agronomy

Article

Work Efficiency Analysis of Multiple Heterogeneous Robots for Harvesting Crops in Smart Greenhouses

Taeyong Choi *, **Jongwoo Park**, **Jeong-Jung Kim**, **Young-Sik Shin** and **Hyunuk Seo**

Korea Institute of Machinery and Materials, 156 Gajeongbuk-ro, Yuseong-gu, Daejeon 34103, Republic of Korea
* Correspondence: taeyongc@kimm.re.kr

Abstract: Extensive research is being conducted on using robots to automate harvest. However, most of the existing research is focused on the realization of harvesting using a single robot, and there have been very few studies on harvesting and transporting crops from a smart-greenhouse perspective. In this study, we demonstrate that the work efficiency is higher when a plurality of harvesting and transporting robots are used in tandem for harvesting crops in a smart greenhouse, compared to that when a single robot is used. The harvesting and transporting speeds of these robots are modeled in accordance with the facility environment. The operating speed of the robot group comprising only the harvesting robot and the harvesting and transporting robots is derived. In addition, the derived operating speed is analyzed based on the experimental data of the developed harvesting and transporting robots, and it was found that the overall operating speed increased when an appropriate combination of harvesting and transporting robots was used.

Keywords: harvesting robot; transporting robot; harvesting speed; smart greenhouse

Citation: Choi, T.; Park, J.; Kim, J.-J.; Shin, Y.-S.; Seo, H. Work Efficiency Analysis of Multiple Heterogeneous Robots for Harvesting Crops in Smart Greenhouses. *Agronomy* **2022**, *12*, 2844. https://doi.org/10.3390/agronomy12112844

Academic Editor: Roberto Marani

Received: 13 October 2022
Accepted: 8 November 2022
Published: 14 November 2022

1. Introduction

The increasing attention to the advanced agricultural concepts in recent years can be attributed to the changes in global climate and food crises. The interest in high-tech open-air agriculture represented by unmanned tractors and indoor agriculture, such as urban agriculture and vertical farms, is increasing. A smart greenhouse significantly improves the production and quality of various crops by grafting automation technology to optimally control temperature, humidity, carbon dioxide, and nutrients required for plant growth in existing greenhouses [1,2]. However, precision work such as leaf pruning, crop pruning, and harvesting still rely on manual work, and as a result, several studies have been conducted to automate harvesting in recent years [3–6].

SWEEPER [7], developed by the Dutch University of WAGENINGEN team, is considered the most advanced harvesting robot, mainly because it is equipped with a robot arm on a mobile platform for moving in a greenhouse, a vision system for paprika recognition, and a cutting mechanism.

In the US, RootAI developed a strawberry harvesting robot [8], which is significantly different from SWEEPER in terms of robot arm and end tool used. Although SWEEPER uses a 6-axis vertical articulated robot, RootAI applies a scara-type robot, which is ideal for two-dimensional movement and crop harvesting. Furthermore, for use as an end tool, SWEEPER developed a unique tool for cutting stiff paprika stems, whereas RootAI applied a unique soft gripper for soft strawberry harvesting.

The configuration of other greenhouse crop harvesting robots is similar. A particular mobile platform that is used for moving in the greenhouse is equipped with a robotic arm and an end tool for harvesting. Depending on the crops to be harvested, the robot arm can be applied in a 6-axis vertical multi-joint, parallel robot or a scara type. The end tool that harvests crops is the most vital element of the harvesting robot. The growing process and harvesting conditions for each crop differ significantly, and the harvesting requirements in consideration of commerciality are also complex. Therefore, most studies are focused on the mechanism of a single harvesting robot [9].

There has been significant research on transporting robots in recent years. The transporting robot was developed to transfer the crops harvested by human workers to the sorting site for the next process. For this purpose, functions that cater to workers and autonomous driving in a facility environment are useful. The practical applications of the transporting robot are investigated in [10].

Although harvesting and transporting robots are being exhaustively studied and developed in facility horticulture, such harvesting and transporting robots are rarely used in tandem for cooperative work. This is mainly because the technologies related to the harvesting robot to consider cooperative work with other robots have not been sufficiently developed [11]. Furthermore, because the harvesting robot usually has its own crop storage space, there is no need for a separate transport means for short work. However, when considering the harvest of the entire facility horticulture, the single harvesting robot must be transferred to the rear crop unloading space whenever the crop storage space is fully filled owing to space limitations, and this is time-consuming.

To overcome this shortcoming, there has been significant research on harvesting crops in facilities such as smart farms with multiple robots that combine harvesting and transfer robots [12]. However, no studies have determined the optimal composition of the harvesting and transporting robots suitable for work efficiency when harvesting the entire facility. Although there was one particular study on the work efficiency of an agricultural robot to harvest strawberry, it was limited to a single robot [13].

Because the research on the field agricultural robot is more exhaustive compared to that on the facility robot and the required functions are more complex, there have been many studies on the cooperation of the field agricultural robot [14–16]. However, these studies primarily focus on the role of each robot and the way of cooperation, and they do not emphasize on the work efficiency.

In this study, we model and analyze the work efficiency of an unmanned harvesting and transporting system using harvesting and transporting robots, when the entire facility is to be harvested, to present a guide for forming a heterogeneous robot team. The remainder of this paper is structured as follows. In Section 2, we model the harvest speed and transfer speed of a single harvesting robot and a transporting robot based on the spatial characteristics and variables of the facility. Furthermore, we model the work efficiency of a robot team composed of harvesting robots and transporting robots for harvesting the entire facility. In Section 3, the harvesting robot and transporting robot developed to show the usefulness of the proposed work efficiency model are described. In Section 4, based on data of actual harvesting and transporting robots, we show that for an entire facility, a composite robot team comprising harvesting and transporting robots is faster than the single robot team comprising single harvesting robots. In Section 5, the generality and limitations of the proposed work efficiency model are discussed. Section 6 concludes this paper.

2. Modeling the Work Efficiency of a Multi-Robot Team

2.1. Harvesting Robot and Transporting Robot Working Speed in Facility Horticulture

Figure 1 shows the structure of the greenhouse. The beds for growing crops are arranged in a vertical direction such as 'Bed_n', where n is number of beds installed. A pipe is laid between the beds to supply the hot water to heat the greenhouse. As shown in Figure 2, the pipe comprises two layers and resembles a rail through which a train passes. The facility's robot is developed to move like a train on a pipe between beds. Those pipes are denoted as '$Rail_n$' of Figure 1. The side A and B areas of Figure 1 are where pipes are not normally installed. This part requires a specific advanced technique and is not currently considered. The greenhouse rails on which the robot moves are usually blocked on one side. Based on Figure 1, the upper part is connected to the concrete floor to move on rails; however, the bottom part is blocked. As the rail is a one-lane with a one-pair pipe, two robots cannot cross the rail simultaneously.

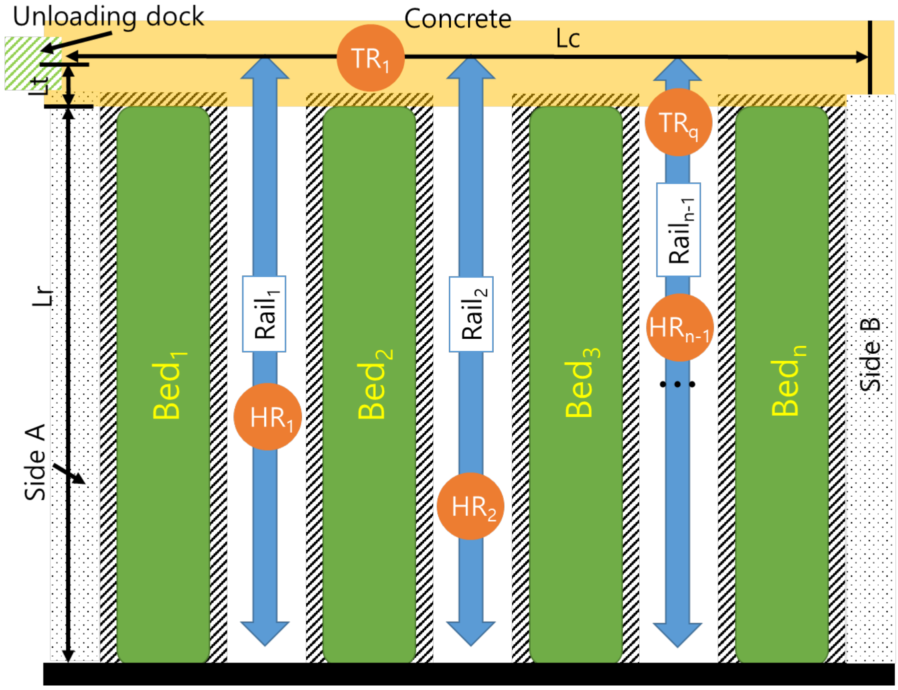

Figure 1. General structure of smart greenhouse.

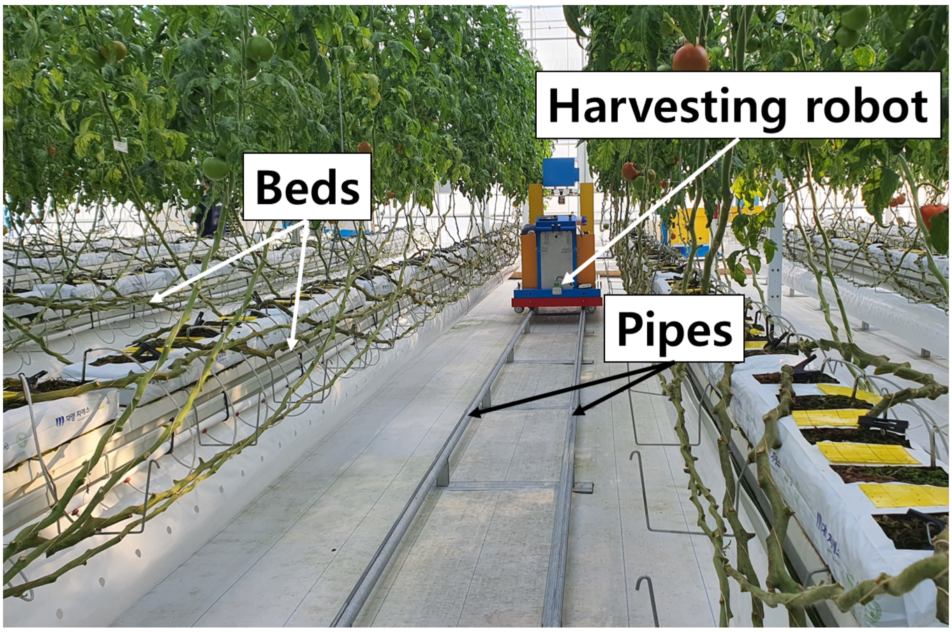

Figure 2. Beds and pipes of greenhouse.

Each plurality of harvesting robots operated in the facility is defined as HR_i in Figure 1. Each plurality of transporting robots is defined as TR_i. HR and TR are abbreviations for harvesting and transporting robots, respectively. The total number of harvesting and transporting robots operated in the facility is defined as p, q for each p, q satisfy $\{p, q | 0 < p, 0 < q\}$. Here, i, j is the index that represents the individual robot, i is the index of the harvesting robot, and j is that of the transporting robot that satisfies the condition $\{i, j | 0 < i \leq p, 0 < j \leq q\}$.

Further, when defining the harvesting and transporting speeds of the harvesting and transporting robots as I_{HR_i} and I_{TR_i}, respectively, the specific meaning of each is as follows (1), and generally $I_{HR_i} \ll I_{TR_i}$.

$$\begin{aligned} &I_{HR_i} : Crop\ yield\ per\ unit\ time\ by\ robot(unit/hour) \\ &I_{TR_j} : Crop\ transfer\ amount\ per\ unit\ time\ by\ robot(unit/hour) \end{aligned} \quad (1)$$

In the definition of I_{HR_i}, I_{TR_i} the unit time is "hour." Harvesting and transporting are not continuous but intermittent events that occur gradually. Therefore, assuming a unit time that is statistically meaningful is necessary to define a meaningful speed, considering each event occurs frequently, and a long time is suitable empirically.

Let β_{HR} be the amount of crop buffer that harvesting robot HR_i can store and β_{TR} be the number of crops that the transfer robot TR_j can carry. I_{HR} denotes the continuous harvest speed, assuming the loading box of the harvesting robot is sufficiently large, such that harvested crops are not transported to the crop drop-off area during harvest. Therefore, additional time except harvesting work is not necessary for the harvesting robot. Considering these assumptions, the harvesting speed of a harvesting robot can be expressed as (2):

$$I_{HR} = \frac{\beta_{HR}}{T_{\beta_{HR}}} \quad (2)$$

$T_{\beta_{HR}}$ is the time required to fill the number of crop buffers β_{HR} of the harvesting robot. In reality, as HR_i harvests while moving on $Rail_i$, and additional time is required along the movement, which reduces I_{HR}. Therefore, the practical harvesting speed $\hat{I}_{HR}$ considering the movement can be expressed as $\hat{I}_{HR} = K_{HR} I_{HR}$. Because this is similar to a typical harvesting robot, the index i representing the individual robot is omitted. K_{HR} is a number between 0 and 1.

I_{TR} assumes that the harvesting robot harvests crops at high speed ($\hat{I}_{HR} = \infty$) and the transporting robot carries the crops without losing time for the harvesting job to be completed. In other words, this is a case where the transporting robot only transfers in facility gardening. At this time, the transporting speed of the transporting robot is defined as (3):

$$I_{TR} = \frac{\beta_{TR}}{K_L \dfrac{L_r}{V_{m_{TR}}} + T_{r_{TR}} + K_C \dfrac{L_c}{Vc_{TR}}} \quad (3)$$

$V_{m_{TR}}$ uses m/h as the speed of the transfer robot. $V_{r_{TR}}$ and $T_{r_{TR}}$ are the speed and time when the transport robot moves from the concrete area of the hallway to the pipe between the beds or from the pipe to the concrete, respectively. L_r is the length of a bed or rail. L_c is the length of the concrete, or the horizontal distance of the greenhouse, as shown in Figure 1. The movement between the pipe and concrete consumes more time than the general movement as it takes additional time to change direction after the movement and there is discontinuity of the connection between the pipe and the concrete. Here, K_L and K_C are the distance constant of the pipe and concrete areas. For example, if HR_1 starts the transfer at the end of $Rail_1$ (bottom of Figure 1), it is $K_L = 1$, whereas if it starts at the 1/2 point, it is $K_L = 1/2$. Similarly, K_C is $K_C = 1$ if the transporting robot moves across the entire length of concrete and $K_C = 1/2$ if it moves from the middle. Because the purpose is to observe the overall trend, it is assumed that the moving speed $V_{C_{TR}}$ in the concrete area is the same as the pipe moving speed $V_{m_{TR}}$. Assuming the transfer starts at the midpoint, which is $K_L = K_C = 1/2$, and (3) can be simplified as (4):

$$I_{TR} = \frac{2\beta_{TR} V_{m_{TR}}}{L_r + L_c + 2T_{r_{TR}} V_{m_{TR}}} \quad (4)$$

Similar to the harvesting speed, I_{HR}, transporting speed I_{TR} assumes an ideal condition, and thus, the practical transporting speed can be expressed as $\hat{I}_{TR} = K_{TR} I_{TR}$, where K_{TR} is a number between 0 and 1.

2.2. Significance of Configuration of Transporting Robot and Harvesting Robot

In the previous section, the harvesting and transporting speeds of a harvesting and transporting robots were modeled, respectively. A case where a transporting robot is required instead of a harvesting robot is considered when the harvest amount in the facility horticulture is considered.

The current facility gardening environment utilizes a hot water pipe installed on the floor as a rail for movement, which limits the mobility of the robot. For example, in Figure 1, for a harvesting robot, HR_1, to move from $Rail_1$ to $Rail_2$, it is only possible when it moves upward and then back to $Rail_2$ through the concrete floor. When there is a harvesting robot, HR_1, in $Rail_1$, HR_2 can go to $Rail_1$ through a concrete area. However, HR_2 cannot cross the HR_1 already there and go further down, and vice versa. Therefore, it is impossible for HR_1 to move across HR_2 into the concrete domain.

If n beds are installed in the facility, the number of pipes (or rails) for robot movement is $(n-1)$. However, harvesting robots are rarely deployed on all rails owing to the mobility restrictions and high prices in horticultural facilities. Therefore, the number of beds or rails is usually much larger than the number of harvesting robots; $p < n$.

If the number of harvestable crops of Bed_i and harvested crops is C_i and γ_i, respectively, the number of crops to be harvested is $(C_i - \gamma_i)$. A harvesting robot HR_i can harvest on the side in contact with Bed_i and Bed_{i+1}. On average, if the density of harvestable crops in the bed is the same, the number of harvestable crops for HR_i is $\left\{\frac{C_i}{2} + \frac{C_{i+1}}{2}\right\}$. If HR_i harvests at the same rate in Bed_i and Bed_{i+1}, the number of crops harvested in each bed can be assumed to be $\frac{\gamma_i}{2}$. At this time, assuming that the growth of adjacent crops is similar, it is $C_i = C_{i+1}$. Accordingly, the total amount of crops that HR_i can harvest from $Rail_i$ is C_i, the number of crops harvested is γ_i, and the number of crops remaining after harvest is $(C_i - \gamma_i)$. Although there are differences in detail, the aforementioned assumption is reasonable given that the environmental conditions within the facility are similar, and the same crops are grown at the same density. In other words, a harvesting robot, HR_i, can be simplified to harvest on Bed_i.

If $\exists HR_i$ for Bed_i and $C_i \leq \beta_{HR}$ for HR_i, the role of the actual transfer robot is minimal, because the harvesting robot only needs to get out of $Rail_i$ with all the crops that can be harvested from $Rail_i$ at once. Conversely, if it is $C_i > \beta_{HR}$, the use of a separate transfer robot would help increase work efficiency. Therefore, to increase the overall work speed, the transporting robot takes over and transfers the crops of the harvesting robot whenever the buffer amount β_{HR} of the harvesting robot is full, and the harvesting robot spends more time on time-consuming harvesting. In the current level of harvesting robot technology, it is clear that $C_i \gg \beta_{HR}$. Therefore, hiring a transporting robot can increase the work efficiency.

2.3. Comparison of Work Efficiency

We compare the work efficiency when using only the harvesting robot and an appropriate combination of the transporting and harvesting robots. Using the model in the previous section, we compare the two cases, as shown in Table 1.

The two cases are compared in the same greenhouse. The first case is when $Team1$ comprises p harvesting robots and q transporting robots with $p > 0$ and $q > 0$ performing harvesting and transporting operations for a unit time, respectively. The second case is when $Team2$ comprises only $(p+q)$ harvesting robots that perform harvesting and transporting operations for a unit of time.

Table 1. Setup of comparison groups to compare yields.

	Number of Total Robots	Number of Harvesting Robots	Number of Transporting Robots
*Team*1	$p+q$	p	q
*Team*2	$p+q$	$p+q$	0

The transfer rate of the harvesting robot is additionally considered for *Team*2. The moving speed of the harvesting robot is defined in the same way as that for the transporting robot. Here, $V_{m_{HR}}$ uses m/h as the moving speed of the harvesting robot. $V_{r_{HR}}$ and $T_{r_{HR}}$ are the speed and time when the harvesting robot moves from concrete to pipe or vice versa, respectively. Because the harvesting and transporting robots often use a similar moving platform, in reality, the moving speed can be considered the same as in (5)–(7) in the entire area of horticulture (pipes, concrete, etc.).

$$V_{m_{HR}} = V_{m_{TR}} \tag{5}$$

$$V_{r_{HR}} = V_{r_{TR}} \tag{6}$$

$$T_{r_{HR}} = T_{r_{TR}} \tag{7}$$

However, there is a significant difference between the transporting and harvesting robots in terms of the number of crops that can be carried at one time. The transporting speed of the harvesting robot is expressed as (8).

$$I_{T_{HR}} = \frac{2\beta_{HR} V_{m_{HR}}}{L_r + L_c + 2T_{r_{HR}} V_{m_{HR}}} \tag{8}$$

The ratio between the transporting speed of the harvesting robot, $I_{T_{HR}}$, and the transporting speed of the transporting robot, I_{TR} in (4), is simplified as the ratio of the number of crops that the loading box can carry at one time, given as (9).

$$I_{TR}/I_{T_{HR}} = \beta_{TR}/\beta_{HR} \tag{9}$$

The primary difference between *Team*1 and *Team*2 in harvesting and transporting is that *Team*1 can harvest and transport simultaneously, and *Team*2 must harvest and transport sequentially from the standpoint of each robot. However, because there are several robots, it can be regarded as a parallel operation between robots.

There are two ways to define work efficiency. The first approach is by comparing the total time to complete harvesting and transporting the entire facility horticulture with n beds, and second involves the comparison of the number of crops harvested and transported per unit time. In this study, the latter is used for the work efficiency, and the previously-described harvesting and transporting speeds are used.

To address this issue, the harvestable crops C_i of Bed_i are assumed to be the same for the whole facility. For continuous crop harvesting, it is ideal to divide the area and stagger the growth cycle of each area. However, this assumption is reasonable for areas that are harvested at once. Additionally, it is assumed that each harvesting robot is placed on an individual bed and work without interference from movement lines, considering it is $p < n$ for economic reasons, as discussed earlier.

Harvesting and transporting speeds are defined when the continuous operation assumes an ideal environment; in reality, there is no continuous operation. For *Team*1, when the buffer β_{HR} of the loading box is filled through the continuous harvesting of the harvesting robot, the transporting robot must be called to deliver the previously-harvested crops. The transporting robot takes some time to reach the harvesting robot and deliver the amount of β_{HR} crops according to the delivery mechanism. The transporting robot can prepare in advance, and this helps reduce the delivery time as soon as the harvesting robot's buffer is full. Because of the effective communication between the harvesting robot and the transporting robot, it is assumed that the time required for crop delivery is negligible.

The work efficiency, which is the crops harvested per unit of time, is defined based on the aforementioned ideal assumption. The yield considers the transport to the drop-off dock of the crop. The yield of *Team*1 is the same as that when p harvesting robots crop continuously for a unit of time. The time taken for the harvesting robot to fill the loading box buffer amount β_{HR} is the same as (10).

$$T_{\beta_{HR}} = \beta_{HR} / I_{HR} \tag{10}$$

According to this assumption, the time the transfer robot takes to transfer the crops does not affect the continuous harvest of the harvesting robot, and hence, the number of crops harvested and transferred per unit time of *Team*1 can be approximated using the following Equation (11). The work efficiency of *Team*1 is given as

$$W_{T1} = p \times I_{HR} = \frac{p\beta_{HR}}{T_{\beta_{HR}}} \tag{11}$$

*Team*2 is more complex than *Team*1. A single group of robots simultaneously performs the same harvesting and transporting tasks without the aid of transporting robots. The round-trip time for the harvesting robot to harvest and transport crops to the drop-off dock in the horticultural environment can be expressed as (12):

$$\begin{aligned} T_{t_{HR}} &= 2(\frac{L_r + L_c}{2V_{m_{HR}}} + T_{r_{TR}}) \\ &= \frac{L_r + L_c}{V_{m_{HR}}} + 2T_{r_{TR}} \end{aligned} \tag{12}$$

Therefore, W_{HR}, the amount of crop harvested and transported by one harvesting robot per unit time is as follows (13).

$$W_{HR} = \frac{\beta_{HR}}{T_{\beta_{HR}} + T_{t_{HR}}} \tag{13}$$

As the harvesting robots of *Team*2 do not interfere with each other, the crop throughput per unit time of *Team*2 is simply expressed as (14) multiplied by the total number of harvesting robots. The work efficiency of *Team*2 is defined as follows.

$$W_{T2} = \frac{(p+q)\beta_{HR}}{T_{\beta_{HR}} + T_{t_{HR}}} \tag{14}$$

However, in reality, as multiple robots are moving, the overlapping movement lines between robots may occur in the concrete area. Because it is assumed that $(p+q)$ harvesting robots start work simultaneously and the harvesting speed is the same, if they operate ideally, the harvesting robots will enter the concrete area at the same time. The interference between robots according to robot path planning is a common problem for *Team*1 and *Team*2. If there are few robots, there will be few problems. However, if the number of robots increases, a phenomenon similar to a traffic jam may occur. This problem should be analyzed in future studies, and it cannot be addressed currently because the high costs and technological limitations associated with the use of many robots in the field. The differences according to the detailed movements have been omitted and not considered in this study.

$$\frac{W_{T1}}{W_{T2}} = \frac{p}{(p+q)} \frac{(T_{\beta_{HR}} + T_{t_{HR}})}{T_{\beta_{HR}}} \tag{15}$$

Although many assumptions were made in the simplified Formula (15), the ratio of the harvest rates W_{T1} and W_{T2} of *Team*1 and *Team*2, respectively, is intuitive. *Team*1 increases the yield by reducing the time required to transport crops to the unloading dock through the transporting robot, and this is proportional to the number of harvesting robots constituting each team. $Team1$ using transporting robots is advantageous when the number of transporting robots q is small and the time $T_{t_{HR}}$ for the harvesting robot to transfer crops is long. In other words, the small number q of the transporting robots is optimal under conditions when the harvesting robot can continuously harvest, and the load capacity and transfer speed of the transporting robot are high.

3. Developing Harvesting Robot and Transporting Robot System

As mentioned previously, the high performance of the transporting robot is significantly beneficial in terms of working speed to form a team by mixing the harvesting and transporting robots. In this study, harvesting and transfer robots were developed for real implementation. The transporting robot was developed to enable continuous harvesting of up to four harvesting robots.

Figure 3 shows the developed harvesting robot. The mobile platform uses Korean company Hada's mobile robot for facility movement [17] to move pipes and concrete in the greenhouse. A 6-axis vertical articulated robot with a payload of 5 kg from Doosan Robotics [18] for crop harvesting is mounted on the mobile platform. The greenhouse working environment is tailored to humans, and the distance between the beds and the working area is narrow. Therefore, a small robot is suitable. Additionally, considering the weight of the end-effector for simple harvesting, a 5-kg payload is suitable. Tools are very important in harvesting robots. Considering there is no universal tool applicable to all crops yet, they are implemented for specific purposes based on the characteristics of crops [19]. OnRobot's commercially available soft gripper [20] was applied for the harvesting tool in this study. Given that tomatoes, which were the target crop, do not have a uniform size and shape, a soft gripper is suitable. The developed harvesting robot comprised a loading box mechanism for loading and delivering harvested crops to transporting robot. When the crops basket of the harvesting robot is full or a preset number of crops is harvested, the crops in a transporting robot are delivered to a transporting robot. Figure 4 shows the harvesting robot delivering the harvested crops to the transporting robot. The detailed procedure of crop deliver is as follows. First, in step 1, raise the crops basket from $(a)Postion$ to $(b)Postion$. Then, in step 2, the crop box of the harvesting robot is tilted and poured into the crop distributer of the transporting robot. In step 3, the crop distributer moves to an empty bin and pours the crop.

Figure 5 shows the developed transporting robot. The transporting robot is equipped with up to four loading boxes. Therefore, one transporting robot can transport the harvested crops to the unloading dock in response to multiple harvesting robots. The use of a box for human workers is more beneficial compared to other harvesting robots that use a dedicated box for harvested crops. In particular, because the loading box is used for human workers, it is possible to link human work after transfer without transitioning from robot work to human work.

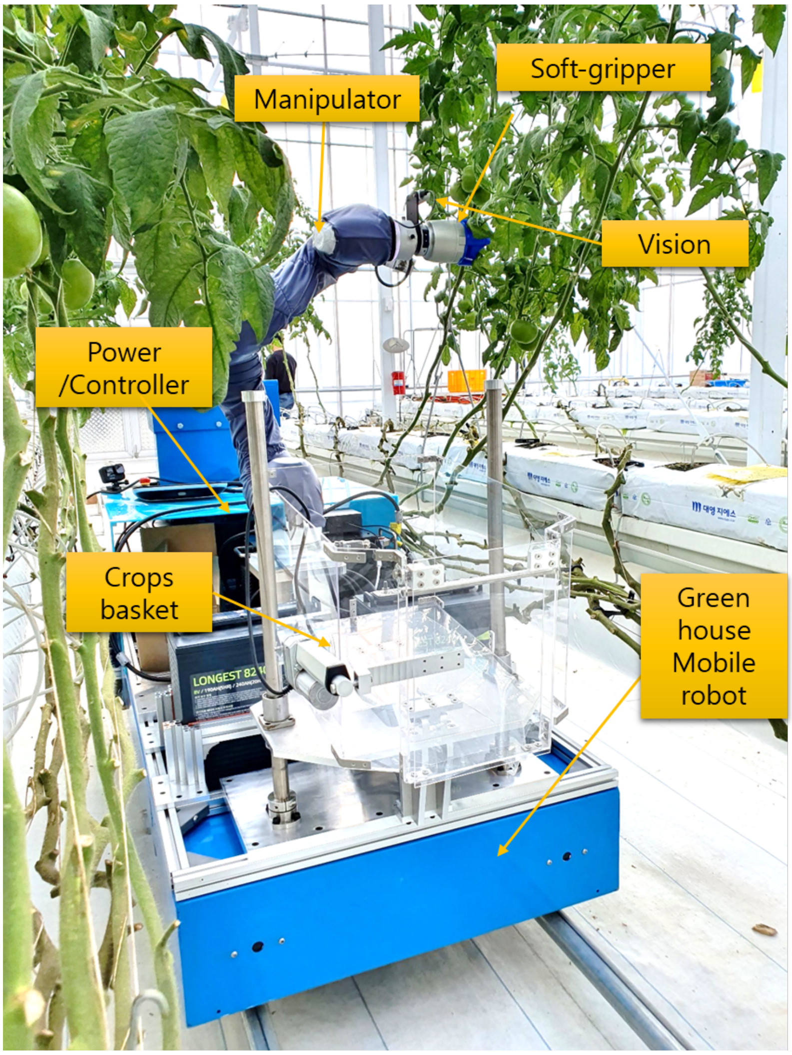

Figure 3. Developed harvesting robot with manipulator.

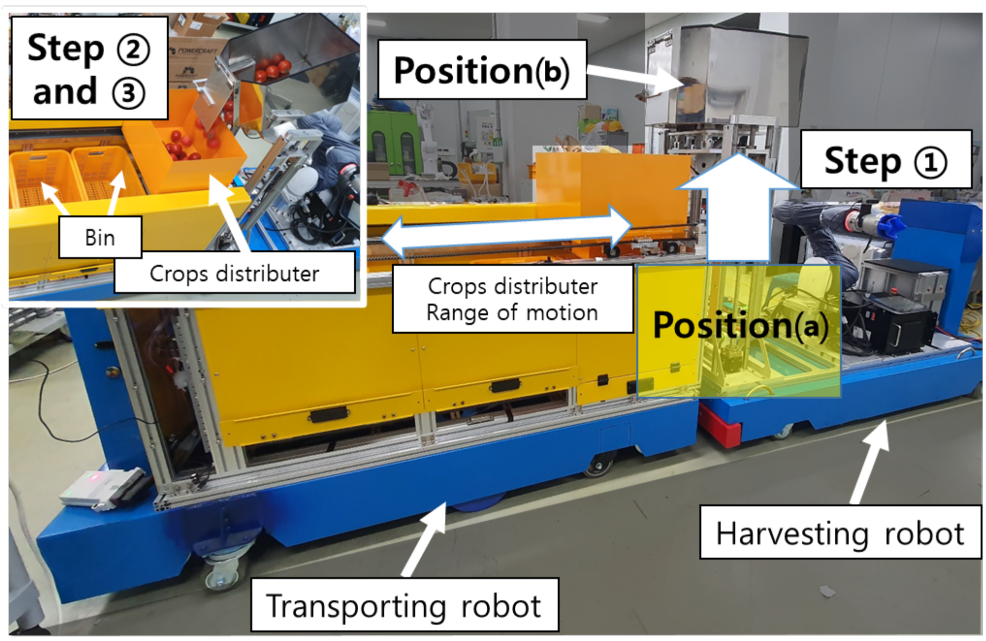

Figure 4. Harvested crops delivering from a harvesting robot to transporting robot.

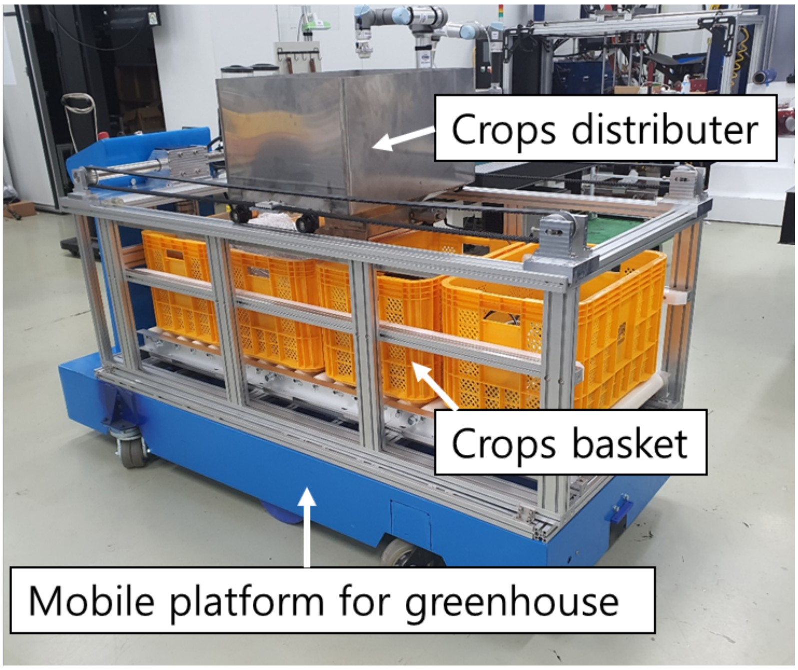

Figure 5. Developed transporting robot with four carrying box.

4. Experimental Analysis of Combined Harvesting and Transporting Robot System

In this section, we compare the work efficiency of *Team*1, which comprises a harvesting robot and a transporting robot, and *Team*2, which comprises only a harvesting robot, using actual experimental data and environmental conditions of facility horticulture.

The loading box used by human workers is aimed at simplifying the loading and unloading of crops required to transport crops and to link with subsequent operations. Therefore, the relation of $\beta_{TR} = K_b \beta_{HR}$ with respect to the natural constant K_b is established. However, in actual development scenarios, it is $K_b = 4$. To experimentally obtain $T_{\beta_{HR}}$, the time required to harvest one crop was measured, and the value was approximately 20 s. The crop harvesting procedure is programmed as shown in Figure 6. Because the robot's unit motion is determined by inputting time and target location, the time required to harvest one crop is almost the same. Figure 6 sequentially shows the required time and process for harvesting tomatoes using the developed harvesting robot. Currently, it is possible to reduce this time. According to the performance of the robot being used, less time is required for a unit operation, and the procedure for harvesting can also be simplified. However, the purpose of this study is not to shorten the harvest time but to check the efficiency when using multiple robots of different types.

β_{HR} was determined to be 20 in design and development. This value varies depending on the target crop. From the aforementioned relationship, the following conclusions are determined: $T_{\beta_{HR}} = 400\ \text{s} \cong 0.11\ \text{h}$ and $I_{HR} \cong 180\ \text{unit/h}$.

The moving speed of the developed transporting and harvesting robots is 50 m/min on flat ground. Further, the environmental variables for facility horticulture were $L_r = 40$ m, $L_t = 2.5$ m and $L_c = 20$ m, assuming a medium-sized facility. According to the experiment, the time for the transporting robot to move from the pipe to the concrete and rotate to the target angle was set to $Tr_{TR} = 3\ \text{min} = 0.05$ h. $T_{t_{HR}} = 0.12$ h according to (12). Substituting the above values into (15), we get (16).

$$\frac{W_{T_1}}{W_{T_2}} \cong \frac{2p}{(p+q)} \tag{16}$$

If we rearrange this, $p > q > 0$ is for $W_{T_1} > W_{T_2}$ and $q > p > 0$ id for $W_{T_1} < W_{T_2}$. Thus, the integration of one or more transporting robots yields a higher work efficiency than using only the harvesting robot. However, if the number of transporting robots is higher than that of the harvesting robots, the work efficiency decreases naturally. Although work efficiency modeling is simplified through many assumptions, the results confirmed through actual data are very intuitive.

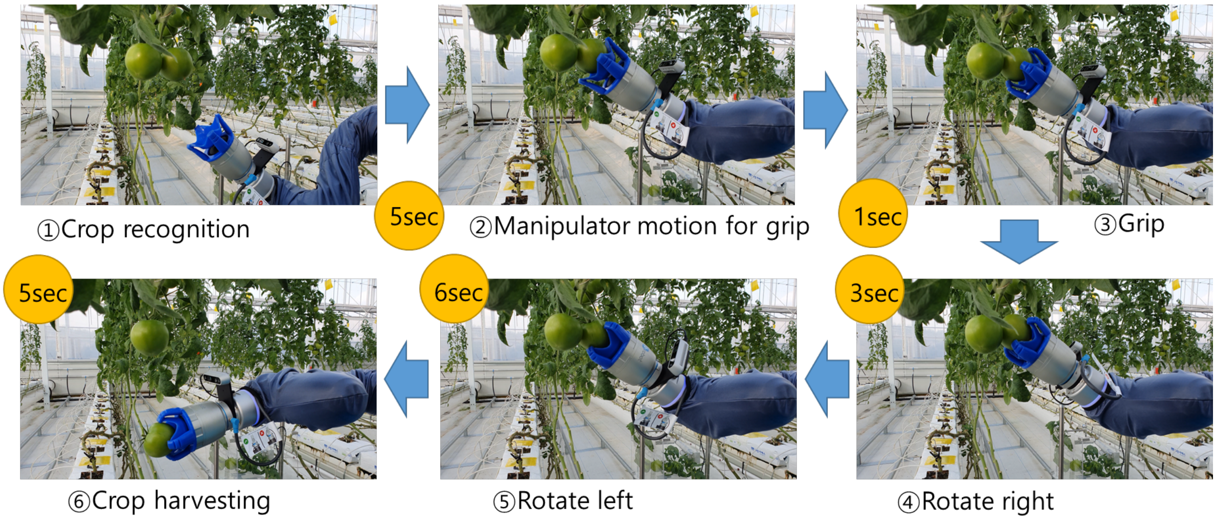

Figure 6. Crop harvesting process and speed measurement experiment using a developed harvesting robot.

Furthermore, it is possible to derive the optimal combination of harvesting and transporting robots that is ultimately required for a given facility horticultural environment by modeling the derived work speed model to represent work efficiency in detail. This optimization model study is planned as an additional study, whereas, this study is relatively limited to showing that it can be more efficient to use transporting robots than only harvesting robots.

5. Discussion

5.1. Generality of Application

This study is applicable to general smart greenhouses with rails. The two-dimensional size and the length of the bed of the greenhouse are primarily used to calculate the work efficiency. A typical smart greenhouse, shown in Figure 1, can be modeled using the method derived in this study. However, it should be noted that in practical applications, the pipe spacing of the smart greenhouse is not standardized. To address this issue, the developed mobile platform has a wheel mechanism similar to that of a train, and it can be used for various pipe spacings in the range 400–600 mm.

Work efficiency models of (11) and (14) depend on facility environment parameters and robot parameters. Harvesting work can be separated into picking and transfer, and picking is independent of the greenhouse environment. Whether the greenhouse is large or small, the harvesting procedure of the harvesting robot is the same. Transport, on the other hand, is entirely dependent on greenhouse properties such as size, beds and pipes configuration, and so on. Naturally, it takes a lot of time to transport in a large greenhouse.

Since *Team*1 is configured so that the harvesting robot can focus on only the harvesting work with the proper arrangement of the transporting robot, the work efficiency is entirely dependent on the harvesting ability of the harvesting robot. In other words, the work efficiency of *Team*1 is independent of the greenhouse environment. On the other hand, *Team*2, which consists of only harvesting robots, does not have a transporting robot, so harvesting robots must spend time to transfer. As transport is included in the work of the harvesting robot, work efficiency is dependent on the greenhouse environment. $T_{t_{HR}}$ in (14) is the greenhouse environment parameter. In any case, the proposed work efficiency modeling method is independent of specific green houses and developed robots. Related variables are summarized in Table 2.

Table 2. The work efficiency model parameters related to the greenhouse and robot.

	Work Efficiency Model	Greenhouse Parameters	Robot Parameters
*Team*1	(11)	None	β_{HR},$T_{\beta_{HR}}$
*Team*2	(14)	$T_{t_{HR}}$ of (12)	β_{HR},$T_{\beta_{HR}}$

5.2. Inaccuracy of Work Efficiency Model

There are some shortcomings in the work efficiency model. The precision of the work efficiency model was reduced by omitting and simplifying many processes for modeling the yield of the harvesting and transporting robots. A simplified model that omitted the time taken by the harvesting robot to move for harvesting and deliver the harvested crops from the harvesting robot to the transfer robot was derived, and the avoidance maneuver owing to overlapping movement lines between the robots.

There are two reasons for this simplification. First, the purpose of this study is not to derive the exact work efficiency, but to derive a suitable ratio for using a combined harvesting robot and the transporting robot system. Second, the actual harvesting work takes place all day, and the work efficiency is also defined as the yield for an hour.

For example, in the case of *Team*1, the harvesting robot calls the transporting robot in advance before the buffer is full. In the actual implementation, the buffer is 20, and the transporting robot is called at 10. Then the transporting robot puts it in the command queue and goes to the harvesting robot position as soon as possible. Therefore, when the buffer of the harvesting robot is full and crops need to be delivered, only the procedure of pouring the buffer harvested by the harvesting robot onto the transporting robot is required. Only steps 1 and 2 in Figure 4 are required. Step 3 is performed when the transporting robot moves. The time required for steps 1 and 2 was set to 40 s with a margin in the experiment. Because the main purpose is to observe the trend, this time that can be omitted from the total working time.

In future work, more precise work efficiency models for mixed robot configurations will be studied. A more accurate model can be obtained by adding factors such as the harvesting speed, moving speed, and the working speed of harvesting and transporting robots that can affect model precision. Moreover, we plan to conduct a study to obtain a proper combination of harvesting and transporting robots for a given application and facility horticulture.

6. Conclusions

This study showed that the work efficiency for harvesting crops in an entire horticulture facility could be increased by adequately mixing harvesting and transporting robots. We derived the working speed using robots for the entire facility gardening. The harvesting and transporting speeds of the harvesting and transporting robots were numerically modeled. Additionally, the work efficiency was defined for the overall operation of harvesting and transporting crops to the unloading dock using robots. By using the developed work efficiency model, we compared the work efficiency of the cases where both harvesting and transporting robots were used and only the harvesting robot was used. It was found that the case where the harvesting and transporting robots were mixed was more efficient.

In addition, the practical significance of the work efficiency model was analyzed using experimental data and practical environmental variables in facility horticulture using the developed harvesting and transporting robots.

Author Contributions: The contributions of the authors of this work are as follows: Conceptualization, T.C., J.P. and J.-J.K.; methodology, J.P. and H.S.; software, J.-J.K. and Y.-S.S.; validation, J.-J.K., H.S. and Y.-S.S.; formal analysis, T.C.; investigation, T.C. and H.S.; writing—original draft preparation, T.C.; writing—review and editing, J.P., J.-J.K. and Y.-S.S.; visualization, T.C.; supervision, T.C.; project administration, T.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through Advanced Agricultural Machinery Industrialization Technology Development Program, funded by Ministry of Agriculture, Food and Rural Affairs (MAFRA) (321059-2).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Karanisa, T.; Achour, Y.; Ouammi, A.; Sayadi, S. Smart greenhouses as the path towards precision agriculture in the food-energy and water nexus: Case study of Qatar. *Environ. Syst. Decis.* **2022**, *42*, 521–546. [CrossRef]
2. Syed, A.M.; Hachem, C. Review of construction; geometry; heating, ventilation, and air-conditioning; and indoor climate requirements of agricultural greenhouses. *J. Biosyst. Eng.* **2019**, *44*, 18–27. [CrossRef]
3. Vrchota, J.; Pech, M.; Švepešová, I. Precision Agriculture Technologies for Crop and Livestock Production in the Czech Republic. *Agriculture* **2022**, *12*, 1080. [CrossRef]
4. Vatavuk, I.; Vasiljević, G.; Kovačić, Z. Task Space Model Predictive Control for Vineyard Spraying with a Mobile Manipulator. *Agriculture* **2022**, *12*, 381. [CrossRef]
5. Zhang, B.; Chen, X.; Zhang, H.; Shen, C.; Fu, W. Design and Performance Test of a Jujube Pruning Manipulator. *Agriculture* **2022**, *12*, 552. [CrossRef]
6. Liu, C.; Feng, Q.; Tang, Z.; Wang, X.; Geng, J.; Xu, L. Motion Planning of the Citrus-Picking Manipulator Based on the TO-RRT Algorithm. *Agriculture* **2022**, *12*, 581. [CrossRef]
7. Arad, B.; Balendonck, J.; Barth, R.; Ben-Shahar, O.; Edan, Y.; Hellström, T.; Hemming, J.; Kurtser, P.; Ringdahl, O.; Tielen, T.; et al. Development of a sweet pepper harvesting robot. *J. Field Robot.* **2020**, *37*, 1027–1039. [CrossRef]
8. RootAI. Strawberry Harvesting Robot-Intelligent Motion. 2022. Available online: https://root-ai.com/#tech (accessed on 10 September 2022).
9. Bagagiolo, G.; Matranga, G.; Cavallo, E.; Pampuro, N. Greenhouse Robots: Ultimate Solutions to Improve Automation in Protected Cropping Systems—A Review. *Sustainability* **2022**, *14*, 6436. [CrossRef]
10. Oliveira, L.F.; Moreira, A.P.; Silva, M.F. Advances in agriculture robotics: A state-of-the-art review and challenges ahead. *Robotics* **2021**, *10*, 52. [CrossRef]
11. Bac, C.W.; Hemming, J.; Van Tuijl, B.; Barth, R.; Wais, E.; van Henten, E.J. Performance evaluation of a harvesting robot for sweet pepper. *J. Field Robot.* **2017**, *34*, 1123–1139. [CrossRef]
12. Choi, T.; Park, J.W.; Kim, J.J.; Shin, Y.S. Development of greenhouse crop harvesting system using multiple robots. In Proceedings of the 21st International conference on Control, Automation and Systems, Jeju, Korea, 12–15 October 2021.
13. Woo, S.; Uyeh, D.D.; Kim, J.; Kim, Y.; Kang, S.; Kim, K.C.; Lee, S.Y.; Ha, Y.; Lee, W.S. Analyses of work efficiency of a strawberry-harvesting robot in an automated greenhouse. *Agronomy* **2020**, *10*, 1751. [CrossRef]
14. Lytridis, C.; Kaburlasos, V.G.; Pachidis, T.; Manios, M.; Vrochidou, E.; Kalampokas, T.; Chatzistamatis, S. An Overview of Cooperative Robotics in Agriculture. *Agronomy* **2021**, *11*, 1818. [CrossRef]
15. Mao, W.; Liu, Z.; Liu, H.; Yang, F.; Wang, M. Research progress on synergistic technologies of agricultural multi-robots. *Appl. Sci.* **2021**, *11*, 1448. [CrossRef]
16. Krizmancic, M.; Arbanas, B.; Petrovic, T.; Petric, F.; Bogdan, S. Cooperative aerial-ground multi-robot system for automated construction tasks. *IEEE Robot. Autom. Lett.* **2020**, *5*, 798–805. [CrossRef]
17. HADA. Full Automatic Robot Sprayer. 2022. Available online: http://hada-korea.com/eng/product/full_automatic_robot_sprayer.php (accessed on 10 September 2022).
18. DoosanRobotics. M0609. 2022. Available online: https://www.doosanrobotics.com/en/products/series/m0609 (accessed on 10 September 2022).
19. Seol, J.; Lee, S.; Son, H.I. A review of end-effector for fruit and vegetable harvesting robot. *J. Korea Robot. Soc.* **2020**, *15*, 91–99. [CrossRef]
20. Onrobot. Soft Gripper. 2022. Available online: https://onrobot.com/en/products/soft-gripper (accessed on 10 Septemer 2022).