployment



1. Navigation



2. Day Shift



3. Night Shift

B. Functionality of System

The FORCE system operates using an integrated network of sensors, actuators, hydraulic mechanisms, and autonomous control logic designed to provide comprehensive construction site support across both daytime operational and nighttime security functions. At its core is a centrally mounted lithium battery pack governed by a Battery Management System (BMS), which ensures efficient power distribution across all subsystems; the electric drive motors, hydraulic pump, onboard processors, and sensor suite.

When a supervisor or project manager initiates the system, the tablet interface allows the operator to authenticate, review system status, and assign tasks or operational parameters to the robot. From this interface, the operator can input material pickup and drop-off locations, adjust cleaning priorities, update patrol schedules, or manually override autonomous behavior at any point during operation. Once initialized, FORCE loads its task queue — either from a digital Gantt chart or direct operator input — and begins executing assigned functions according to a structured priority hierarchy: emergency response, advanced mapping and construction tasks, material transport, and site cleaning, in descending order of urgency.

For mobility, four independently driven wheels powered by high-torque electric motors allow FORCE to traverse the rugged, uneven terrain typical of active construction sites. A dual-processor control system — comprising a Central Processing Unit for task planning and navigation and a dedicated Sensor CPU for real-time perception processing — coordinates movement using GPS, odometry, and inertial measurement unit data. The navigation algorithm continuously generates and updates optimal travel paths, with micro-adjustments executed every 0.05 to 0.15 seconds to account for new obstacles or changes in the site environment.

When performing material transport, FORCE utilizes its internal hydraulic forklift system. The robot raises its chassis via a hydraulic lift, positions itself over the target pallet, lowers back down, and deploys its internally housed forks horizontally beneath the load through a sliding actuation mechanism. Once secured, the chassis re-elevates and FORCE navigates to the designated drop-off point, where the sequence is reversed for unloading. For irregularly shaped or loose materials, a front-mounted articulating claw — connected through four universal joints providing full multi-axis movement — grasps and transfers items onto a retractable rolling bed at the rear of the chassis for transport or disposal.

For site cleaning, FORCE activates front and rear rotary sweepers alongside a centralized vacuum system with an extendable hose. Onboard sensors scan for debris-heavy areas, prioritizing high-traffic zones, and generate an efficient cleaning route. Collected waste is deposited into an internal dustbin, which FORCE empties autonomously at designated disposal areas when capacity is reached before resuming its task queue.

The Sensor and Perception Suite provides FORCE with continuous, comprehensive awareness of its environment. Four surround cameras deliver 360° visual coverage, while multiple LiDAR distance sensors enable precise spatial mapping and obstacle detection. Low-profile ground-level sensors provide redundancy for small or overlooked objects near the chassis. High-intensity flood lights and tail lights ensure operational visibility in low-light conditions, and an onboard speaker system delivers audible alerts to nearby workers, communicates warnings, and supports emergency signaling.

Throughout daytime operations, the Sensor CPU continuously aggregates data from the full perception suite to generate and update dynamic 3D maps of the worksite. These maps are used to optimize navigation paths, track construction progress, and provide project managers with real-time spatial intelligence through the tablet interface and optional cloud upload — enabling proactive identification of hazards, layout changes, and scheduling conflicts before they escalate.

At the close of the workday, FORCE would transition into Night Shift Security mode. Using object-recognition algorithms, the proposed system would classify on-site assets by value and location and generate a weighted surveillance map prioritizing high-value zones. A randomized patrol path would then be calculated to support regular site coverage while reducing predictable movement patterns. During patrol, FORCE would follow its waypoint path, scan for environmental anomalies against a stored baseline map, and identify potential unauthorized activity.

Upon detecting a possible intrusion, the system would log the event and notify a designated human supervisor. FORCE could then direct its cameras toward the area of concern and activate onboard alarms. Any escalation involving external security personnel or law enforcement, including the transmission of location data or live video, would require human verification and would be carried out only through approved communications procedures and in compliance with applicable privacy, cybersecurity, and legal requirements.

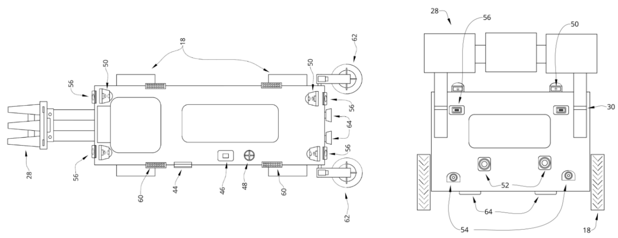
During operation, FORCE would continuously monitor sensor health, power levels, and overall system integrity. If a critical fault were detected, the robot would initiate a controlled safe-stop protocol and generate an automated incident report for human review. At the end of an operational cycle, FORCE would return to its designated charging station, reconnect through the onboard charging port, and prepare system logs and mapping data for the next day's use.

C. Systems Applied in FORCE

System	**Function**
Site Maintenance	FORCE creates significant improvements in hygienic control on construction jobsites, utilizing high-quality sensors, real-time spatial analytics, and navigational systems to ensure continuous debris removal without harming current work efficiency. This unit not only strengthens regulatory compliance, but also creates an atmosphere of commitment to overall excellence and proficiency.
Asset Distribution and Relocation	FORCE contributes significant advancements in the relocation of assets on construction sites, leveraging high-precision sensors, real-time spatial analytics, and autonomous navigational systems to ensure continuous, efficient material handling without disrupting ongoing operations. This system not only reinforces adherence to safety and logistical standards, but also fosters a culture of operational excellence and accountability around the workplace.
Intelligent Perimeter Surveillance	FORCE's security system operates during off-hours using a weighted surveillance path, prioritizing high value areas based on assets and location. In case potential threats are detected, FORCE assesses the severity of the situation through its LiDAR system and takes necessary action.

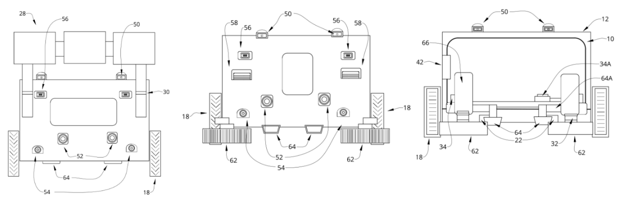
Table 1: Systems in FORCE and Their Functions

D. Structural Design



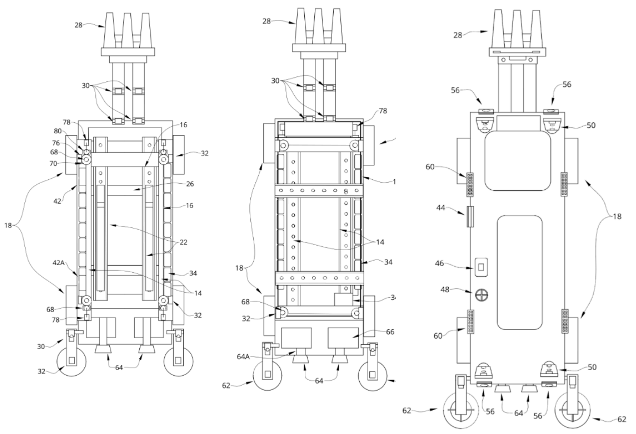
18	Wheels	52	LIDAR Distance Sensor
28	Claw	54	Low Profile Object Detection Sensor
30	Universal Joint	56	Flood Lights
44	Tablet Interface	60	Speaker
46	Receiver/Transmitter	62	Sweeper
48	GPS	64	Vacuum
50	Surround Camera		

4. FORCE Outer Front/Top Schematic



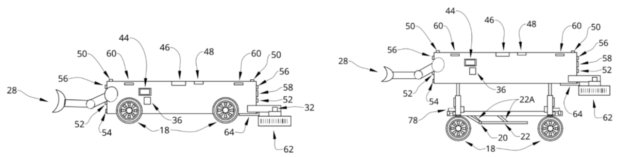
10	Frame	52	LIDAR Distance Sensor
12	Housing	54	Low Profile Object Detection Sensor
18	Wheels	56	Flood Lights
22	Forklift	58	Tail Light
32	Electric Motor	62	Sweeper
34	Lithium Battery Pack	64	Vacuum
34A	BMS	64A	Vacuum Hose
42	CPU	66	Dustbin
50	Surround Cameras		

5. FORCE Front/Back Schematic



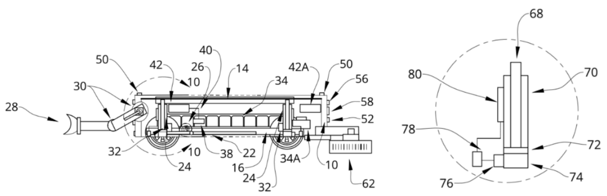
10	Frame	32	Electric Motor	66	Dustbin
14	Top Bracing	34	Lithium Battery Pack	68	Piston
16	Chassis	34A	BMS	70	Cylinder
18	Wheels	42	CPU	76	Directional Control Valve
22	Forklift	42A	Sensor CPU	78	Pump
26	Rolling Bed	62	Sweeper	80	Reservoir
28	Claw	64	Vacuum	82	Bottom Bracing
30	Universal Joints	64A	Vacuum Hose		

6. FORCE Sectional Outer/Top View



18	Wheels	50	Surround Camera
20	Cylindrical Joints	52	LIDAR Distance Sensor
22	Forklift	54	Low Profile Obstacle Detection Sensor
22A	Forklift supports	56	Flood Lights
28	Claw	58	Tail Light
32	Electric Motor	60	Speaker
36	Charging Port	62	Sweeper
44	Tablet Interface	64	Vacuum
46	Receiver/Transmitter	78	Pump
48	GPS		

7. FORCE Side/Extended



10	Frame	34	Lithium Battery Pack	58	Tail Light
14	Top Bracing	34A	BMS	62	Sweeper
16	Chassis	38	Power Converter	68	Piston
22	Forklift	40	Wiring System	70	Cylinder
24	Hydraulic Lift	42	CPU	72	Rear Piston Head
26	Rolling Bed	42A	Sensor CPU	74	Hydraulic Fluid
28	Claw	50	Surround Camera	76	Directional Control Valve
30	Universal Joints	52	LIDAR Distance Sensor	78	Pump
32	Electric Motor	56	Flood Lights	80	Reservoir

8. FORCE Left Sectional/ Hydraulic System

E. Hardware Design Description

All of the components in the FORCE system are supported structurally by the frame and chassis, which are composed of lightweight aluminum and composite materials. The chassis is fabricated with a central cavity that houses the internal forklift mechanism, while a protective outer housing encloses all embedded electronic components, shielding them from the dust, moisture, and debris typical of active construction environments. A top bracing element reinforces the upper body, distributing mechanical stress evenly across the structure and maintaining rigidity under load.

Mobility is provided by four independently driven wheels mounted at each corner of the chassis, each powered by a dedicated high-torque electric motor to allow precise maneuvering across rugged, uneven job site terrain. A hydraulic suspension system integrated into the chassis enables the robot to raise and lower its entire body relative to the ground, a function essential to the forklift operation and pallet handling mechanism.

The internal forklift system is housed within the chassis cavity, with two forks extending horizontally through structural forklift supports that run along the inner walls of the cavity. These supports incorporate cylindrical joints that provide minor articulation and load balancing during fork deployment. Fork actuation is achieved through a horizontal sliding mechanism powered by the hydraulic system, which consists of pistons housed within cylinders, a rear piston head for vertical actuation, hydraulic fluid pressurized by a pump, a central fluid reservoir, and a directional control valve that manages flow direction and velocity. A retractable rolling bed is mounted at the rear of the chassis along guide tracks, extending and retracting via small electric motors to carry additional payloads or debris collected during operation.

At the front of the robot, a multi-jointed articulating claw is mounted through four universal joints, providing full multi-axis movement including rotation, tilting, and gripping across multiple planes. High-torque electric motors drive each joint, allowing the claw to handle irregularly shaped construction materials and debris from difficult angles.

The cleaning system consists of dual rotary sweepers mounted at the front and rear of the chassis, each driven by dedicated electric motors to clear surface-level debris. A centralized vacuum is mounted beneath the robot body, connected to a flexible vacuum hose, with collected material deposited into an internal dustbin located at the rear of the chassis for periodic emptying at designated disposal areas.

The power system is driven by a centrally mounted lithium battery pack managed by a Battery Management System (BMS), which regulates power distribution across all subsystems, monitors charge levels, and prevents over-discharge. A power converter regulates voltage for the various subsystems, and an externally accessible charging port allows for wired recharging at a designated station. All power and signal routing between components is handled by an integrated wiring system running throughout the chassis.

Navigation and autonomous control are supported by a dual-processor system consisting of a Central Processing Unit governing task planning and navigation, and a dedicated Sensor CPU processing real-time perception data from the robot's full sensor suite. A GPS module mounted on the chassis provides real-time geolocation and geo-referenced mapping, while a receiver and transmitter unit enables wireless connectivity with external systems and the project management interface.

The sensor and perception suite includes four surround cameras positioned for 360° environmental coverage, multiple LiDAR distance sensors for spatial mapping and obstacle detection, and low-profile ground-level obstacle detection sensors mounted near the chassis base for identifying small objects overlooked by higher-mounted sensors. High-intensity flood lights and tail lights are mounted on the chassis exterior to provide illumination and signaling during low-light and nighttime operations. An onboard speaker system delivers audible alerts, communicates warnings to nearby workers, and supports emergency signaling and security response.

To support operator interaction, a tablet interface is mounted along the chassis exterior, sealed against dust and debris while remaining accessible for task assignment, system monitoring, and parameter adjustment.

This fully integrated mobile platform seamlessly combines material handling, autonomous cleaning, real-time environment mapping, and security patrol into a single unified system, ensuring adaptability across the full operational demands of a modern construction site.

F. Components of FORCE and their Functions

	Components	***Function***
Main Vehicle	Frame (*United Alloy, USA*)	Cost efficient, durable, heavy load bearing material used to provide a structure and housing for all sub systems
	Housing (Protolabs, USA)	Lightweight protective casing used to shield internal electronics from common workplace debris
	Top Bracing (Infra-Metals, USA)	Increases the rigidity of the chassis. Prevents bending of important parts.
	Chassis (Fraser Steel, USA)	The base of the robot that supports all of its components.
	Wheels (Hamilton, USA)	These allow the robot to be mobile in the construction environment. They are durable and resistant to most oils and solvents.
	Cylindrical Joints (MiSumi, USA)	This allows two parts of a robot that are attached to a single axis rotate about and slide along that axis.
Motion Load Handling	Forklift (Metal Zenith, China)	This is the part of the robot that is used to lift and carry heavy loads. It is in the front or back of the bot.
	Forklift Supports (Metal Zenith, China)	These support the forks with structural stability.
	Hydraulic Lift (Lange Lift, USA)	This will enable the robot to lift up, drive over objects, and then lower itself.
	Rolling Bed (Great Mats, USA)	The mechanism that closes under pallets for the robot to transport.
	Claw (Northern Metal Fab, USA)	Gives the robot the ability to grab and move objects or trash in its way.
	Universal Joints (Belden Universal, USA)	This transmits rotational motion between two shafts of any angle of each other.
Power System	Electric Motor (*ElectroCraft, USA*)	Provides mechanical power to the drive wheels, articulating claw, rotary sweepers, and rolling-bed mechanism. High-torque motors enable reliable movement and actuation under construction-site loads.
	Lithium Battery Pack (Enersys, USA)	This lithium battery pack is used to power a vast array of mechanisms. This battery pack can power up to 80V. This battery also contains a battery management system (BMS) to prevent it from overcharging or overheating.
	Charging Cable (Enersys, USA)	This is the place where the bot docks to charge. Up to 80 volts of power. This charges the battery pack.
	Power Converter (Texas Instruments, USA)	The power converter is an electrical device that converts electrical energy from one form to another.
	Wiring System (Wiring Depot, USA)	A wiring system refers to the electrical installation of cabling and associated devices such as switches, distribution boards, sockets, and light fittings within a structure.
Control & Processing	Central Processing Unit (CPU) (Acceleration Robotics)	The CPU is the primary component of a computer that processes instruction, performs calculations, and manages data flow within the systems.
	Sensor CPU (Texas Instruments, USA)	A dedicated processor that collects and processes real-time data from the cameras, LiDAR sensors, and obstacle-detection sensors. It sends environmental and obstacle information to the main CPU for navigation and task execution.
	Tablet Interface (Getac, Taiwan)	The tablet interface refers to the user interface of a tablet device which includes the way users interact with the devices software, applications, and features.
	Receiver / Transmitter (Ezurio, USA)	This component allows FORCE to receive and transmit signals that can be used to communicate messages and even help with location tracking.
	GPS (Hemisphere GNSS, USA)	This component allows FORCE to locate where it is globally, with a map that is widely used, which makes it easier for it to communicate its location. Additionally, this component enhances its navigational capabilities.
Sensor and Perception Suite	Surround Camera (ibeam, USA)	This camera is able to capture and record 360 degree views around the robot for security purposes.
	LIDAR Distance Sensor (SICK, USA)	Uses laser-based distance measurements to detect obstacles, map the surrounding environment, and support safe autonomous navigation.

	Low-Profile Obstacle Detection Sensor (Microvision, USA)	The system to detect objects and prevent collisions.
	Flood Lights (Ittech, USA)	Lights up the area, and can scare intruders at night.
	Tail Light (Sunway Autoparts, CHN)	Light up when the robot is coming to a stop or reversing.
	Speaker (Misco, USA)	Produces audible warnings, operational alerts, emergency signals, and security alarms for nearby workers and supervisors.
Cleaning System	Sweeper (Smith Equipment, USA)	Rotary brush that loosens and gathers surface debris toward the vacuum intake.
	Vacuum (AMETEK, USA)	Generates suction to draw loosened debris from the floor through the hose into the internal dustbin.
	Vacuum Hose (Flexaust, USA)	Flexible conduit that carries suctioned debris and air from the intake to the dustbin.
	Dustbin (U.S. Plastic Corp., USA)	Onboard container that collects swept and vacuumed debris until emptied at a disposal area.
Hydraulic System	Piston (Stertil Koni, Netherlands)	The moving component in a cylinder that is pushed by hydraulic fluid.
	Cylinder (Parker Hannifin, USA)	Houses the piston and converts pressurized hydraulic fluid into linear mechanical motion.
	Rear Piston Head (Parker Hannifin, USA)	Seals the piston within the cylinder to maintain hydraulic pressure.
	Hydraulic Fluid (Kendall, USA)	The fluid used in pistons to move them.
	Directional Control Valve (Nachi America Inc., USA)	Controls the direction of fluid flow in the system.
	Pump (Parker Hannifin, USA)	Pulls and pushes fluid.
	Reservoir (Parker Hannifin, USA)	Where hydraulic fluid is stored.

Table 2: Components of FORCE and Their Functions

G. Assembly of Innovation

The assembly of the FORCE system involves constructing the Main Vehicle Platform and configuring its integrated operational subsystems, which carry out the robot's core construction site functions. Begin by fabricating the aluminum and composite material chassis frame, ensuring that the central cavity is built into the structure during this stage to accommodate the internal forklift mechanism. Secure four wheel assemblies at each corner of the chassis, verifying ground clearance and stability for operation across the uneven, debris-laden terrain of active construction environments. Install the independent high-torque electric motors for each wheel, connecting them through the internal wiring harness to the central power and control systems.

Next, mount the lithium battery pack centrally within the chassis for balanced weight distribution and connect it to the Battery Management System, which monitors charge levels and regulates power flow to all operational components. Install the power converter to regulate voltage across the various subsystems, and integrate the charging port into the rear panel of the chassis to allow convenient wired recharging at the designated docking station. Install the hydraulic system components within the lower chassis bay, beginning with the fluid reservoir and pump, then routing reinforced hydraulic lines through a directional control valve to the pistons, cylinders, and rear piston heads that enable the chassis lifting mechanism. Verify hydraulic pressure and fluid integrity before proceeding.

With the power and mobility systems in place, install the internal forklift assembly within the chassis cavity. Insert the forklift forks into the structural forklift supports running along the inner walls of the cavity, ensuring the cylindrical joints are properly seated for load balancing and minor articulation during deployment. Connect the horizontal sliding actuation mechanism to the hydraulic system and calibrate the extension and retraction sequence. Mount the retractable rolling bed at the rear of the chassis along internal guide tracks, connecting its dedicated drive motors to the wiring harness and verifying smooth extension and retraction under load.

At the front of the chassis, assemble and mount the articulating claw through four universal joints fastened to the forward structural frame. Connect the high-torque electric motors driving each joint to the wiring harness and verify full multi-axis articulation — including rotation, tilting, and gripping — across the claw's operational range. Mount the dual rotary sweepers on motorized brackets at the front and rear of the chassis undercarriage, and secure the centralized vacuum unit beneath the robot body, routing the flexible vacuum hose to the internal dustbin compartment at the rear of the chassis. Test all cleaning components for alignment and suction integrity before proceeding.

Mount the Central Processing Unit and dedicated Sensor CPU on shock-absorbing supports within the protective internal housing, optimizing weight distribution while safeguarding sensitive electronics from vibration and impact typical of construction environments. Wire both processors into the central wiring harness, connecting them to all motors, sensors, actuators, and the hydraulic control system. Install the GPS module on the upper chassis exterior for unobstructed signal acquisition, and position the receiver and transmitter unit for reliable wireless connectivity with the tablet interface and external project management systems.

Strategically distribute the sensor and perception suite across the chassis exterior. Mount four surround cameras at intervals around the upper housing for full 360° environmental coverage, secure multiple LiDAR distance sensors at mid-body height for spatial mapping and obstacle detection, and fasten low-profile ground-level obstacle detection sensors near the base of the chassis to identify small objects overlooked by higher-mounted sensors. Install high-intensity flood lights at the front and tail lights at the rear of the chassis exterior, sealing all light fixtures against dust and moisture intrusion. Position the onboard speaker system for omnidirectional audio projection to ensure alerts and warnings are audible across the surrounding work area. Mount the dust-sealed tablet interface along the accessible exterior of the chassis for operator configuration and real-time system monitoring.

Enclose all internal components within the protective outer housing and fasten the top bracing element across the upper body of the frame to distribute mechanical stress and maintain structural rigidity under operational load. All critical components should be mounted on quick-release brackets where possible to facilitate efficient inspection and servicing without compromising structural integrity during operation.

Following prototype construction, FORCE would require a comprehensive calibration and validation process to align sensor inputs, verify motor and actuator functions, assess hydraulic pressure and lift sequences, and evaluate the forklift, claw, and cleaning mechanisms for operational accuracy. The navigation algorithms would then be uploaded to the Central Processing Unit and tested against representative site maps to assess path generation, obstacle avoidance, and task sequencing. Autonomous docking and recharging routines would also require verification before field deployment. Successful completion of these testing and validation stages would be necessary before FORCE could be considered ready for use on an active construction site.

H. Mechanism of Components

The FORCE system operates through a series of precisely coordinated component interactions, each designed to maximize construction site support effectiveness while ensuring system reliability and safety. The mechanism's operation can be divided into two primary phases: active site operations and post-operational site layout planning.

1) Active Site Operations

The operational sequence initiates through the tablet interface, where the operator authenticates the system and loads the current task queue. The Central Processing Unit performs automated diagnostic routines, verifying motor responsiveness, hydraulic pressure, sensor calibration, and battery charge levels through the Battery Management System before authorizing movement. Once system readiness is confirmed, the CPU downloads updated mission parameters including the current Gantt chart phase, material transport assignments, and priority cleaning zones, then generates an optimal travel path using the Field D* algorithm, drawing on the most recent site map and current GPS position data.

With navigation initialized, the four independently driven wheel motors activate in a coordinated sequence, propelling FORCE toward its first assigned task location. Simultaneously, the Sensor CPU begins processing incoming data from the LiDAR sensors, surround cameras, and ground-level obstacle detection sensors at intervals of 0.05 to 0.15 seconds. Detected obstacles are immediately incorporated into the active site map by the Sensor CPU, which triggers real-time path recalculation by the Central Processing Unit to maintain safe and efficient navigation across the dynamic construction environment. The GPS module continuously feeds positional data to the CPU, while odometry and inertial measurement unit data provide supplementary positional verification to maintain navigational accuracy in areas of limited GPS signal.

For material transport tasks, the hydraulic system engages upon arrival at the target pallet location. The pump draws hydraulic fluid from the reservoir and pressurizes it through the directional control valve, routing force to the pistons and cylinders that elevate the chassis via the rear piston heads. Once raised to the appropriate height, FORCE positions itself directly over the pallet using fine motor adjustments from the wheel drive system, guided by the surround cameras and LiDAR sensors. The chassis then lowers as the directional control valve reverses fluid flow, and the horizontal sliding mechanism simultaneously deploys the internal forks outward through the forklift supports, with the cylindrical joints absorbing minor load imbalances as the forks slide beneath the pallet. The hydraulic system re-pressurizes to elevate the chassis and secured pallet, and the CPU generates a navigation path to the designated drop-off point. Upon arrival, the sequence reverses precisely — the chassis lowers, the forks retract through the forklift supports, and the hydraulic system re-elevates FORCE, releasing the pallet at the target location. For loose or irregularly shaped materials, the universal joint-mounted articulating claw activates through its dedicated electric motors, with each joint's multi-axis range of motion allowing the claw to reach, grip, and transfer items of varying shapes onto the extended rolling bed at the rear of the chassis. The rolling bed's drive motors then retract it inward along its guide tracks, securing the collected load against the chassis for stable transit.

During cleaning operations, the front and rear rotary sweepers engage simultaneously alongside the centralized vacuum system. The sweeper motors drive the rotating brush assemblies, displacing surface debris toward the vacuum intake, where suction generated by the vacuum unit draws particulates through the flexible hose and into the internal dustbin. The Sensor CPU monitors dustbin capacity through integrated fill sensors and, upon reaching capacity, autonomously redirects the Central Processing Unit to route FORCE to the nearest designated disposal area. Once emptied, FORCE resumes its sensor-generated cleaning route or transitions to the next queued task according to the priority hierarchy. Throughout all cleaning and transport operations, the Sensor CPU simultaneously aggregates perception data from the full sensor suite to continuously update the dynamic 3D site map, logging environmental changes, flagging potential hazards, and tracking construction progress for project manager review through the tablet interface.

During Night Shift Security operations, the proposed object-recognition algorithm would process the most recent 3D site map to generate a value-weighted security map that classifies on-site assets by location and estimated value. The Central Processing Unit would use this map to calculate a randomized patrol path intended to provide regular site coverage while reducing predictable movement patterns. As FORCE patrols, its floodlights, surround cameras, and

LiDAR sensors would scan for deviations from the stored baseline map.

If a potential anomaly were detected, the Sensor CPU would generate an incident log and notify a designated human supervisor through the receiver and transmitter unit. Following human verification, FORCE could activate audible alarms, direct its cameras and floodlights toward the area of concern, and transmit relevant location data or video to authorized personnel. Any communication with external security services or law enforcement would occur only through approved procedures and in compliance with applicable privacy, cybersecurity, and legal requirements.

2) Post-Operational Site Layout Planning

Upon completion of each operational cycle, one of FORCE's most consequential contributions to construction site management emerges through the synthesis and application of the spatial data collected throughout the day. The Sensor CPU compiles the full dataset gathered during active operations, including continuous LiDAR scans, surround camera imagery, GPS-referenced positional logs, and material transport records into a comprehensive, updated 3D map of the construction site. This map reflects the current state of the environment with precision, capturing changes in material stockpile locations, equipment positions, debris accumulation zones, high-traffic pathways, and completed construction elements that have altered the site's physical layout since the previous cycle.

The Central Processing Unit then processes this updated spatial data against the project's blueprint and Gantt chart parameters, comparing the current site layout to the planned configuration for the active construction phase. Discrepancies between actual and planned layouts — such as misplaced materials, obstructed access routes, encroached safety zones, or inefficiently positioned equipment — are automatically flagged and compiled into a site layout report transmitted to the project manager through the receiver and transmitter unit and displayed on the tablet interface. This report provides actionable recommendations for layout adjustments, such as optimal repositioning of material stockpiles to shorten transport routes, reallocation of equipment to reduce on-site displacement, and identification of areas where debris accumulation is impeding workflow or creating hazard zones.

By identifying inefficiencies in the current site layout, FORCE directly supports the reduction of unnecessary on-site transport, shortening of access routes, and more strategic positioning of temporary fixtures and materials — outcomes that research has shown to meaningfully reduce air pollution, lower bioenvironmental risk, and improve overall project efficiency [9]. The GPS module ensures that all flagged locations and recommended adjustments are geo-referenced with precision, allowing project managers to act on the layout intelligence with spatial accuracy rather than relying on manual observation or estimation.

As the construction project progresses through successive phases, the cumulative spatial data collected and synthesized by FORCE across multiple operational cycles builds an evolving historical record of site development. This longitudinal dataset enables project managers to identify recurring layout inefficiencies, track the accuracy of construction progress against the project schedule, and make increasingly informed decisions about resource allocation, workflow sequencing, and hazard prevention. The result is a construction site management approach that becomes progressively more intelligent and responsive over time — transforming the raw sensor output of FORCE's daily operations into a continuously refined foundation for safer, more efficient, and more precisely planned construction environments.

I. Applications of FORCE

When the project manager or operator approaches FORCE, the system is powered on via the tablet interface, which guides the user through an automated pre-operational check. This initialization sequence verifies battery levels, sensor health, motor responsiveness, hydraulic pressure, and wireless connectivity. Once verified, the operator authenticates through the tablet interface and loads the current project parameters, including the site's digital Gantt chart, task priorities, and any pre-configured patrol or cleaning schedules. From this point, FORCE operates across two primary modes depending on the time of day and operational requirements: Day Shift Operations and Night Shift Security.

Day Shift Operations:

In Day Shift mode, the operator assigns tasks to FORCE through the tablet interface, either individually or as a pre-scheduled queue. Once tasks are loaded, the Central Processing Unit activates the drive motors and navigation systems, and the Sensor CPU begins processing real-time data from the LiDAR sensors, surround cameras, and GPS module to generate an optimal travel path. FORCE then navigates autonomously across the job site, continuously scanning for obstacles and dynamically updating its path to avoid collisions with workers, equipment, and debris.

Task execution would follow a structured priority hierarchy. If a potential emergency were detected through the camera array or reported through the onboard alert system, FORCE would notify the on-site manager and provide relevant location data and visual information to support human assessment. Under supervisor direction, the robot could navigate toward the incident area, illuminate the scene, and transmit a live video feed to authorized personnel. FORCE would function as an emergency-support tool rather than an independent responder, and any operational response would remain subject to human oversight and established site-safety procedures.

When performing material transport, the operator assigns a pickup and drop-off location through the tablet interface. FORCE navigates to the target pallet, activates its hydraulic lift system to raise its chassis, and positions itself over the load. The chassis then lowers, the internal forks extend horizontally through the forklift supports beneath the pallet, and the chassis re-elevates to secure the load for transport. Upon arriving at the designated drop-off point, FORCE reverses the sequence to precisely position and release the material before proceeding to its next assigned task. For irregularly shaped or loose materials, the articulating claw grasps and transfers items onto the retractable rolling bed at the rear of the chassis, which extends to receive the load and retracts to secure it during transit.

When no higher-priority tasks are active, FORCE defaults to site cleaning operations. The Sensor CPU scans the site to identify debris-heavy areas, prioritizing high-traffic zones, and generates an efficient cleaning route. The front and rear sweepers and centralized vacuum system activate as FORCE navigates the route, depositing collected debris into the internal dustbin. When the dustbin reaches capacity, FORCE autonomously navigates to the nearest designated disposal area, empties its contents, and resumes cleaning or transitions to the next queued task. Throughout all daytime operations, the Sensor CPU continuously updates the site's 3D map, logging environmental changes and providing the project manager with real-time spatial intelligence through the tablet interface and optional cloud synchronization.

Night Shift Security:

At the close of the workday, FORCE would transition into Night Shift Security mode. The proposed system would use the most recent site map and object-recognition algorithms to classify on-site assets by value and location, producing a weighted security map that prioritizes high-value areas such as equipment storage zones and material stockpiles. FORCE would then generate a randomized patrol route intended to provide regular site coverage while reducing predictable movement patterns.

As FORCE patrols, its floodlights, cameras, and LiDAR sensors would scan the environment and compare current conditions with the stored baseline map to identify potential anomalies or unauthorized activity. If a possible threat were detected, the system would log the event and notify a designated human supervisor. Following human verification, FORCE could direct its cameras and lights toward the area of concern, activate onboard alarms, and transmit relevant location data or video to authorized personnel. Any escalation to external security personnel or law enforcement would occur only through approved procedures and in compliance with applicable privacy, cybersecurity, and legal requirements. After the incident had been reviewed or resolved, FORCE could resume its patrol route.

Throughout both shift modes, FORCE continuously monitors its own system health, power levels, and sensor integrity. Should a critical fault be detected at any point, the robot initiates a controlled safe-stop protocol, generates an automated incident report, and alerts a human supervisor for intervention. At the conclusion of each operational cycle, FORCE autonomously navigates to its designated charging station, reconnects via the onboard charging port, and uploads all logs, maps, and incident records for review and use in the following day's operations.

In conclusion, FORCE is proposed as a versatile operational platform designed to integrate into the daily workflow of a modern construction site. Its planned transition between Day Shift and Night Shift modes could reduce the need for continuous human intervention, while the priority-based task hierarchy is intended to ensure that critical site needs are addressed before routine functions. Through its proposed navigation, mapping, material-handling, and security capabilities, FORCE could provide project managers with continuous site intelligence and semi-autonomous support, potentially improving safety, efficiency, and operational oversight.

III. Expected Results and discussions

As a conceptual design proposal, FORCE has not yet undergone prototype construction or experimental validation. The following discussion evaluates the anticipated benefits of the proposed system based on its intended architecture, operational functions, and the construction-industry challenges identified in existing research. Through its proposed combination of automated cleaning, hydraulic material transport, real-time 3D environment mapping, and intelligent security patrol, FORCE could contribute to improved worker safety, operational efficiency, and project management outcomes.

A. Worker Safety and Hazard Reduction

A critical consideration in construction site management is ensuring that new operational systems reduce rather than introduce risks to workers. FORCE is designed to address persistent sources of occupational hazard on active job sites. Its proposed LiDAR sensors, surround cameras, and low-profile obstacle-detection sensors would provide continuous environmental awareness, supporting hazard identification and the maintenance of safe operating distances from workers and equipment. By automating repetitive and physically demanding tasks such as debris removal, material transport, and site cleaning, FORCE could reduce the frequency with which skilled workers are exposed to hazardous conditions and may therefore lower the risk of acute injury and chronic illness. Research has established a relationship between safer working conditions and higher construction quality, suggesting that the anticipated safety benefits of FORCE could extend beyond worker well-being to the quality of the built environment.

B. Operational Efficiency and Labor Optimization

FORCE is designed to address one of the construction industry’s persistent inefficiencies: the diversion of skilled labor to repetitive, non-specialized tasks. By assuming responsibility for debris removal, pallet transport, and routine site upkeep, the proposed system could allow skilled workers to focus more fully on specialized tasks that contribute directly to project progress and quality. The internal hydraulic forklift is intended to support pallet handling with reduced dependence on dedicated manual operation, while the articulating claw would provide flexible handling of irregularly shaped materials that might otherwise require additional labor. The priority-based task hierarchy is designed to address the most operationally critical needs first, potentially reducing downtime and improving workflow continuity. Together, these capabilities could improve resource allocation, reduce labor inefficiencies, and support more predictable project timelines.

C. Contribution to Site Organization and Project Oversight

Construction site disorganization is a significant contributor to project delays, safety incidents, and cost overruns. FORCE is designed to address this challenge through continuous 3D environment mapping using LiDAR, surround cameras, GPS, and dual onboard processors. The proposed system would generate and update dynamic spatial maps of the worksite, potentially providing project managers with current visibility into site conditions, material locations, and construction progress. This information could support earlier identification of hazards, layout inefficiencies, and scheduling conflicts.

Proper site-layout planning has been shown to reduce pollution and mitigate bioenvironmental risks by minimizing unnecessary equipment displacement and shortening on-site transport routes. FORCE's proposed mapping and organizational capabilities could support these outcomes by converting sensor data into actionable spatial information for project managers. In this way, the system could help shift construction-site management from a reactive approach toward a more proactive one.

D. Autonomous and Scalable Operation

A central objective of the FORCE design is to support semi-autonomous operation across both daytime construction tasks and nighttime security functions while minimizing the need for continuous human oversight. The proposed Field D* navigation algorithm, combined with sensor fusion from LiDAR, cameras, GPS, and inertial measurement units, would support navigation through dynamically changing construction environments. The planned transition between Day Shift and Night Shift modes could provide continuous site coverage with limited operator intervention at shift boundaries.

FORCE is also designed with scalability in mind. In future implementations, multiple units could potentially be deployed across large construction sites as coordinated fleets, dividing tasks and communicating in real time to improve coverage and operational efficiency across different site conditions and project phases.

E. Security and Crime Prevention

During off-hours, construction sites remain vulnerable to equipment theft and vandalism, which can introduce unplanned costs, reduce labor efficiency, and negatively affect worker morale. FORCE is designed to address this challenge through a proposed Night Shift Security mode that would generate weighted patrol paths prioritizing high-value asset zones while seeking to provide regular site coverage. Randomized path generation could reduce predictable movement patterns, while the anomaly-detection system would compare real-time sensor input against a stored baseline map to identify potential unauthorized activity.

If a potential intrusion were detected, FORCE would log the event and notify a designated human supervisor for verification. Following human confirmation and in accordance with applicable site procedures, privacy requirements, communications protocols, and local regulations, the system could activate onboard alarms, direct cameras toward the area of concern, and transmit relevant location data or video to authorized personnel. These capabilities would require prototype testing, cybersecurity safeguards, and regulatory review before deployment.

F. Economic and Social Benefits

FORCE could offer meaningful economic and social benefits if its proposed capabilities are successfully developed and validated. Persistent inefficiencies, safety incidents, theft, and project delays continue to create substantial costs for developers, contractors, workers, and clients. By reducing the need for skilled workers to perform repetitive support tasks, the proposed system could improve labor allocation and allow personnel to focus on specialized work.

FORCE could also help reduce costs associated with occupational injuries, absenteeism, material loss, equipment theft, rework, and scheduling delays. Its proposed spatial-mapping and site-monitoring capabilities may support more accurate planning and earlier identification of operational problems. However, the economic value of the system would depend on factors such as prototype performance, acquisition and maintenance costs, site size, deployment conditions, and the level of human oversight required. A formal cost-benefit analysis would therefore be necessary before FORCE could be considered a cost-effective solution for commercial construction sites.

IV. Conclusion

The Functional Operations Robot for Construction Environments (FORCE) is a conceptual systems-level design intended to address persistent challenges in construction site safety, operational efficiency, environmental management, and security. By integrating automated site cleaning, hydraulic material transport, continuous 3D environment mapping, and after-hours security patrol within a single proposed platform, FORCE offers a unified alternative to the fragmented tools and manual processes commonly used across construction sites.

The design is intended to reduce reliance on skilled labor for repetitive support tasks, improve site organization, and provide project managers with continuous spatial information. Its proposed Day Shift and Night Shift operating modes, along with a priority-based task hierarchy, could support more consistent site coverage and allow urgent needs to be addressed before routine tasks. If successfully developed and validated, these capabilities could help reduce occupational hazards, improve workflow efficiency, deter theft and vandalism, and support more informed project management.

FORCE is designed with modularity and scalability in mind, allowing future versions to incorporate coordinated fleet operation, vertical mobility, machine learning, and additional task-specific tools. The platform could also have applications beyond construction, including warehouse logistics, disaster response, and industrial maintenance.

Further prototype development, testing, safety validation, cost analysis, and regulatory review would be required before real-world deployment. Nevertheless, FORCE presents a promising conceptual framework for integrating multiple construction-site support functions into a single adaptable robotic platform and provides a foundation for future research and engineering development.

V. Future Work

While the FORCE concept presents several promising capabilities, future development could extend its effectiveness and broaden its potential impact across construction site operations. Integration of augmented reality projection capabilities could allow FORCE to display virtual installation guides, blueprint overlays, and spatial markers directly onto work surfaces, reducing the risk of misalignment and providing workers with real-time visual guidance during complex construction tasks. Advanced sensor arrays incorporating thermal imaging and air quality detection could improve early warning systems for hazardous site conditions, enabling FORCE to identify heat stress risks, toxic substance exposure, and fire hazards before they escalate into emergencies.

Machine learning integration could significantly optimize FORCE's operational decision-making over time, allowing the system to analyze historical site data, predict high-risk areas, anticipate material transport demands based on project phase, and refine patrol strategies based on observed patterns of unauthorized activity. Expanded fleet coordination capabilities could allow multiple FORCE units to operate simultaneously across large-scale job sites, dividing tasks intelligently and communicating in real time to maximize coverage and efficiency. Mobile autonomous docking stations could further extend operational range, enabling FORCE to recharge without returning to a fixed location and maintaining continuous coverage across sprawling or multi-level construction environments.

Future iterations could also explore vertical mobility enhancements, such as stair-climbing mechanisms or drone-assisted aerial mapping integration, to extend FORCE's operational reach across multi-story construction projects where ground-level navigation alone is insufficient. The development of modular attachment systems could allow FORCE to accept task-specific tools — such as concrete surface finishers, paint applicators, or inspection probes — expanding its functional range without requiring a complete hardware redesign. Enhanced natural language processing capabilities integrated into the speaker and tablet interface systems could further simplify operator interaction, allowing project managers to assign tasks, request status updates, and adjust operational parameters through voice commands rather than manual input. These advancements would build upon FORCE's existing systems-level foundation while expanding its role as a comprehensive, intelligent platform for the future of construction site automation.

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