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Design of Community Inspection Robot System

Baojing Cheng[1], Hao Feng[#] and Ning You[#]

[1]Nanjing Foreign Language School, China
[#]Advisor

ABSTRACT

With the continuous development of the global economy, urban centers have experienced a consistent increase in size. Consequently, the number of schools, parks and residential communities within cities are also on the rise. The increasing quantity of various types of communities has juxtaposed a notable dilemma: a shortage of security and maintenance personnel. In order to address this issue, employing robotic automated inspection within these communities, coupled with autonomous navigation, obstacle avoidance, and AI recognition technology, is proposed. This project aims to alleviate the burden on human staff, improve recognition accuracy, and enhance the overall efficiency of operation and maintenance. This paper analyzes the operational needs of these communities, presents a design concept for a community inspection robot system, and discusses issues that require further research in the future.

Introduction

With the continuous development of the global economy, the number of large and medium-sized cities is increasing year by year, and the construction progress of various types of communities such as schools, parks, and residential areas within cities is accelerating. These communities play a crucial role in people's learning, living, and leisure, making their operation and maintenance highly important. Traditionally, community inspections have been conducted manually, with security personnel regularly patrolling the communities to maintain safety. Maintenance staff conduct regular inspections and repairs of the power supply, water supply, gas supply equipment, sports facilities, and other amenities in the community. There are three typical types of communities:

Schools:

Security personnel safeguard the safety of the campus and inspect entrances such as school gates/fences to prevent unauthorized access.

Parks:

Maintenance staff inspect public facilities such as streetlights and control panels for damage and check for incidents like elderly falls.

Residences:

Property management conducts inspections of water, electricity, and gas meters, as well as other utilities. They also monitor entrances such as gates/fences for unauthorized access.

The allocation principles for security personnel, based on a study of the relevant residential areas in Nanjing and reference to the Standardization Law of the People's Republic of China, are outlined in Table 1.

Table 1. Security Staff Configuration Data

No.	Community Type	Area (m^2)	Security Staffs
1	School	7500	2

No.	Community Type	Area (m^2)	Security Staffs
2	Park	100000	30
3	Residence	20000	3

From a data perspective, the security configuration ratio appears to be reasonable. However, China's urbanization rate has surged rapidly, escalating from 17.92% in 1978 to 65.2% in 2022. Consequently, community development is accelerating, yet specialized personnel such as security and operations and maintenance are relatively inadequate. Moreover, during inspections, human staff may encounter issues like varying physical conditions, adverse weather, or other objective factors, leading to erroneous readings of utility meters or failure to identify unauthorized personnel, resulting in unwarranted economic losses.

With the rise of robotics and artificial intelligence technologies, the prospect of employing robots to either fully or partially replace humans is a topic of significant interest across various industries. Combining robotic capabilities with AI recognition technology and designing an automated inspection robot system to inspect the community is highly beneficial. This approach not only enhances recognition accuracy but also significantly reduces the burden on human resources. It effectively addresses the discrepancy between the scarcity of manpower and the increasing number of communities, ultimately elevating the overall operation and maintenance efficiency of the community.

Demand Analysis

In accordance with the requirements for community inspections, the robot inspection system is designed to autonomously perform inspection tasks and generate reports. The robot is capable of automated navigation along predefined routes, obstacle detection and avoidance, as well as AI (Artificial Intelligence) recognition. This includes automated reading of utility meters (e.g., water and electricity) and facial recognition of unauthorized individuals.

The inspection system is equipped with a backend computer that facilitates the issuance of inspection tasks, analysis of inspection results, report generation, display of the robot's movement trajectory and inspection task status, as well as remote robot control. The robot establishes a communication mechanism with the backend computer to receive commands and upload inspection results. Given the robot's prolonged outdoor operations and extensive operating area, it is impractical to deploy a wired network. Therefore, Wi-Fi wireless communication is employed to ensure seamless connectivity.

Overall Design

System Architecture

The community robot inspection system is composed of three parts: backend computer, communication network, and robots. The system architecture is illustrated in Figure 1.

1. The inspection backend computer provides the functions including inspection task issuance, report generation, robot route display, robot remote control and camera viewing.
2. Communication network consists of Wi-Fi. The Wi-Fi hotspots are deployed on the inspection path in the community, and the robot establishes a connection with the Wi-Fi hotspots, and then sends the information to the backend inspection computer by Wi-Fi.
3. The robot has two physical forms: wheeled robot and quadruped robot. The former adopts wheels for its motion mechanism and the latter adopts bionic design. Both are equipped with various types of sensors such as laser radar (LIDAR) and cameras.

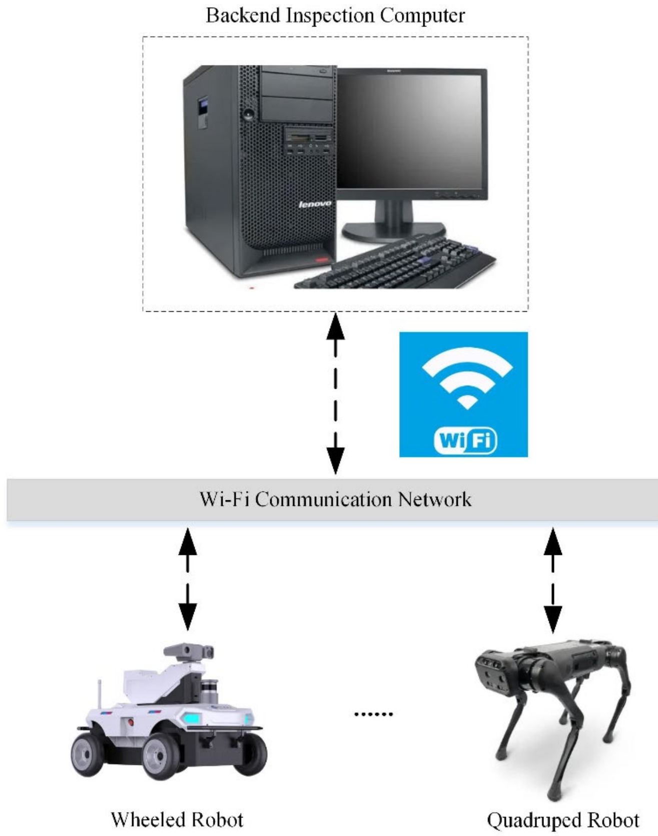

Figure 1. Robot inspection system architecture

Inspection Backend Computer

The inspection backend computer provides the following functions: inspection task planning, route display, remote control, camera control, and AI recognition, which are elaborated below.

1. Inspection Task Planning: Planning robot inspection tasks and waypoints. Inspection tasks are divided into two types:

a) Routine Inspection: Conduct daily inspections of the community, strategically planning inspection points from Monday to Sunday.

b) Emergency Inspection: In the event of a major incident like a fire, staff can remotely assign robot inspection locations, and the robot will autonomously plan its inspection route.

2. Inspection Route Display: Real-time display of the robot's operational data, enabling staff to understand the robot's position and orientation, including coordinates, speed, and heading.

3. Robot Remote Control: Remote control of the robot's movement (forward, backward, left, right) and the ability to set its speed.

4. Camera Control: Remote control of the robot's integrated camera, allowing horizontal and vertical rotation, auto-focusing, and real-time viewing of video feeds to promptly identify equipment hazards.

5. AI Recognition: Utilize a deep learning framework in the backend to pre-configure trained models for AI recognition, capable of identifying meter readings, intrusion by small animals, and personnel falls. Refer to Table 2 and Figure 2 for AI recognition data and results.

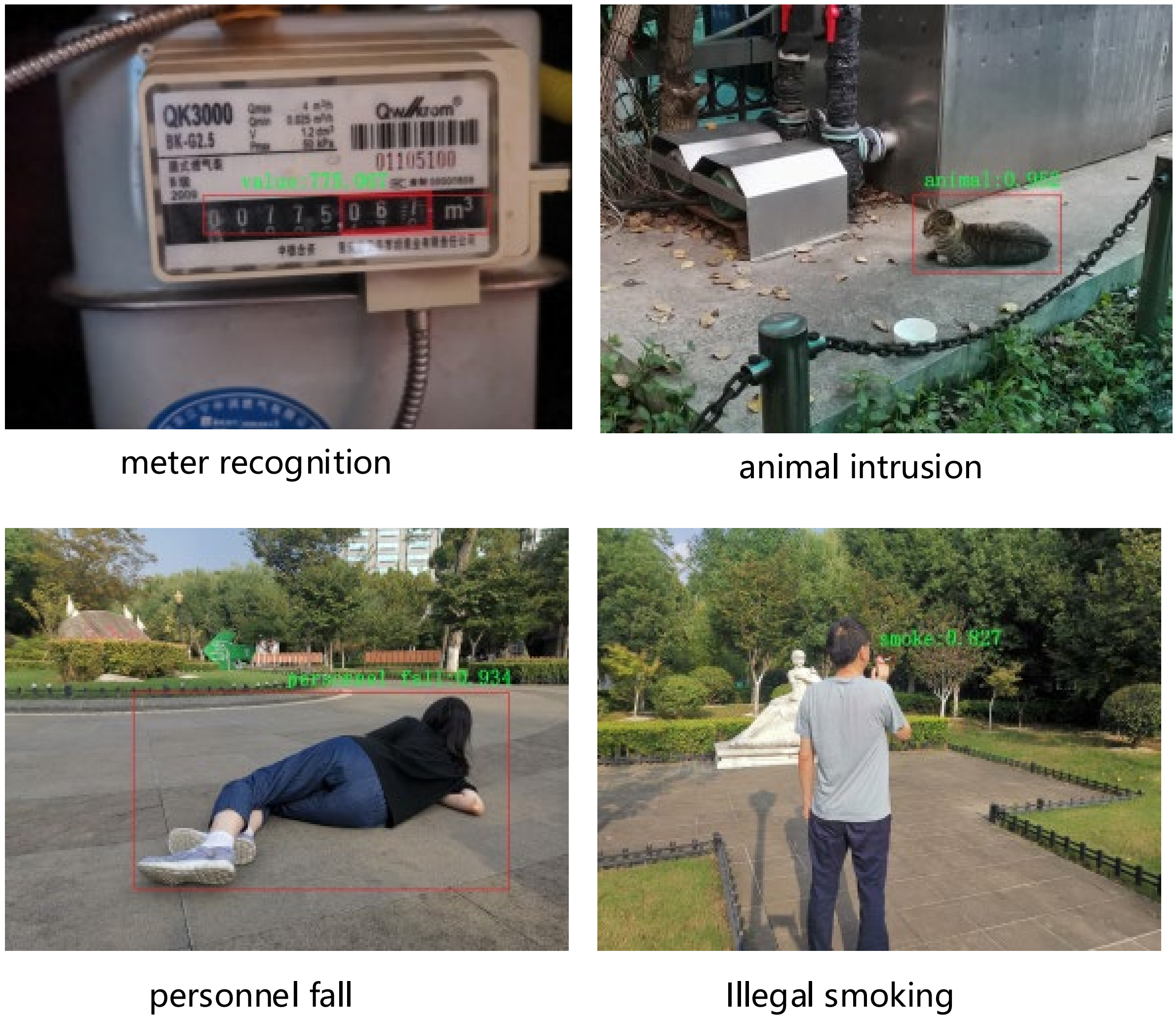

Figure 2. AI Recognition

Table 2. Recognition Data

No.	Recognition Type	Confidence Value	Recognition Value
1	Meter	-	775.067
2	Animal	0.952	-
3	Personal fall	0.934	-
4	Soke	0.827	-

Wireless Communication

Wireless communication is responsible for transmitting commands from the inspection backend to the upper end and relaying robot status information to the lower end. Since the robot is a mobile device and its movement path is not fixed, wired communication cannot be deployed. Wireless communication can utilize multiple base stations, providing wide coverage without the need for communication cable installations. Therefore, by deploying several wireless base stations within the community, complete network coverage can be achieved, enabling the robot to establish real-time communication with the inspection backend.

The selection of an appropriate protocol stack is essential for wireless communication. Typically, there are two main protocols: TCP and UDP. TCP provides a connection-oriented communication method, ensuring error-free information transmission at the transport layer. UDP, on the other hand, does not require a connection and relies on the application layer for data integrity, resulting in higher transmission efficiency compared to TCP. In this paper, a Wi-Fi wireless solution is adopted. In areas with insufficient signal strength within the community, frame loss may occur. Therefore, choosing TCP mode ensures higher reliability.

The Robot

Robots are the executing agencies in the community inspection service and the most important part of the entire system. The design of robots should consider both hardware and software design factors.

Robots serve as the operational units in community inspection services, constituting the most critical component of the entire system. The design of robots should consider both hardware and software aspects.

1. Hardware Design: The robot should be equipped with motion motors, LiDAR, and cameras, with specific functionalities outlined below:

a) Motion Motors: Wheeled robots are equipped with motors to control wheel steering and speed. Quadruped robots have 12 motors distributed among their 4 legs, allowing control in three directions: front/back, left/right, and up/down.

b) LiDAR: This technology captures three-dimensional point cloud data through laser scanning. Coupled with SLAM (Simultaneous Localization and Mapping) technology, it enables autonomous robot positioning, map creation, and path planning.

c) Cameras: The robot should possess both visible and infrared binocular cameras. The visible light camera is used to identify utility meters and detect equipment defects, with a resolution of 1920×1080. The infrared camera measures the temperature of devices during inspections, with a resolution of 320×240.

2. Software Design: The robot's software should incorporate various functionalities such as motion navigation, obstacle avoidance, and AI (Artificial Intelligence), with specific features outlined below:

a) Autonomous Navigation: The robot should receive coordinates from the backend system and autonomously navigate based on the map. Achieving autonomous navigation involves addressing two main challenges in finding the shortest path from the starting point to the endpoint, often tackled using algorithms like Dijkstra and in determining the shortest global path, encompassing multiple inspection points and returning to the charging station, typically a Traveling Salesman Problem (TSP). TSP can be solved using greedy algorithms, where the robot selects the next target point as the nearest one from its current position. Alternatively, the branch and bound algorithm ensures a globally optimal solution by treating the original problem as the root node of a search tree and subdividing it into smaller problems.

To illustrate the difference between the greedy algorithm and the branch and bound algorithm, a map of Yingzhou Island in Xuanwu Lake Park, Nanjing, China was utilized for verification. The map includes one starting point and eleven inspection points, denoted by S (starting point) and A/B/C/D/E/F/G/H/I/J/K, respectively. The red line signifies the route, as depicted in Figure 3. Table 3 presents the path data between each point, with a "-" indicating no direct connection between the two points. To calculate the global shortest path, calculations were initiated to determine the shortest path between any two points. Employing the Dijkstra algorithm and selecting any point as the starting point, all reachable points were computed. After 12 rounds of calculation, the resulting data is displayed in Table 4.

Figure 3. Map of Yingzhou Island in Xuanwu Lake

Table 3. Direct distance between nodes (unit: meter)

No \ No	S	A	B	C	D	E	F	G	H	I	J	K
S	0	190	-	-	-	-	-	-	-	-	-	-
A	190	0	140	-	-	-	-	-	-	-	-	100
B	-	140	0	310	-	300	-	-	-	-	-	-
C	-	-	310	0	360	-	-	-	-	-	-	-
D	-	-	-	360	0	220	210	230	-	-	-	-
E	-	-	300	-	220	0	215	-	-	-	-	-
F	-	-	-	-	210	215	0	-	-	-	180	
G	-	-	-	-	230	-	-	0	160	190	-	-
H	-	-	-	-	-	-	-	160	0	-	165	-
I	-	-	-	-	-	-	-	190	-	0	120	-
J	-	-	-	-	-	-	180	-	165	120	0	295
K	-	100	-	-	-	-	-	-	-	-	295	0

Table 4. The shortest distance between nodes (unit: meter)

No \ No	S	A	B	C	D	E	F	G	H	I	J	K
S	0	190	330	640	850	630	765	895	750	705	585	290
A	190	0	140	450	660	440	575	705	560	515	395	100

B	330	140	0	310	520	300	515	750	700	655	535	240
C	640	450	310	0	360	580	570	590	750	780	750	550
D	850	660	520	360	0	220	210	230	390	420	390	685
E	630	440	300	580	220	0	215	450	560	515	395	540
F	765	575	515	570	210	215	0	440	345	300	180	475
G	895	705	750	590	230	450	440	0	160	190	310	605
H	750	560	700	750	390	560	345	160	0	285	165	460
I	705	515	655	780	420	515	300	190	285	0	120	415
J	585	395	535	750	390	395	180	310	165	120	0	295
K	290	100	240	550	685	540	475	605	460	415	295	0

Utilizing the data from Table 4, we applied both the greedy algorithm and the branch and bound algorithm to traverse points A/B/C/D/E/F/G/H/I/J/K from point S, and then return to point S. The traversal paths are illustrated in Table 5. From Table 5, we observe that the branch and bound algorithm's path is 250 meters shorter, saving approximately 8% of the path compared to the greedy algorithm's path. This path saving becomes even more significant when the inspection area is larger and there are more inspection points. However, it's worth noting that the branch and bound method demands more CPU and memory resources, making the greedy algorithm more suitable for practical applications. The route maps for both algorithms are depicted in Figures 4 and 5 (where red indicates the reachable path and black indicates the inspection path).

Table 5. Algorithm Comparison

No.	Item	Search Path	Total Path	Path Percentage	Complexity	CPU and memory resources
1	greedy algorithm	S→A→K→B→E→F→J →I→G→H→D→C→S	3085	100%	Low	Low
2	branch and bound algorithm	S→A→B→C→D→E→ F→J→I→G→H→K→S	2835	92%	High	High

Figure 4. Greedy algorithm inspection route

Figure 5. Branch and bound algorithm inspection route

Avoiding and Stopping Obstacles

There are usually two ways to handle obstacles: 1. obstacle avoidance: automatically identify and bypass obstacles, such as sand piles and pedestrians on the forward route. 2.stopping obstacle: after identifying the obstacle, stop moving until the obstacle disappears. Whether avoiding or stopping obstacles, it is necessary to recognize the contour information of the object in front, usually using LiDAR or depth camera.

AI Recognition

Using a deep learning framework, such as TensorFlow, to collect samples for model training. The trained model can complete face, surface, ground, and other recognition tasks. After the inspection equipment photo is captured, it can automatically recognize the readings of the power supply, water supply, and gas supply meters. Automatically identify whether park vehicles have stopped illegally. The face model is used for staff verification. If facial information is detected to be inconsistent with the database, a sound of "illegal intrusion" will be emitted.

b) Obstacle Avoidance and Halt due to Obstacles:

There are typically two approaches to handling obstacles:

Obstacle Avoidance: Automatically identifying and navigating around obstacles, such as sand piles and pedestrians encountered on the route.

Halt due to Obstacles: Identifying an obstacle and coming to a stop until the obstacle is removed.

Whether employing obstacle avoidance or stopping strategies, it's crucial to recognize the contour information of objects ahead. This is typically achieved using LiDAR or depth cameras.

c) AI Recognition:

Utilizing deep learning frameworks like TensorFlow to gather samples for model training. The trained model can effectively recognize various elements, including faces, utility meters, and ground conditions. When capturing images of utility meters during inspections, the system can automatically identify readings for power, water, and gas meters. Additionally, it can autonomously detect if vehicles within the park are parked illegally. The facial recognition model is employed for staff verification. If the detected facial information does not match the database, an "unauthorized personnel detected" alert is triggered.

Discussion

In this paper's design, there are several issues that require further research:

1. Wi-Fi Security:

When utilizing Wi-Fi communication, it is essential to consider Wi-Fi encryption and authentication to ensure data integrity, prevent tampering, and guard against potential hacker attacks.

2. Map Self-Update:

Changes in ground conditions, such as high grass, can affect LiDAR's point cloud scans, leading to a mismatch with the map and subsequent positioning failures. Research is needed to determine how to trigger map self-updates based on information that does not align with the scanned point cloud.

3. Global Shortest Path:

Currently, the greedy algorithm is employed to solve the challenge of finding the shortest global path for multiple inspection points to return to the charging station. Greedy algorithms prioritize local optimal solutions, making them unable to achieve a global or suboptimal optimum. Although the branch and bound algorithm can attain a global optimal solution, it tends to consume excessive CPU and memory. Therefore, continuous exploration for new algorithms is warranted.

4. Insufficient AI Samples:

Due to a limited sample dataset, the AI model fails to recognize all meter types. It is imperative to gather a more extensive set of samples to train mature and stable models.

5. AI Deployment:

Both the backend computer and the robot have been equipped with AI recognition functionality, resulting in redundancy. Further research is required to evaluate whether a more refined decomposition of functionality is necessary in the future.

Conclusion

This paper introduces a design concept for a community inspection robot system. The system architecture comprises three main components: the inspection mainframe, a Wi-Fi communication network, and the robot. The inspection mainframe handles tasks like task planning, remote control of the robot, and status display. Wi-Fi facilitates seamless data transmission. The robot is responsible for autonomous navigation and AI recognition.

Future research will need to address challenges such as Wi-Fi security, map auto-updating, optimal global path determination, inadequate AI sample data, and functional deployment. The system architecture is well-structured with clear layers and comprehensive service modules, offering crucial design insights for the community robot inspection system. This approach effectively reduces the workload of human operators and enhances on-site operational efficiency.

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