Efficiency Analysis and Improvement of an Intelligent Transportation System for the Application in Greenhouse

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Abstract: In view of the future lack of human resources due to the aging of the population, the automatic, Intelligent Mechatronic Systems (IMs) and Intelligent Transportation Systems (ITSs) have broad application prospects. However, complex application scenarios and limited open design resources make designing highly efficient ITS systems still a challenging task. In this paper, the optimal load factor solving solution is established. By converting the three user requirements including working distance, time and load into load-related factors, the optimal result can be obtained among system complexity, efficiency and system energy consumption. A specialized visual navigation and motion control system has been proposed to simplify the path planning, navigation and motion control processes and to be accurately calculated in advance, thereby further improving the efficiency of the ITS system. The validity of the efficiency calculation formula and navigation control method proposed in this paper is verified. Under optimal conditions, the actual working mileage is expected to be 99.7%, and the energy consumption is 83.5% of the expected value, which provides sufficient redundancy for the system. In addition, the individual ITS reaches the rated operating efficiency of 95.86%; in other words, one ITS has twice the ability of a single worker. This proves the accuracy and efficiency of the designed ITS system.

Keywords: intelligent transportation systems (ITSs); multiple conditional constraints for ITS; automated guided vehicle; greenhouse environment; spraying systems

1. Introduction

With the aging of the global population and the deepening of urbanization, the contradiction between the loss of agricultural population, rising labor costs and the demand for agricultural production and supply has become an important issue faced by the sustainable development of agricultural production [1]. The development of high-efficiency, high-quality, low-cost intelligent mechatronic systems that can replace human operations is an important means of dealing with the current situation from an engineering perspective [2]. Agricultural labor intensity, high production costs, only harvesting costs can be accounted for more than 25% of total production costs [3,4]. The labor intensity in operations such as pest control is also very high, and directly threatens the health of workers [5]. Automated Guided Vehicle (AGV) as an important part of ITS can effectively reduce the risk of workers in hazardous operations [6], help increase production efficiency and deal with the lack of labor due to the aging of the population [7]. A variety of agricultural robots, including grazing [8], farming [9], fruit collection, and sorting [11] robots, have been applied.
Compared to industrial robot applications, the development of agricultural robots is limited by the complexity of the work scene and task complexity [12]. The Dutch greenhouses and food factories are widely used and important agricultural production sources [2]. Due to its closed agricultural application scenario, highly standardized, hardened pavement, crop singularity and a high degree of structural work make it an ideal agricultural robot application scenario. However, there is still a lack of more mature applications. Warehousing logistics has similar application conditions to the Dutch greenhouse, although the former environment is much more closed than the latter. However, in the field, especially the development of AGV has important reference [13]. There is no doubt that Amazon’s “KIVA” [14,15] and Ali Group’s “CaiNiao” [16] ITSs are among the leaders in the field. These robots work in a standardized closed warehouse, which effectively reduces the dependence of human resources, reduce the work intensity of workers, and greatly improves the management efficiency of warehousing and logistics [17].

Even so, the ITSs system for the Dutch greenhouse design is still challenging [13,18]. Although the Dutch greenhouse and storage are semi-closed applications, they have high complexity: (1) firstly, crops rely on natural light rather than constant scattering sources in the warehouse. As time and season change, the lighting conditions in the greenhouse will fluctuate drastically and affect the navigation system. (2) Secondly, the density of crops in the greenhouse is high, the working space is extremely limited, and the irregularity of crop growth makes it possible for the leaves, stems and the like of the crops to hinder the ITS in the established workspace. This requires more redundancy in the design of the ITS. (3) In addition, applications such as pesticide spraying are variable load systems. Moreover, this type of work has strict timeliness requirements, which are determined by the nature of the volatilization and precipitation of pesticides. (4) Finally, due to the patent protection of existing products and research, the technical reference we can obtain is limited, and there are many alternative implementation methods. These factors determine the design of efficient ITSs remains challenging.

In this paper, we propose a high-efficiency ITS design for greenhouse applications, and we can apply this design method to other environments such as warehouses and terminals. Our work makes the following contributions:

- We have provided an optimal load factor solving solution. By converting the three user requirements including working distance, time and load into load-related factors, the optimal result can be obtained among system complexity, efficiency and system energy consumption. The specifications of the main components of the ITS such as drive structure, power and battery components are constrained to a limited range according to the load factor and the work scenario. The specification of constraints helps other researchers determine the design of ITS and the choice of key components.

- We propose a special weighted connected graph structure to support map modeling and navigation applications. Based on this, a specialized visual navigation and motion control system has been proposed. With a fixed control action and boundary-defined Proportion Integral Differential (PID) control algorithm, the repeat path accuracy of the error < 0.02 m can be obtained without relying on third-party positioning. This makes prior path planning, accurate mileage and energy consumption prediction possible. It can help researchers and designers further improve the efficiency of the ITS system.

- We present an efficient example of an ITS system and its detailed design based on the proposed method with optimal calculation results. Test results include working paths and mileage, speed and energy consumption are described in detail under different test conditions, including conditions beyond the rated load. The performance of the system, which is verified in the test environment, is described in detail.

The working environment, requirements, and design goals are described and three known input parameters in detail in Section 3. In Section 4, the overall design framework of the ITS is explored according to the working environment, and then the requirements are converted into three key
constraints of load-volume ratio, working distance and work efficiency. In Section 5, a specialized visual navigation and motion control system has been proposed to simplify the path planning, navigation and motion control processes. The ITS prototype designed according to this constraint is elaborated, which is one of the main contributions of this paper. In Section 6, an improved ITS system is implemented as a case, and its detailed design parameters are calculated based on instance greenhouse environment. In addition, then, the validity of the proposed constraints and the efficiency of the ITS prototype are verified by actual verification. Section 8 concludes this paper.

2. Related Works

Agriculture is a labor-intensive industry. With the degeneration of the demographic dividend and the rapid growth of the population, the pressure on agricultural production is increasing. As the most important and labor-intensive operation in agricultural production [5], the pesticides used in pest control have high toxicity and corrosive characteristics [19], which greatly threaten the health of production personnel. Strict and comprehensive protection measures, as well as a lower level of participation of practitioners, further increase the cost of such operations [20]. The United States Environmental Protection Agency (US-EPA) has finalized stronger standards “Agricultural Worker Protection Standard (WPS)” for people who apply for Restricted Use Pesticides (RUPs) [20,21]. These revisions to the Certification of Pesticide Applicators rule will reduce the likelihood of harm from the misapplication of toxic pesticides.

Agricultural automation and intelligent development are one of the effective means of solving these problems [18]. The agricultural robot originated from agricultural machinery is a new type of multifunctional agricultural machinery. It is the result of adding intelligent attributes to agricultural machinery [22]. The earliest agricultural robots date back to the autopilot tractors of the 1970s [18]. To date, various agricultural robots have emerged, such as shearing robots, milking robots [8], transplanting robots [23–25], grafting robots [23,24], harvesting robots [10,26], and weeding robots [27]. According to the use and operation characteristics, the existing agricultural robots can be roughly divided into livestock management robots, field farming management robots, fruit and vegetable harvesting robots, seedling breeding robots, agricultural product sorting robots, etc.

Due to the complexity of agricultural operations, the complexity of work tasks, and the current level of software and hardware technology development, there are many types of agricultural robots and prototypes, but there are only a handful of cases that can effectively improve the efficiency of production. The more successful cases of agricultural robots are either similar to industrial lines or similar to large agricultural machines such as milking robots, agricultural sorting robots, self-driving tractors, weeding robots, etc. It must be said that, compared with the industrial robot represented by the dexterous mechanical arm [28], the highly intelligent transformers in the traditional concept of human beings [29], there is still a big gap in the development level of agricultural robots. Among the factors such as the agricultural work scene, the complexity of the work tasks and the current development level of hardware and software technology, the complexity of the work scene is the key factor [2,28].

The traditional agricultural production conditions with manual work as the main body do not match the requirements of the robot for the structured working environment, which is an important factor that restricts the agricultural robots from entering the laboratory and entering the farmland. Relative to the industrial structural environment, the special conditions of the sun in the agricultural production environment [12], the disordered crops and the soft and fragile working objects [30] are the objective problems faced by the robots in the agricultural environment [31].

Compared to the open farmland environment, the Dutch greenhouse has the potential to produce under a variety of weather conditions. These closed plant production systems, such as artificially illuminated and highly insulated plant factories, have offered perspectives for urban food production [13]. In terms of economic efficiency, the annual Net Financial Return (NFR) for the Dutch greenhouse is very high [32]. Even so, there are fewer agricultural robot systems available in the greenhouse. Compared with the complex agricultural environment, the industrial application
environment is “compendious”: the environmental closure and the highly structured operation. This is an important realization condition for the rapid development of industrial robots. Warehousing robots receive special attention among them. There are also a series of intelligent robot systems for greenhouse development, some of which are practical applications, such as Amazon KAVA, Richo M2, River System, Meituan Segway, Postmates, etc. [16,33–45]. Comparison of major ITS systems in recent years is as shown in Table 1.

Table 1. Overview of Intelligent Transportation Systems (ITS) and typical agricultural robot.

| Application Field | Name             | Size * (L × W × H,m) | Turning Radius (m) | Speed (m/s) | Load (Kg) | Endurance (h) | Open Source |
|-------------------|------------------|-----------------------|--------------------|-------------|------------|---------------|-------------|
| Warehouse         | Richo M2 [33]    | 0.5 × 0.6 × 0.7       | 0.6                | 0.5         | 60         | N/A           | F           |
|                   | Kiva [14]        | 1.0 × 0.6 × 0.4       | 0.6                | 1.3         | 450        | N/A           | F           |
|                   | River [15,34]    | 0.9 × 0.6 × 1.25      | 0.7                | N/A         | 72         | N/A           | F           |
|                   | Butler GL [35]   | 1.3 × 0.8 × 0.3       | 1.1                | N/A         | 1300       | N/A           | F           |
| Delivery          | Cainiao G2 [16]  | 1.0 × 0.8 × 1.2       | 0.8                | 4           | 50         | 8             | F           |
|                   | JingDong [16]    | 1.0 × 0.8 × 0.6       | 2.2                | 2           | 40         | 6             | F           |
|                   | Yelp EAT24 [46]  | 1.1 × 0.6 × 1.2       | N/A                | 1.9         | 12         | N/A           | F           |
|                   | Segway [45]      | 1.2 × 1.0 × 1.2       | 1.0                | N/A         | 200        | 8             | T **        |
|                   | Postmates [57]   | 0.5 × 0.5 × 0.8       | 0.5                | N/A         | 25         | >10           | F           |
| Agriculture       | AGROBOT [39]     | 4.8 × 6.2 × 3.2       | >6                 | N/A         | >100       | >10           | F           |
|                   | Bluriver [39]    | 1.2 × 1.0 × 1.0       | >0.8               | 2           | N/A        | N/A           | F           |
|                   | LettuceBot [40]  | 1.4 × 6.8 × 0.8       | >4.0               | N/A         | N/A        | N/A           | F           |
|                   | RMAX II [41]     | 3.2 × 3.2 × 0.55      | >3.5               | N/A         | 16         | 1             | F           |
|                   | BoniRob [47,48]  | 3.6 × 2.5 × 1.5       | >3.5               | N/A         | N/A        | N/A           | T **        |
| Retail            | Bossanova        | 0.3 × 0.3 × 0.5       | 0.3                | 0.5         | N/A        | N/A           | F           |
|                   | ICE RS26 [42]    | 1.65 × 0.86 × 1.37   | >2                 | 1.8         | ~130       | 4             | T **        |
|                   | Navi [43]        | 0.5 × 0.5 × 1.52      | >0.5               | ~0.5        | N/A        | 8–10          | F           |
|                   | Tally [44]       | 0.47 × 0.47 × 1.62    | >0.5               | ~0.45       | N/A        | 2–4           | F           |

* These dimensions may be biased due to the lack of published documentation and measurement standards.
** Limited open source.

As shown in Table 1, there are many robot systems that are used in different fields. However, the useful reference for design is very limited. In addition to different application environments and conditions, larger factors may be a limitation of commercial intellectual property. In the above robot system, only the Segway system [45] supports limited open source, and other products or prototype systems do not provide the necessary technical information. Although these systems provide some design references, the role of efficient ITS system design in the Dutch greenhouse application scenario is limited. Therefore, the author’s team hopes to analyze the various factors and key conditions in the design one by one based on the project research experience and the basic conditions that need to be given. A normalized conditional formula is given giving detailed design and performance testing, providing a visual reference for other researchers.

3. Problem Description and Objectives

3.1. An Application Case: ITS in a Greenhouse Environment

The application environment comes from an ITS design project of our team. Six Dutch greenhouses with an area of 6000 m² are deployed in the research base of the cooperative company. Figure 1 shows the schematic diagram of one of the standard greenhouses. As shown in Figure 1b, we can divide the entire space into three parts: ① operating area, ② working area, and ③ crop growing area. The operating area is mainly used for installation, temporary storage of equipment, and equipment turnover in the working area. Workers are also working in the area. The working area and the crop area are deployed at intervals, and there are n + 1 crop areas separated by n work areas. The length of each work area is \( l_n \) (referred to as height \( H \)), the width is \( d_p \) and the spacing between work areas is \( d \). The width of the entire working interval is \( W \).
Taking pest control as an example, the role of pesticide spray control is limited because a large number of insect pests have light-shielding properties and gather behind the foliage. In addition, the role of other control measures is also limited, such as larval boards and other means. This requires workers to use equipment to spray pesticides from the bottom up to remove pests. Corrosive, highly toxic, volatile pesticides are bound to pose a threat to the health of workers, even when protective measures exist. In addition, carrying out the work in such a large range makes the workers have a very high working intensity. This is determined by the characteristics of the pesticide such as volatility and precipitation. The spray work must be completed within the specified time after the pesticide configuration is completed. Otherwise, its medicinal properties will be greatly weakened or even have side effects. Therefore, the use of highly efficient robots to perform similar tasks is not only economical, but also effective in protecting the health of workers.

3.2. Definition of Requirements and Input Conditions

It is challenging to design an ITS that meets user requirements and is optimal especially when there is a limited reference. This requires us to start the analysis from known and user-expected conditions. Firstly, we need to convert the user’s requirements into key metrics based on the requirements analysis, as shown in Figure 2. The key metrics are then converted into sub-conditions that affect the ITS design, such as operating speed, load, and output torque, and the boundaries of these conditions are determined. Finally, the optimal values of key conditions are obtained under multiple conditions and their boundary constraints, and the detailed design scheme of ITS is determined.
(1) Work efficiency. If the time required for a standard job is $T_{\text{norm}}$ and the actual completion time is $T_{\text{practical}}$, the productivity $e_p$ can be defined as:

$$e_p = \frac{T_{\text{norm}}}{T_{\text{practical}}} \times 100\%.$$  

(1)

This means that the more time is spent, the lower the efficiency. $T_{\text{norm}}$ is derived from actual needs and historical work experience, such as $T_{\text{norm}} = 5400$ s in this scenario. This is determined by the nature of the liquid and the operating specifications. In addition, in the above conditions, the efficiency of a single worker is $e_p' = 50\%$ because one greenhouse requires two workers to work together. Thus, we can evaluate the efficiency of the designed ITS through $e_p$.

(2) Work mileage. As shown in Figure 1b, the spraying operation only occurs in the working area, and we refer to such areas as “effective working areas”. Obviously, for a given site, the “effective working distance” for each work area is known as $l_1, l_2, \cdots, l_n$. Therefore, the total effective working distance $L$ can be described as the second condition:

$$L = \sum_{i=1}^{n} l_i.$$  

(2)

If the length of each workspace is the same and the length is $H$, then $L = n \times H$. The moving distance in the actual job will far exceed this value, whether it is manual or ITS because it needs to work—interval within the interval, switching the working range, and returning the replenishment. In addition, the appropriate ITS system design and path planning system will help reduce these “extra” ‘travels’—these will directly affect the actual time spent on the operation $T_{\text{practical}}$, which will affect the work efficiency $e_p$.

(3) Unit workload. Since the total volume of liquid medicine $\text{vol}_{\text{tank}}$ and the effective working distance $L$ are known, the unit distance dose $SV_p$ can be calculated:

$$SV_p = \frac{\text{vol}_{\text{tank}}}{L} = \frac{\text{vol}_{\text{tank}}}{\sum_{i=1}^{n} l_i} = \frac{\text{vol}_{\text{tank}}}{l_H \times n}.$$  

(3)

Of course, this value is more appropriately calculated by professional agronomists based on different pests and crops. $SV_p$ will directly interfere with two key issues: (1) determine the specifications of the pumb deployed on the ITS; (2) affect the specification and continuous working time of $\text{vol}_{\text{ITS}}$—this will further affect the mission planning of the ITS and the implementation process, and ultimately affect the efficiency of the work.

4. Multiple Conditional Constraints Reasoning

In this section, we will explore in detail and contraction the main conditions affecting efficient MIS design based on known input conditions and expectations. The first problem to be identified is to choose the appropriate overall design for the MIS. An integrated design that differs from existing split operations is more advantageous. As shown in Figure 1b, the hose line connects the separate spray assembly to the pesticide tank assembly in the existing split mode of operation. The main advantage of split scheme is that the existing syrup supply system can be used directly. In addition, the complexity of the MIS system will be reduced because it does not need to carry a heavy tank and pump system itself. An integrated scheme that differs from existing split operations is more advantageous. However, the solution makes the pipeline system extremely complicated in practical applications. There are two reasons for this: firstly, the ITS needs to enter the working area so that the length of the pipeline will exceed $l_H$. Secondly, when the ITS switches the working area, the tank also needs to move synchronously to the corresponding operating area, which will increase the complexity of the synchronous control system and the communication system. In comparison, the pesticide tank, the sprinkler system, and the ITS system body are brought together in the integrated design. Its main
advantage is its compact structure, no external equipment support, and good independence. The key questions here can be expressed using \( \text{vol}_{\text{ITS}} \), as shown in Figure 3.

| ITS volume | Resistance | Output Torque | Motor Power | Motor Speed | Replenishment Count | Practical mileage | Practical Time |
|------------|------------|---------------|-------------|-------------|---------------------|------------------|----------------|
| \( \text{vol}_{\text{ITS}} \) | \( F_{\text{res}} \) | \( F_{\text{out}} \) | \( P_{\text{moto}} \) | \( V_{\text{moto}} \) | Fixed | \( \text{addition} \) | \( \text{addition} \) |
| Smaller | reducing | reducing | reducing | Fixed | \( \text{addition} \) | \( \text{addition} \) | \( \text{addition} \) |
| Larger | addition | addition | addition | Fixed | reducing | reducing | reducing |

Figure 3. Relationship between main conditions and \( \text{vol}_{\text{ITS}} \).

It can be seen that, when the fixed \( V_{\text{moto}} \) is indirectly fixed to the running speed of the AGV, the larger volume is beneficial to reduce the working mileage and working time, which will directly improve the final working efficiency \( e_p \), reducing the distance of reentry due to lesser replenishment count. In addition, the side effect is that it directly increases the system’s energy consumption and requires greater output torque—500 L is a big challenge for ITS design. In other words, a viable, efficient ITS system relies on the determination of the optimal \( \text{vol}_{\text{ITS}} \).

4.1. Load Constraint and Factor

In order to determine the appropriate \( \text{vol}_{\text{ITS}} \), we will search for favorable clues from known conditions: containers are a huge challenge, but not an incomplete design. However, in the feasible design, we will still find the favorable constraints: First, the width of the working area \( l_d \) and the interval spacing will limit the width and length of the MIS and tank, respectively; then, the height and centroid of the tank will follow the volume—increasing and increasing, but the stability of the system will decrease. Finally, greater capacity means greater torque demand and energy consumption pressure.

(1) Load factor. \( SV_{p} \) reflects an indirect relationship between tank and distance, that is, the working distance that the agent in tank can support should be an integer multiple of \( l_H \). It can effectively reduce the number of invalid round trips due to insufficient liquid pesticide. That additional replenishment will generate additional working mileage, which will directly affect the efficiency of ITS. It can be calculated that the amount of medication in a single work area is \( \text{vol}_{\text{tank}} / n = SV_{p} \times l_H \). In addition, the volume of \( \text{vol}_{\text{veh}} \) should be an integral multiple of it, as a key constraint of an efficient design. We defined \( m \) as load factor, and:

\[
\text{vol}_{\text{ITS}} = m \times \frac{\text{vol}_{\text{tank}}}{n} = m \times SV_{p} \times l_H, \tag{4}
\]

where \( m \in [1, n] \) is an integer.

In addition, the number of supplemental options \( Pst \) can be calculated when the pump position is fixed:

\[
Pst = \left[ \frac{\text{vol}_{\text{tank}}}{\text{vol}_{\text{ITS}}} \right] = \left[ \frac{\text{vol}_{\text{tank}}}{SV_{p} \times l_H \times m} \right] = \left[ \frac{\text{vol}_{\text{tank}}}{l_d \times m} \times l_H \times m \right] = \left[ \frac{n}{m} \right] \tag{5}
\]

In this way, we simplify the complex capacity problem to the relationship between the two scalars \( m \) and \( n \).

4.2. Work Planning and Mileage Calculating

Through Equation (5), we can determine the number of times ITS returns to the pesticide tank, and we can also calculate when it is necessary to return the supply. Therefore, we can divide work planning into two parts: spray and replenishment, as shown in Figure 4. Correspondingly, the calculation of the mileage is also divided into two parts.
(1) Mileage of spray operation.

Each sub spray sequence such as \( A_1 \rightarrow B_1 \rightarrow C_1 \) consists of three parts: ① entering work area \( A_1 \); ② performing spray \( B_1 \); ③ returning \( C_1 \) ready to enter the next work area. Equation (4) reflects the critical relationship between the operating distances \( L \) and \( \text{vol}_{ITS} \). In addition, this allows us to ensure that no pesticide shortages occur during the spray step \( B_1 \). The spray operation distance \( L_{\text{spary},i} \) of each work area can be expressed as:

\[
L_{\text{spary},i} = d + l_i \times 2, i \in [1, n].
\]  

The total spray operation distance \( L_{\text{spary},\text{total}} \) can be calculated because the working conditions \( l_i = l_H \) are fixed. In addition, we also incorporate the return step \( E \) into the process:

\[
L_{\text{spary},\text{total}} = \sum_{i=1}^{n} L_{\text{spary},i} + L_E = n \times (d + l_{H} \times 2) + n \times d = 2 \times n(d + l_{H}).
\]  

(2) Mileage of refueling operation.

We avoided interrupting the spray operation in the middle of the working area according to Equation (5). At this point, the pesticide exhaustion at node \( n_i \), and the “return-replenishment-reset” process needs to be performed. By defining the serial number of the replenishment as \( j \), we can calculate the line number of the dosing that occurred in \( i \) via Equation (5):

\[
i_j = m \times (j - 1), j \in [1, Pst].
\]  

That is, the refueling must occur after one spray is completed. At this point, the ITS will return to the tank to perform the dosing, and its moving distance \( L_{\text{supply},ij} \):

\[
L_{\text{supply},ij} = 2 \times d \times m(j - 1).
\]  

The total distance of this replenishment operation \( L_{\text{supply},\text{total}} \) can be calculated:

\[
L_{\text{supply},\text{total}} = \sum_{i=1}^{Pst} L_{\text{supply},ij} = \sum_{i=1}^{Pst} 2 \times d \times m(j - 1) = \frac{d \times m \times \left\lceil \frac{n}{m} \right\rceil (\left\lceil \frac{n}{m} \right\rceil - 1)}{2}.
\]  

As a key condition, total working mileage \( L' \), regarded as an enhancement of the input condition \( L_s \), can be expressed as:

\[
L' = L_{\text{spary},\text{total}} + L_{\text{supply},\text{total}} = 2 \times n(d + l_{H}) + \frac{d \times m \times \left\lceil \frac{n}{m} \right\rceil (\left\lceil \frac{n}{m} \right\rceil - 1)}{2}.
\]
4.3. Resistance with Load Capacity

Changes in vol_{ITS} will directly affect the system’s resistance \( F_{res} \), and also require output torque \( F_{out} > F_{res} \) to drive ITS. Consider the weight \( WT_{ITS} \) of the ITS itself and its load \( WT_{load} \), the driving resistance \( F_{res} \) can be calculated:

\[
F_{out} > F_{res} = (WT_{ITS} + WT_{load})\mu_s e f g,
\]

where the \( e_f \) is the empirical coefficient \([49]\), mainly considering the deceleration of motor, transmission part of the loss. In addition, to consider when the work surface water stains will have a reduced friction coefficient, one needs to leave a margin for torque. For example, the efficiency of the primary reducer is about 85\%–96\%. Considering the power loss and redundancy caused by the variable friction coefficient, the effective power is about 70\% of the theoretical, that is, \( e_f \approx 1.42 \). Select the maximum friction coefficient of the asphalt pavement \( \mu_s \) \([50]\) in order to simplify the calculation. \( WT_{load} \approx vol_{ITS} \) when the specific pesticide density is not considered. It can calculate the resistance data under the load and tyre size, according to Equation (12). This is to calculate the motor output torque and even motor drive system selection provided by the basis. Whether a reducer is needed to amplify the output torque depends on the actual size of \( F_{res} \). This will also limit the selection of the motor.

4.4. Speed Condition under Efficiency Constraints

Let us define the average speed of ITS to be \( \bar{V} \); then, the actual working time \( T_{practical} \) can be calculated by Equation (11):

\[
T_{practical} = \frac{L'}{\bar{V}}.
\]

Thus, if you want to ensure \( e_{ITS} \geq e_p \), ask for \( T_{practical} \geq T_{total} \), and we can get:

\[
\bar{V} \geq \frac{L'}{T_{total}}.
\]

It is more accurate to substitute the total fixed replenishment time \( T_{supply} = vol_{tank} / Q \) and the ITS state to determine the loss time \( T_{loss} \) into Equation (14). A more accurate average speed can be expressed as \( \bar{V}' \):

\[
\bar{V}' = \frac{L'}{T_{total} - T_{supply} - T_{loss}}.
\]

Then, according to the Equations (12) and (14), the output speed, torque and power of the motor can be pushed back to provide the basis for the selection and further detailed design. The output speed \( V_{PGR} \) of the planetary gear reducer (PGR) and the output speed \( V_{moto} \) of the motor can be calculated by Equation (16) with different loads according to the rotational speed formula. In addition, we further shrink the selection conditions of the drive system:

\[
V_{moto} = V_{PGR} \times Rto_{PGB} = \frac{\bar{V}'}{\pi \times D_{wheel}} \times Rto_{PGB}.
\]

4.5. Structural Stability Conditions

A larger tank volume will increase the center of gravity of ITS and affect the stability of the system structure. In actual operation, it is also necessary to consider the ability of ITS to pass through obstacles. In addition, it also needs to consider the system stability under variable load conditions \([51]\). Calculated in a circular or equivalent circular tank with a radius of \( r_t \), tank height is \( h_t \) and vehicle height is \( h_v \). This allows us to calculate the aspect ratio of vehicle diameter and total height, as shown in Figure 5.
Excessive height and proportion will affect the stability of the system. Consider the capacity to run the system tilt angle $\theta_{sloped}$. Therefore, the height of the vehicle barycenter can be estimated. At this point, the vertical center of mass must be located within the vehicle support point. If the radius of the AGV is $r_v$, and the safety height can be calculated taking into account the mass factor $h_{mass}$:

$$h_{mass} = r_v \times \frac{\sin(90^\circ - \theta_{sloped})}{\sin \theta_{sloped}}.$$  \hspace{1cm} (17)

### 4.6. Normalization and Optimal Solution of Multiple Conditional Constraints

Although the above conditions can converge the design conditions of the ITS to a large extent, the single is still insufficient to give a specific most preferred result. These conditions are all related to the capacity coefficient $m$ and are divided into two categories: (1) proportional, as $\text{vol}_{veh}, L, F_{res}$; and, (2) inversely, as $Pst, \bar{V}$. Operating speed $\bar{V}$ and output torque $F_{res}$ are the two factors that have the greatest impact on ITS. The speed of work $\bar{V}$ can be replaced by the working mileage $L'$ when the upper limit of the total working time is fixed. In addition, they are all related to the volume of the pesticide tank—further related to the factor $m$. By mapping them to the same scalar space by normalization, although their units are different, the optimal solution can be calculated. Therefore, taking the factor $m$ as a reference variable, we then employ the Matlab function “mapminmax(parameters, 0, 1)” to classify the main condition parameters into scalars and compare them.

Through the analysis, we can pass the factors in Sections 3 and 4 through a normalized heuristic method. $\sum_{j=1}^{Pst} l_{spary,j}$ in Equation (11) can be simplified using the summation formula of the arithmetic progression $S_n = \frac{n(a_1 + a_n)}{2}$, where $a_1, a_2, \cdots, a_n$ is an arithmetic progression. In addition, we can create an optimal evaluation function $f(m)$ related to $m$ because parameters other than $m$ can be obtained through specific examples:

$$f(m) = \text{abs(mapminmax}(L) \Leftrightarrow \text{mapminmax}(F_{res}))$$

$$= \text{abs(mapminmax}(2n(d + l_h) + \frac{dm([\frac{H}{l_h}]([\frac{H}{l_h}] - 1))}{2})$$

$$- \text{mapminmax}((WT_{ITS} + \frac{\text{vol}_{tank}}{l_h \times n} [Hm]\mu_{se} G)).$$  \hspace{1cm} (18)

When $f(m) \rightarrow 0$, the optimal value of the result and $m'$ can then be calculated.
5. Efficient Visual Navigation and Motion Control System

Before giving the test site and other conditions, we need to briefly introduce the designed ITS navigation system because this will have a direct impact on actual operation and testing. Considering the operating environment in the greenhouse, the design principles of the navigation system are: simple, reliable, accurate and inexpensive. We have proposed and established a special navigation-control scheme which includes a map system, visual navigation system and navigation control system.

5.1. Specialized Undirected Weighted Connected Graph and Fixed Action Control

We propose a special map representation model called: specialized undirected weighted connected graph. As shown in Figure 6a, simplify the expression of the map by adding some restrictions, which is different from the general navigation map expression.

- All nodes $Node = \{n_1, n_2, \ldots, n_i\}, i \in [1, N]$ in the graph are connected, but loops are not allowed.
- The relative positions between the nodes are limited to four types of up, down, left, and right. For example, for a node $N_i$, the node adjacent to it is only allowed to appear in its $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ in four positions. This also limits the direction of ITS movement to four, which can significantly reduce the complexity of graph and control algorithms.
- The association between the nodes is given a weight of $w_j$ according to the distance between the nodes. For example, the weight between nodes $n_0$ and $n_1$ is $w_1 = d$, and the weight between nodes $n_1$ and $n_1'$ is $w_1' = H$. This weight value helps to control the distance heuristics in the algorithm.

This design can significantly reduce the cost of map modeling and path planning algorithms. Since the starting point and the target node are given, only one optimal/shortest path is generated. For example, the shortest path between $n_0$ and $n_1'$ can be expressed as $n_0 \rightarrow n_1 \rightarrow n_1'$. Nodes can be expressed only by one edge, and there is no need to equidistantly set a large number of auxiliary nodes (a small number of auxiliary nodes that do not participate in the calculation help the system’s own state check, avoiding the possibility of falling into the algorithm when moving long distances. In the problem of defects).

Based on this specialized graph navigation map, a “fixed action control” scheme was proposed as shown in Figure 6b. There are only four sports programs here: 1) Turn Left 90°; 2) Turn Right 90°; 3) Turn Around 180° and 4) Forward. These four types of actions are further divided into two types of events to match the event processing mechanisms: forward and turn. Thus, whenever the vision system recognizes a node identifier, the algorithm will prioritize whether to ignore the point to continue straight or perform a “special turn”. Take the $n_2 \rightarrow n_3 \rightarrow n_1 \rightarrow n_3$ process as an example:
First, AGV will perform a forward action until the center of the ITS $p$ overlaps with $N_3$; then, the "left90" action will be triggered, i.e., the AGV will turn left and its azimuth is 90° to point to $n_1$. Then, go straight to the $n_1$ node and trigger the "trun180" action, i.e., ITS rotates 180° in place and points to $n_3$. Finally, go straight to the $n_3$ node to complete the task.

This control method is obviously not optimal, such as moving the farthest distance and consuming more time when cornering. However, this simple control method does not require complex algorithm support.

5.2. Vision-Based Navigation System

Each node $Node$ or $n_i$ uses a “Quick Response Code (QR Code)” to mark it [17]. Thus, the ITS knows its current relative position, thereby constructing a complete path navigation system and supporting the concrete navigation algorithm. In addition, in a “QR Code Annotated Map” (QR-CAM) visual navigation system based on a specialized graph [52,53], as shown in Figure 7a, guide line connections are used between nodes to provide effective assistance in visual guidance and control.

![Image of visual navigation system composed of QR-Code and guide line.](image)

(a) Visual navigation system composed of QR-Code and guide line.

![Image of framework of navigation control algorithms.](image)

(b) Framework of navigation control algorithms.

Figure 7. High-precision navigation scheme based on guide line and QR code assisted.

(1) We can determine the actual distance between the center point of the ITS, $P$, and the QR Code, using the “Pixel-Distance” formula established by camera calibration. ITS will trigger the “turn” event and perform the turn immediately after the $l_{node}$ distance. In addition, when the event is triggered, the cumulative state of the system is reset—the accumulated error is also set to zero, which increases the reliability of the navigation and control algorithms.

(2) Set 5 evaluation points $S = \{s_1, s_2, s_0, s_3, s_4\}$ on both sides of the image center. The distance between the evaluation points is $\Delta d$. Thus, when the center of the ITS is near the guide line, its deflection angle can be calculated as $\theta_1 = \arctan(\Delta d/l_{O})$ and $\theta_2 = \arctan(2 \times \Delta d/l_{O})$. This allows a quick evaluation of the positional relationship between the ITS and the guide line, thus providing a $p$-value reference for the PID control (if the settings are appropriate, in an ideal environment, only proportional adjustment can be used to complete the effective control of the ITS).

(3) The specific control process is divided into three parts, as shown in Figure 7b. In addition, this process can be called “Setting-Find-Task Execution”. At first, the staff sets the task target and work path through the terminal equipment such as the wired or wireless touch panel on the vehicle [54]. In addition, then, the vehicle will then complete the movement between the nodes in units of sub-paths and eventually reach the target node. For example, the $n_0$ to $n_1'$ path can be split into $n_0 \rightarrow n_1$ "forward", "turn right 90°", $n_1 \rightarrow n_1'$ "forward" as shown in Figure 6c. That is, all tasks can be
planned and calculated in advance, just like Programmable Logic Controller (PLC), and each task can be completed in steps—this can greatly reduce the computational burden caused by dynamic programming and real-time control. The motion control only has two simple control processes: ① “turn” and ② “go forward”. This ensures that the vehicle can move precisely along the guide line, inspired by θ₁ and θ₂, based on the PID control algorithm. The deviation can be controlled at 0.5% or ±2 m, even if there are machining and assembly errors.

(4) Repeat the “move-search” process according to the planned route until all tasks have been completed or reached a “termination point”. (Note: The user can manually set the termination node or when the ITS needs to return to the service station when it detects a failure [55].)

6. Improved ITS System Selection and Implementation

6.1. Qualification Calculation Based on Instance

The example parameters of the greenhouse environment can be given according to the greenhouse structure shown in Figure 1 and the user requirements and input conditions in Section 3. Table 2 lists instances of the main parameters.

| Params Name                      | Symbols | Quantity | Params Name        | Symbols | Quantity |
|----------------------------------|---------|----------|--------------------|---------|----------|
| greenhouse width                | W       | 90 m     | pesticide tank     | volₐₑₚₐₜ | 500 L    |
| greenhouse height               | H       | 50 m     | Pump flow          | Q       | 1.17 L/s |
| total operating time            | Tₜₒᵗₐˡ | 1.5 h    | working area count | n       | 22       |
| area path length                 | lₜₛ = H | 50 m     | operational area width | dₚ | 2.5 m |
| space path length               | lₜₓ = W | 90 m     | area path width    | dₚ     | 0.6 m    |
| space path spacing              | d       | 4 m      | spray volume       | SVₗₚ | 0.46 L/m |
| worker efficiency               | ₑₚ     | 50%      | required efficiency | ₑₚ = 2 × ₑₚ | 100% |
| frictional coefficient (asphalt pavement) | ₑₚ | 0.6 [58] |                   | g       | 9.8 m/s  |
| vehicle self-weight             | WTₐₑₚₚ | 25 Kg    | load weight        | WTₜₒᵈ | m × 22.7 Kg |
| wheel size                      | Dₜₒₐₑ | 3~16 inches | experience factor | ₑₚ | 1.42 |

The above example parameters are brought into the formula one by one. Bring the parameters listed in Table 2 into the formula one by one, derived according to the theory. In addition, finally, determine the optimized ITS selection design.

1. First of all, the quality factor  ∈ [1, 22] can be determined according to the working area count  = 22.
2. Then, the total working distance can be calculated according to the factor  that  ∈ [2376, 3300].
3. In addition, the total effective working time limit can be calculated:  =  −  −  ∈ [4640, 4955] s, where the total replenishment time is  =  /  ≈ 430 s. The loss time is  ∈ [15, 330] s and the time for the device status to confirm the fixed loss is about 15 s per replenishment.
4. The average speed of the system can be determined by mileage and time, which is  ∈ [0.51, 0.71] m/s.

When the three factors of workload, distance, and time are known, the resistance of the ITS system, ₉ₑₑ, and the output torque of the motor can be calculated. As shown in Figure 8 by a two-coordinate graph (‘plotyy’), here is a comparison of the resistance and the required output torque of three different radius drive wheels with different loads.
It can be seen that as the load factor \( m \) increases: (1) The average output speed of the motor are 55, 72 and 88 rpm with different \( D_{\text{wheel}} \) or \( D \). Respectively, minor changes when \( m > 3 \). (2) However, the output torque is increasing rapidly, \( F_{\text{res}} \in (13.7 \sim 21.9) \text{ N} \cdot \text{m} \) when \( m = 10 \). When \( m = 22 \), it grows to 28.4\sim 45.5 \text{ N} \cdot \text{m}, which is over the limit of ordinary DC motors and reducers.

Because the general motor is characterized by low torque and low torque, it is difficult to meet the drive of large loads. Therefore, it is necessary to use PGR to increase the output torque. The range of conditions for output torque can be determined by Figure 8 and the motor selection code. “Limitation conditions (3)” \( F_{\text{out}} = 10 \text{ N} \cdot \text{m} \) when \( m > 10 \) to offset the resistance according to Equation (12). In addition, the unit N of \( F_{\text{res}} \) or \( F_{\text{out}} \) has been converted to \( \text{N} \cdot \text{m} \) according to the power wheel radius.

The output torque is related to the driving wheel diameter, the motor torque and the deceleration ratio of the reducer. The ITS can only move when \( F_{\text{res}} \leq F_{\text{out}} / D_{\text{wheel}} \) (especially static state). In addition, the \( V_{\text{PGR}} \in [50 \sim 140] \text{ rpm} \) and \( V_{\text{moto}} \in [300 \sim 1400] \text{ rpm} \) based on drive wheel diameter 5–8 inches.

According to the analysis of Section 4.6, the key conditions of \( F_{\text{res}} \) and \( L \) are combined with factor \( m \), and the results are as shown in Figure 9.

Substituting Equation (18) into Equation (4) according to the given condition, we can see that \( m' = 5 \).

Larger volume capacity provides more redundancy and shorter distance, such as nozzle loss during liquid spray. It should be noted that the excessive load can lead to a significant increase in the probability of ITS system failure and difficulty in diagnosing [56]. Compared to \( m' = 6 \), when \( m' = 6 \), the center shifts by only 0.08 m and the height of tank is about 0.65 m, which is still within the design tolerance. In addition, the working distance is reduced by 2.2%.

Based on the obtained optimal coefficient \( m' \), the structural stability of the system can be verified. The working area \( d_p = 0.6 \text{ m} \) and the bottom radius of the container is \( 0.4 \leq r_l \leq 0.5 \text{ m} \). In addition, \( r_p \in [0.5, 0.6] \text{ m} \). Bring these parameters to Equation (17) to calculate \( h_{\text{mass}} = 1.45 \sim 2.25 \text{ m} \). In addition, considering that the liquid in the container may be shaken, the safety height should be set at least 80% of the limit value at design time. Therefore, the safety height \( h'_{\text{mass}} = h_{\text{mass}} \times 80\% \) is 1.45–1.8 m.
Because at this time the bottom area of tank is about 0.196 m$^2$, it can thus be limited to the car cabinet volume within 200 L, that is, $m < 9$. Although this result is larger than the optimal value ($m = 5$) we obtained in the normalization condition calculation, since the height of the vehicle is easy to estimate, the calculation condition can be contracted earlier by this method.

6.2. An ITS Instance for Greenhouse Spraying Application

We designed and implemented a complete ITS system based on the above analysis and given the greenhouse application scenario [55]. Figure 10a shows the schematic diagram of a full-featured prototype. Figure 10b shows a 3D view of the ITS. More information on subsequent versions can be found in 2017—the 15th China International Agricultural Trade Fair (http://www.xinhuanet.com/politics/2017-09/22/c_129710586.htm) and the 24th China Yangling Agricultural High-tech Achievements Expo (http://www.chinanews.com/cj/shipin/cns-d/2017/11-05/news739705.shtml).

![Schematic diagram of a full-featured prototype](image1)
![3D view of integrated ITS](image2)

Figure 10. An ITS instance for greenhouse spraying application.

We can see the composition of the system for pesticide spraying applications by Figure 10a. It consists of nine parts, including a full-featured version of the entire ITS base system, and the final version is the result of this prototype’s improvement and optimization. It can be divided into two parts from the perspective of use:

1. Pesticide spraying subsection. Two 15 l water tanks form the medicine box and the main load; a self-priming booster pump (E-CHEN EC-RV-03L) is used to draw the liquid from the chamber and provide sufficient pressure to the nozzle. A solenoid valve system monitors the system pressure while controlling each nozzle. In addition, a variety of filtration systems are available for different liquids to prevent clogging of the above components.

2. ITS and control system. In the prototype system, the power system and ECU parts of the ITS are integrated into the chassis. The main processor (NVIDIA TK1) and the first-view visual sensor (wireless image transmission system based on GoPro Hero 5) are external. Although the image sensor (Logitech C920, CH: Switzerland) for visual navigation is installed in the ITS chassis, its data are still processed by [52].

Among them, is used to identify information of each object in the environment, such as the plant or pest as and is also used for remote control of the ITS by the user from the first perspective. is mainly responsible for the identification of the node QR-Code and the guide line, and provides upper decision information for path planning and navigation. Eventually, this decision information will be sent to the ECU in the ITS for specific implementation. More details of the actual operation can be seen in the “video abstract”.

The ITS (version “BigPan-III”) shown in Figure 10b is an upgraded version of the prototype. All the necessary components, including the power supply, drive system and controller, are integrated...
together, and the high degrees of independence and autonomy are the advantages of this transitional version. Nine major modules are divided into two categories:

1) Control system. Compared to the prototype, the external intelligent processing device (6) is integrated into the ITS (10) after it has been redesigned and miniaturized. The image sensor (7) is replaced with a smaller camera module (45 (L)*15(W)*15(H) mm) so that it can be mounted to the (15) position. In addition, the front and rear dual cameras allow ITS to achieve the same level of navigation in an environment that cannot be turned. The ECU (16) is updated to accommodate high temperature and high humidity environments. It integrates four currents, four voltages, three-axis accelerometers and three-axis angle sensors. This information will be combined with the rotary encoder (18) to perform attitude fusion calculations inside the Electronic Control Unit (ECU) (core chip is Freescale MC9S12X, Austin, TX, USA) to obtain the current speed of the ITS (relative) information such as position and power consumption. This information will all be uploaded to the intelligent controller (10) for decision, and the generated issued instructions will be sent to the (11) actuator to drive the actual movement of the ITS.

2) Power and drive system. Two motors (13) (5PC120GU-24 rated power 120 W, 1800 rpm) are installed in a symmetrical manner, with the 5-inch drive wheel to form a differential drive system. The output section is equipped with a gear unit (12) (5GU10K supports 180 RPM output speed). This provides an output torque of >8.5 N·m at an output speed of 120 rpm (0.75 m/s). A battery (14) (48 V 12 Ah) allows the system to operate for at least one hour at maximum power consumption, while a second backup battery doubles the system’s endurance to meet demanding mission’s requirements.

The specifications of an experimental ITS are shown in Table 3.

| Components              | Specification            | Components          | Specification            |
|-------------------------|--------------------------|---------------------|--------------------------|
| Moto power              | $P_{moto} = 120$ W * 2   | ECU                 | Freescale MC9S12X $P_{ECU} = 5$ W |
| Moto output torque      | 8.5 N·m                  | Pump                | $P_{pump} = 120$ W (rated) |
| Total ITS weight        | 25 Kg                    | Main Controller     | NVIDIA Tegra K1/X2 $P'_{ECU} = 10$ W |
| Rated load              | 150 Kg 250 Kg MAX        | Main battery        | 48 V 12 Ah * 1$^*$        |
| Wheel diameter          | 5 inch                   | Size (include tank) | 0.52(L) * 0.52(W) * 0.75(H) m |

Therefore, the total power consumption of the system is approximately $P_{MAX} = 2 \times P_{moto} + P_{ECU} + P_{pump} = 410$ W. The total energy demand approximately 615 W·h. In practice, not all of the time is the maximum power—for example, the ECU and control computer average power consumption of about 15 W. While the pump system works less than half its working time, it can consider its average power consumption as 60 W. According to full load operation, the total power consumption of the system is about $P_{total} = 315$ W and the total energy consumption is 472.5 W·h. Therefore, the optional lithium battery specification is 36 V·16 Ah or 48 V·12Ah. Except for the battery, the electricity consumption is lower than 36V, which still meets the safety requirements (GB/t 3805–2008) [57]. Considering the effect of actual loss, battery life and temperature on the battery, the battery with larger capacity should be selected in the actual selection. We can give the overall architecture of the ITS system when the two key components of the motor and battery are determined.

7. System Efficiency Testing and Result Analysis

7.1. Test Environment Settings

We have selected a complete cabin as shown in Figure 1b for system testing. The main parameters are shown in Table 2. It is then converted to a digitized map of the XY markers to facilitate the description of the test results, as shown in Figure 11.
In order to more clearly show the movement of the AGV under different loads, i.e., different load factor $m$. We define replenishment − work as the task group $WS$. Thus, when $m = 6$, $WS_1$ can be described according to Section 5:

$$WS_1 = Fill(n_0) \rightarrow (n_1 \rightarrow n'_1 \rightarrow n_1) \rightarrow (n_2 \rightarrow n'_2 \rightarrow n_2) \cdots (n_6 \rightarrow n'_6 \rightarrow n_6) \rightarrow Fill(n_0),$$  \hspace{1cm} (19)

where a pesticide filling job $Fill()$ needs to be performed before each working group starts or end in $n_0$. For a 70 L/min replenishment pump, it takes about 430 s to complete the filling of $vol_{tank} = 500$ L tank. In addition to $m = 22$, the AGV will return to the medicine box several times for replenishment. Since the total dose is the same, the total dosing time is still 430 s, but this time will be allocated to each replenishment process. Thus, the working distance of each group is $L_{WS_i}, i \in [1, Pst]$ and the total distance $L'$ can be calculated:

$$L_{WS_i} = \begin{cases} 2 \times m \times l_H + 2 \times m \times d, & i = 1, \\ 2 \times m \times d \times i + WS_{i-1}, & i > 1. \end{cases}$$ \hspace{1cm} (20)

The motion control method proposed in this paper divides the motion of ITS into two types: linear and fixed turn. Therefore, through Section 6, we know that the spraying operation and the straight travel speed $\bar{V}_2 \approx 0.67$ m/s. In addition, within the rated load range, the acceleration both are fixed at 0.2 m/s$^2$.

7.2. DAQ System

As shown in Figure 12 and Table 4, we built a DAQ system [55] to obtain the main operating parameters of the ITS runtime in order to accurately evaluate its work efficiency. An ADI AD7606 DAQ model (8-channel DAS with 16-bit) is integrated into the ECU for the acquisition and conversion of numerical data. Four of them are used for voltage detection, and the other four are used with Allegro ACS758LCB-050B linear hall current sensors (Worcester, MA, USA) for current detection. Two AVAGO HEDS-9140 encoders (San Jose, CA, USA) monitor the operating speed of the two drive wheels. An MPU-6050 triaxial accelerometer sensor is used to obtain ITS acceleration information for Inertial Measurement Unit (IMU) assisted positioning and measurement.

![Figure 12. Multi-channel sensor signal acquisition.](image-url)
Table 4. Sensor parameter setting.

| Part | Target   | Sensor | Feature | Values | Rate |
|------|----------|--------|---------|--------|------|
| (1)  | Moto 1   | Current| $F_1$   | 50 mA  |      |
| (2)  | Moto 1   | Voltage| $F_2$   | 50 mV  |      |
| (3)  | Moto 2   | Current| $F_3$   | 50 mA  |      |
| (4)  | Moto 2   | Voltage| $F_4$   | 50 mV  |      |
| (5)  | Moto 1   | Encoder| $F_5$   | 1024 PPR | 10 Hz |
| (6)  | Moto 2   | Encoder| $F_6$   | 1024 PPR |      |
| (7)  | Pump     | Voltage| $F_7$   | 50 mV  |      |
| (8)  | Pump     | Current| $F_8$   | 50 mA  |      |
| (9)  | Control System | Voltage | $F_9$ | 50 mV |      |
| (10) | Control System | Current | $F_{10}$ | 50 mA |      |
| (11) | –(13) Triaxial accelerometer | XYZ | $F_{11} \sim F_{13}$ | 16,384 LSB/g |      |

7.3. System Test and Result Comparison

The test mainly includes five items: working path, total mileage, speed, power and total power consumption. Based on load factor $m = 1 \rightarrow 8$, eight sets of effective experiments were carried out here. It should be noted that the rated load of the given ITS instance is $m = 6$, i.e., 138 Kg. The system’s power performance will gradually decrease when the rated load is exceeded, such as the system load at $m = 9$. At the limit, the acceleration is only 0.03 m/s, and the maximum speed is only 0.1 m/s. This is much lower than the efficiency users need. Eight sets of valid experiments were carried out, and the corresponding load factor was set to $m = 1, 2, 3, 4, 5, 6, 7, 8$.

1) The results of the work path are as shown in Figure 13.

2) The results of the center speed of the ITS are as in Figure 14. It can be seen that, due to the existence of the “fixed action control” described in Section 6.1, the speed curve of ITS is very similar to that of PLC, showing a high degree of regularity.

3) The results of the work mileage comparison are as shown in Figure 15:

It can be seen that, when the load factor $m$ changes, it will cause changes in the WS process, the working path, and the work history, and exhibit similar changes. In addition, the change in total working distance is consistent with that shown in Figure 9, where the total working distance is the shortest when $m = 6$.

A summary of the above main test results are shown in Table 5.

Table 5. Test results and comparison.

| Load Factor (m) | Mileage (m) | Mileage Error (%) | Consumption (Wh) | Discharge Rate (%) | Time (s) Actual | Efficiency (%) Actual |
|----------------|-------------|-------------------|------------------|-------------------|----------------|----------------------|
| 1              | 4224        | 2414.7            | 99.78            | 532.8            | 92.5           | 8644                 | 62.47                |
| 2              | 3256        | 3247.6            | 99.74            | 524.2            | 91.0           | 6775                 | 79.70                |
| 3              | 2880        | 3040.1            | 105.56           | 483.8            | 84             | 6353                 | 85.00                |
| 4              | 2856        | 3068.1            | 103.94           | 496.5            | 86.2           | 6191                 | 87.22                |
| 5              | 2616        | 2768.5            | 105.83           | 490.2            | 85.1           | 5831                 | 92.61                |
| 6              | 2664        | 2656.5            | 99.72            | 481.1            | 83.5           | 5633                 | 95.86                |
| 7              | 2544        | 2704.8            | 106.32           | 484.4            | 84.1           | 5701                 | 94.72                |
| 8 *            | 2568        | 2712              | 105.61           | 535.7            | 93             | 5749                 | 93.93                |

* Exceeding rated load.
Figure 13. Results of the work path.
Figure 14. Comparison of working speed under different load factor $m$.

Figure 15. Total mileage comparison at different $m$. 
We can draw the following conclusions:

- The trend of the above results is consistent with that shown in Figure 9, indicating that the optimal Equation (18) expression is valid for the design of the ITS system.
- When \( m = 5 \), the main indicators of the system are optimal, and the \( m = 6 \) sub-optimal result is only 3% different. This provides some redundancy for system design.
- The average error between the actual working mileage and the ideal calculated value is only 2%, which proves the accuracy of the navigation and control system designed in this paper. When \( m = 6 \), the actual working distance is 99.7% of the ideal value. Due to the presence of sensor errors and the response speed of the PID controller, the AGV is unlikely to reach exactly above the target node. It is possible for the AGV to stop during the previous sample-execution cycle or to stop during the next cycle. Thus, the AGV has a \( \Delta t_{\text{delay}} < 0.1 \) m error from the target node, and the accumulation of the error will cause a positive and negative deviation between the total mileage of the AGV and the ideal value.
- In the above test of \( m \), although the predicted value is exceeded by about 5%, the total system energy consumption is lower than the battery power supply capacity. Existing power supply systems are feasible, especially if a backup battery is enabled.
- In terms of efficiency, \( e_{\text{ITS}} = 95.86\% \) when \( m = 6 \) is equivalent to two workers due to the maximum output speed limit, in other cases in which system efficiency is lower than \( e_p \), but still higher than the efficiency of a single worker \( e'_p \). This proves the high efficiency of the ITS system designed in this paper.

The test results demonstrate the effectiveness of the design method presented in this paper. The proposed ITS system demonstrates features such as efficiency, accuracy, and energy control for the application in greenhouse.

8. Conclusions

In this work, a high-efficiency ITS system for greenhouse applications based on our proposed ITS efficiency formula was designed and validated. Designers can significantly reduce the range of critical components such as drive systems, energy supply systems, ITS mechanical frames, etc., by shrinking complex requirements to three main conditions. This provides guidance for the rapid design of high efficiency ITS systems required for composite applications. First, we present a real greenhouse application scenario. Then, according to the scenario, the designing process of the efficiency formula is elaborated. Finally, the efficiency of the designed ITS system is proved by experiments. In the future, the authors will further study the efficient ITS design issues in complex application environments (not limited to greenhouse applications); in addition, multi-ITS collaboration is an important research direction to further improve work efficiency.

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Abbreviations
The following abbreviations are used in this manuscript:

AC: Alternating Current Power
ADC: Analog-to-Digital Converter
AGV: Automated Guided Vehicle
AI: Artificial Intelligence
AWPS: Agricultural Worker Protection Standard
CAN: Controller Area Network
CPU: Central Processing Unit
CUDA: Compute Unified Device Architecture
DAQ: Data Acquisition
DC: Direct Current Power
ECU: Electronic Control Unit
IMS: Intelligent Mechatronic Systems
IMU: Inertial Measurement Unit
ITS: Intelligent Transportation Systems
MMC-AGV: Multiple Conditional Constraints for AGV
MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor
NFR: Net Financial Return
PGR: Planetary Gearboxes Reducer
PLC: Planetary Gearboxes Reducer
QR: Quick Response
RUPs: Restricted Use Pesticides
PWM: Pulse Width Modulation
US-EPA: United States Environmental Protection Agency

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