

Research on the Composite Grid Map Construction Method for Greenhouse Mobile Robots: Postprint

Authors: Shi Bing, Duan Suolin, Li Ju, Wang Peng, Zhu Yifei

Date: 2018-05-18T00:00:00+00:00

Abstract

To address the issue where robots in greenhouse environments frequently commit path planning errors due to the inability of their onboard sensors to acquire comprehensive environmental information, a method is proposed that integrates external sensor systems to obtain greenhouse environmental data and construct composite grid maps. First, a wireless sensor network periodically collects temperature and humidity environmental information that influences robot traversability and transmits it to the robot. Second, when the rate of change in temperature or humidity data reaches a predefined threshold, the robot utilizes threshold segmentation and interpolation methods to separately establish temperature and humidity grid maps. Finally, by combining the temperature grid map, humidity grid map, and indoor obstacle grid map, a dynamically updated composite grid map is constructed. Experimental results demonstrate that when employing the conventional A* algorithm for path planning, the success rate and completion time of the composite grid map based on an environmental data change rate threshold of $\pm 10\%$ are 2.5 times and 1.05 times those of ordinary grid maps, respectively. The findings indicate that the composite grid map can enhance path planning success rates without causing a significant increase in robot response time due to dynamic updating, and its real-time performance satisfies the practical requirements of the system.

Full Text

Preamble

Research on Composite Grid Map Construction Method for Mobile Robots in Greenhouses

Shi Bing^{1,2}, Duan Suolin^{1,2}, Li Ju², Wang Peng¹, Zhu Yifei¹

¹School of Urban Rail Transit, ²Center for Robot Research, Changzhou University, Changzhou, Jiangsu 213164, China

Abstract: In greenhouse environments, mobile robots often encounter path planning errors due to their inability to obtain comprehensive environmental information using only onboard sensors. To address this problem, we propose a method that integrates external sensor systems to acquire greenhouse environmental information and construct a composite grid map. First, a wireless sensor network periodically collects temperature and humidity data that affect robot traversability and transmits this information to the robot. Second, when the rate of change in temperature or humidity data reaches a preset threshold, the robot establishes temperature and humidity grid maps separately using threshold segmentation and interpolation methods. Finally, these temperature and humidity grid maps are combined with the indoor obstacle grid map to build a dynamically updated composite grid map. Testing demonstrates that when using the conventional A* algorithm for path planning, the success rate and completion time based on a composite grid map with an environmental data change rate threshold of $\pm 10\%$ are 2.5 times and 1.05 times those based on a conventional grid map, respectively. The results show that the composite grid map improves path planning success rates without causing significant increases in robot response time due to dynamic updates, thereby meeting the real-time performance requirements of the system.

Keywords: greenhouse; mobile robot; grid map; threshold segmentation; wireless sensor network

0 Introduction

Mobile robot application technology has been extensively studied, with autonomous navigation methods representing a key research focus. Greenhouse mobile robots serve as a concentrated embodiment of greenhouse automation technology, primarily performing tasks such as transportation, harvesting, and precise fertilization in greenhouse environments, thereby improving labor efficiency and reducing production costs. Currently, scholars both domestically and internationally have proposed various navigation approaches for greenhouse robots. One method involves manually setting navigation markers, such as laying magnetic guidance strips along predetermined paths for the robot to follow, or installing dedicated tracks on greenhouse roads to enable robot movement. While these methods offer high reliability and fast movement speeds, they increase implementation costs, particularly the dedicated track approach, which is only suitable for large-scale greenhouses [1,2].

Grid maps represent a commonly used environmental map format in robot autonomous navigation, discretizing traditional geometric maps by dividing the target area into continuous grid cells, typically uniform squares. Based on obstacle positions, corresponding grids are assigned values indicating occupancy

status. Grid maps offer clear, intuitive representation and are widely applied in greenhouse robot autonomous navigation [3].

Artificial navigation marker methods require modifying existing greenhouse environments, increasing costs and limiting versatility, making them impractical for widespread use. Current applications of grid maps in greenhouse environments typically consider only physical obstacles while ignoring other factors such as temperature and humidity, or alternatively, suspend operations like irrigation and heating during robot movement [4-5]. The former approach cannot obtain comprehensive environmental information and may lead to path planning errors, while the latter lacks flexibility, has low automation levels, and hinders efficiency improvement. This paper proposes a solution combining grid maps with external sensor systems, using wireless sensor networks to periodically monitor environmental information and incorporating potentially harmful high-temperature and high-humidity environmental data into the grid map to construct a composite grid map. This approach ensures comprehensive and accurate map information while improving the operational efficiency of greenhouse mobile robots.

1 System Architecture

The composite grid map construction process in this system consists of three main steps: environmental information acquisition, key environmental information modeling, and composite grid map generation. The overall system comprises three components: the worksite unit, monitoring center unit, and remote unit, as illustrated in [Figure 1: see original paper].

The worksite unit consists of a wireless sensor network and a mobile robot. The wireless sensor network collects real-time greenhouse environmental data, while the mobile robot autonomously navigates to destinations based on generated environmental maps to complete tasks such as transportation and harvesting. The worksite unit operates as follows: First, wireless sensor nodes collect greenhouse environmental parameters every second and transmit them to a gateway node installed on the mobile robot via single-hop or multi-hop communication. The gateway node then sends data to the robot through a USB interface, and the robot forwards this information to the monitoring center via a wireless local area network. Second, upon receiving movement commands, the robot generates maps and performs localization. With its position, destination, and map information available, the robot employs path planning algorithms to determine a globally optimal path. The motion controller then generates control commands, which are executed by motor drivers to achieve robot movement.

The monitoring center unit serves as the upper-level component, comprising a communication server, database server, and web server. The communication server acts as an intermediary layer for lower-level data upload and higher-level command download, employing multi-threading mechanisms to manage Socket communication between the mobile robot, remote control clients, and

database server. The database server stores various greenhouse environmental data including temperature, humidity, illumination, CO concentration, and oxygen content, serving as the system data center and interacting with the web server to provide data services.

The remote unit represents the highest-level users, including remote browsing clients and remote control clients. Remote browsing clients can access the web server directly through various browsers to display data in graphical interfaces. Remote control clients require installation of client software and communicate with the monitoring center's communication server via Socket connections. Control commands from remote clients are received by the communication server, which then controls the robot. This intermediate layer architecture significantly enhances system security by preventing direct control of the mobile robot by remote units. This paper focuses on the construction method of composite grid maps in greenhouse environments.

3.1 Environmental Information Acquisition

This system employs a wireless sensor network to acquire greenhouse environmental information, with temperature and humidity parameters being used for map construction. The greenhouse measures $100\text{m} \times 40\text{m}$, with sensor nodes arranged at 20m intervals in both rows and columns, as shown in [Figure 3: see original paper], where the lower-left corner coordinate is $(0,0)$.

Sensor nodes typically adopt a two-layer structure: the bottom layer consists of various sensor devices and their conditioning circuits (measuring temperature, humidity, illumination, CO concentration, and oxygen content), while the upper layer uses Texas Instruments' CC2530 wireless transceiver chip—a powerful microprocessor integrating memory, an enhanced 8051 processor, and a ZigBee protocol-supported wireless transceiver unit [6-8]. Based on TI's Z-STACK development kit, programs for sensor nodes, routing nodes, and gateway nodes can be developed relatively easily [9-11]. The three node types share identical hardware, distinguished only by sensor connections and different software programs, ensuring strong versatility.

Sensor nodes collect data every second and transmit it to the gateway node, which then passes the data to the robot. At this stage, the data remains discrete, representing environmental information only at sensor node locations. Since greenhouse temperature and humidity remain relatively stable most of the time, we simulated special conditions by placing a heating furnace at coordinate $(80,0)$ and activating a sprinkler at $(60,20)$ to demonstrate map construction under exceptional circumstances and robot movement behavior.

3.2 Key Environmental Information Modeling

Based on known discrete temperature and humidity information, continuous models are established on the MATLAB platform using Equation (3), as shown

in [Figure 4: see original paper], where Figure 4(a) represents the temperature model and Figure 4(b) represents the humidity model.

The modeling objective is to transform discrete key environmental information into continuous equations covering the entire target area. Once established, the model enables calculation of environmental parameter values at any coordinate within the target region, preparing for map construction. The system employs triangular interpolation, which partitions known spatial points into non-overlapping triangles that maximize the minimum interior angle among all possible partitions, thereby minimizing error.

As shown in [Figure 2: see original paper], assuming a partitioned triangle with known vertices A, B, and C, the value at any interior point D can be estimated through interpolation. The spatial vectors satisfy the following relationship:

$$\begin{vmatrix} x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \\ x & y & z & 1 \end{vmatrix} = 0$$

Expanding this determinant yields:

$$z = \frac{\begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix} - \begin{vmatrix} x & y & z \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix} - \begin{vmatrix} x_1 & y_1 & z_1 \\ x & y & z \\ x_3 & y_3 & z_3 \end{vmatrix} - \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x & y & z \end{vmatrix}}{\begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}}$$

Using this equation, the value at any point within the triangle can be calculated. When points (x,y) are densely selected, a continuous surface is formed. The temperature model in [FIGURE:4(a)] shows the highest temperature at coordinate (80,0), gradually decreasing with distance, demonstrating that even at 20m distance, temperature elevation is significantly affected by heat radiation. The humidity model in [FIGURE:4(b)] indicates maximum humidity at (60,20), also decreasing with distance, though humidity affects a smaller range—beyond 20m, humidity is barely influenced.

3.3 Composite Grid Map Construction

The mobile robot used in this system measures 485mm in width, 494mm in length, and 495mm in height. To ensure safe passage with margin, the greenhouse floor plane is logically divided into 4m × 4m square grids, as shown in [Figure 5: see original paper].

Since a grid represents a plane, using a single point to represent the entire grid area for logical value determination using Equations (3) and (4) may cause misjudgment, with larger grid areas increasing misjudgment probability. Therefore, sample points are taken at the grid vertices and edge midpoints (a, b, ..., h) with corresponding coordinates, modifying Equation (4) to:

$$G(x, y) = \begin{cases} 1 & \text{if } (Z(a) \geq Z_0) \vee (Z(b) \geq Z_0) \vee \dots \vee (Z(h) \geq Z_0) \\ 0 & \text{otherwise} \end{cases}$$

In this system, the temperature threshold is set to 50°C and humidity threshold to 80%RH. Grids with a logical value of 1 are filled in black, indicating occupancy. Combining Equations (3) and (6) yields temperature and humidity grid maps, shown in [FIGURE:6(a)] and [FIGURE:6(b)] respectively. Crop areas in the greenhouse, as major obstacles to robot movement, must also be reflected in the grid map. This is accomplished by manually inputting obstacle coordinates for simple computer processing to generate the obstacle grid map, shown in [FIGURE:6(c)].

Finally, Equation (5) combines the temperature grid map, humidity grid map, and obstacle grid map to obtain the complete composite grid map:

$$T(x, y) = G_1(x, y) | G_2(x, y) | \dots | G_n(x, y)$$

where $T(x, y)$ represents the composite grid logical value and $G_n(x, y)$ represents the grid logical value under the nth environmental information.

The composite grid map in [Figure 7: see original paper] is drawn based on sensor network data from a single collection. Although the sensor network collects data every second, generating a new composite grid map each time would significantly burden the robot, causing slow response and poor real-time performance. In practice, the system updates the entire greenhouse composite grid map and replans paths only when the temperature or humidity data change rate reaches the $\pm 10\%$ threshold, as illustrated in the dynamic process shown in [Figure 8: see original paper].

4.1 Mobile Robot Platform

This system employs a wheeled mobile robot from Shanghai Ingenious Automation Technology Co., Ltd. as the development and testing platform. The robot is a multifunctional modular development platform that enables various functions through different hardware modules and corresponding software packages. Researchers can replace specific software packages with their own algorithms or control strategies to verify performance and achieve secondary development [12-14]. The main parameters are listed in .

4.2 Robot Movement Testing

In the greenhouse, point A(16,4) is designated as the starting point, with T1(20,20), T2(48,20), ..., T10(60,12) as target points, as shown in [Figure 9: see original paper]. The mobile robot uses the widely adopted traditional A* path planning algorithm for route planning [15-18].

Ten target points were tested in groups, with each group representing four scenarios: non-updatable conventional grid map and dynamically updated composite grid maps with temperature/humidity data change thresholds of $\pm 5\%$, $\pm 10\%$, and $\pm 20\%$. The test statistics are presented in , where \surd indicates successful obstacle avoidance and \times indicates failure.

The results show that the conventional grid map achieved only 40% success in obstacle avoidance, while dynamically updated composite grid maps achieved 100% success at $\pm 2\%$ and $\pm 10\%$ thresholds, and 80% at $\pm 20\%$ threshold. The low success rate for conventional grid maps stems from incomplete environmental information from onboard sensors and lack of map updates, leading to path planning errors. Composite grid maps incorporate comprehensive environmental information and conditional updates, dramatically improving success rates. The 20% failure rate at $\pm 20\%$ threshold occurs because the high change rate threshold results in excessively slow map updates.

[Figure 10: see original paper] illustrates completion time trends, where X-axis values 1-4 correspond to conventional grid map, composite grid maps with $\pm 2\%$, $\pm 10\%$, and $\pm 20\%$ thresholds respectively, and Y-axis represents completion time. Curves T1, T2, T3, and T10 show completion times for different targets. The results indicate that completion times at $\pm 2\%$, $\pm 10\%$, and $\pm 20\%$ thresholds are $1.60\times$, $1.05\times$, and $1.05\times$ that of the conventional grid map, respectively.

Comprehensive analysis of and [Figure 10: see original paper] reveals that when the composite grid map update threshold is set to $\pm 10\%$, the robot successfully avoids both actual obstacles and simulated high-temperature/humidity zones, achieving a success rate 2.5 times that of conventional grid maps. The completion time is only 1.05 times longer, demonstrating that composite grid map updates do not significantly impact robot response speed and meet system real-time requirements.

5 Conclusion

Based on real-time acquisition of critical greenhouse temperature and humidity environmental information via wireless sensor networks, this study employs threshold segmentation and cell decomposition methods with appropriate temperature/humidity data change rate thresholds to construct and dynamically update composite grid maps. Testing demonstrates that at a $\pm 10\%$ data change rate threshold, traditional A* path planning based on composite grid maps successfully avoids obstacle zones. Compared with conventional grid maps, dynamically updated composite grid maps do not significantly affect robot response

speed and satisfy system real-time requirements. Moreover, incorporating additional environmental information will further enrich composite grid maps and improve success rates. Future work will focus on updating local grid map information to further reduce computational workload and enhance real-time performance.

References

- [1] Tan M, Wang S. Research progress on robotics technology [J]. *Acta Automatica Sinica*, 2013, 39(7): 963-973.
- [2] Hu JT, Gao L, Bai XP, et al. Research progress on automatic navigation technology for agricultural machinery [J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2015, 31(10): 1-10.
- [3] Gao GQ, Li M. Greenhouse mobile robot navigation path recognition based on K-means algorithm [J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2014, 30(7): 25-33.
- [4] Wang XZ, Han X, Mao HP, et al. Greenhouse tomato inter-row visual navigation path detection based on least squares method [J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2012, 43(6): 161-166.
- [5] Jia SW, Li JM, Qiu Q, et al. Greenhouse robot road edge detection and path navigation based on laser rangefinder [J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2015, 31(13): 39-45.
- [6] Cao PF, Zhao Z. Review of key technologies for wireless sensor networks [J]. *Microcomputer Information*, 2012, 35(9): 389-391.
- [7] Harun A, Ndzi DL, Ramli MF, et al. Signal propagation in aquaculture environment for wireless sensor network applications [J]. *Progress In Electromagnetics Research-Pier*, 2012, 131(4): 477-494.
- [8] Tuna G, Gungor VC, Gulez K. An autonomous wireless sensor network deployment system using mobile robots for human existence detection in case of disasters [J]. *Ad Hoc Network*, 2014, 13(5): 54-68.
- [9] Li X, Falcon R, Nayak A, Stojmenovic I. Servicing wireless sensor networks by mobile robots [J]. *IEEE Communication Magazine*, 2012, 50(7): 147-154.
- [10] Lee WY, Hur K, Hwang KI, et al. Mobile robot navigation using wireless sensor networks without localization procedure [J]. *Wireless Personal Communication*, 2012, 62(2): 257-275.
- [11] Zhang W, Liu Y, Zhang CF, et al. Real-time path planning for greenhouse robot based on directional A* algorithm [J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2017, 48(7): 22-28.
- [12] Wang HW, Ma Y, Xie Y, et al. Mobile robot path planning based on smoothing A* algorithm [J]. *Journal of Tongji University: Natural Science Edition*

tion, 2010, 38(11): 1647-1650, 1655.

[13] Ma F, Yang H, Gu Q, et al. Navigation path planning for underground unmanned loader based on improved A* algorithm [J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 46(7): 303-309.

[14] Jian Y, Zhang Y. Research progress and prospect of mobile robot global coverage path planning algorithm [J]. Computer Applications, 2014, 23(10): 2844-2849.

[15] Vakilian KA, Massah J. A farmer-assistant robot for nitrogen fertilizing management of greenhouse crops [J]. Computer Electronic Agriculture, 2017, 139(12): 153-163.

[16] Li TC, Hu JT, Gao L. Robust adaptive path tracking control for agricultural machinery based on cascade control strategy [J]. Robot, 2014, 36(2): 241-249.

[17] Li TC, Hu JT, Gao L. Robust adaptive path tracking control for agricultural machinery based on cascade control strategy [J]. Robot, 2014, 36(2): 241-249.

[18] Zhao DA, Jia WK, Zhang Y, et al. Research on improved adaptive filter controller for agricultural robot autonomous navigation [J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 46(5): 1-6.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.