Indoor Hydroponics Robot System for Automated Seeding and Logistics

Hon Kit Hui [1], Jimmy H. M. Lee [1], Anthony K. W. Sum [1] and Darwin Lau [2]

***Abstract*— In recent years, indoor hydroponics farming has been a promising new mode to ensure stable and increased density food production regardless of weather and location. However, the lack of development of hydroponic robot systems limit the automation of smaller space indoor environments where automated hydroponic mechatronic racks are not suitable nor economical. This work presents an automated robot system for exactly this purpose. It comprises of: 1) a seeding end-effector for 6 degree-of-freedom robot arms to plant small seeds; 2) a mobile robot tray logistics robot; and 3) an automated software to schedule and operate the system. The novel robot system has been implemented and in operation for over 2 years at the Controlled Environment Hydroponic Research and Development Centre in Hong Kong, showing its efficacy to minimise human labour and increase efficiency.**

Fig. 1. Developed Hydroponics Robot System

I. Introduction

Agriculture and farming play an important role in providing a stable food source for human beings. Historically, the farming of crops have required a significant amount of manpower, complex number of steps, and large amounts of land area. Moreover in recent years, the urbanisation of cities, shortage of farmers, global warming and changes in the climate have placed burden on the supply of food through traditional farming on the fields.

As such, modern farming concepts, such as indoor hydroponics and vertical farming, have been increasingly popular [1]. Hydroponics refer to the plant growing method that substitutes the soil by water, with their roots submerged in water added with nutrients. One significant advantage of hydroponics is that it can be grown all year round indoors, regardless of climate and weather conditions. While growing indoors, vertical farming stacks the plants in trays and hence allows an increased farming density.

Furthermore, indoor hydroponics create the possibility for fruits and vegetables to be produced in buildings within cities, in a distributed manner compared with farming on the fields. This is particularly for high density cities with a shortage of land, such as in Hong Kong. However, indoor hydroponics still involves vast amounts of manpower and complex tasks within the agriculture cycle, including seeding, germination, fertigation, moving and harvesting. As such, the use of automation and robotics within hydroponic farms has been of interest to farmers.

Over the years, the development of hydroponic automation and robots have taken two primary directions, either robots that perform individual tasks and complete mechatronic rack systems. Individual task specific robots aim to perform specific actions within the hydroponics workflow, such as harvesting [2], [3], [4], [5] and transplanting [6], without integration into a complete system. On the other hand, complete systems are typically mechatronics systems that are integrated into the racks that store the trays of the plants [7], [8]. Although efficient and able to complete a broader range of tasks within the complete flow, complete systems typically are more expensive and more suited to large-scale farming. Table I presents a comparison of the capabilities and space requirement of different hydroponics systems.

	Sowing Capability	Transplanting Capability	Harvesting Capability	Space Requirement	Crop Versatility
[2]	No	No	Yes	N/A	Strawberry
[3]	No	No	Yes	N/A	Lettuce
[4]	No	No	Yes	N/A	Fruit Vegetables
[8]	No	Yes	No	Large	Leafy Vegetables
Ours	Yes	Yes	No	Small	Leafy Vegetables

TABLE I

Comparison of different hydroponics system

In summary, there are several outstanding challenges involved in hydroponic farming within smaller space environments. First, the lack of space, both floor space and interior height, makes it uneconomical to deploy existing automated hydroponic farming systems. Second, the limited floor space makes it difficult for robot, and particularly multiple robots

[1]H. K. Hui, J. H. M. Lee and A. K. W. Sum are with the Department of Computer Science and Engineering, The Chinese University of Hong Kong, Hong Kong, 1155064769@link.cuhk.edu.hk, jlee@cse.cuhk.edu.hk, kwsum@cse.cuhk.edu.hk

[2]D. Lau is with the Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, darwinlau@cuhk.edu.hk

to operate within. Third, the seeding operation is challenging to automate, as the seeds for hydroponic plants, such as ice lettuce and baby watercress, are particularly small.

In this paper, an automated robotic system for hydroponic farming in smaller indoor environments is presented. The developed system consists of three primary components: a) seeding robot system to automatically plant small seeds onto trays (Section III); b) logistics system using multiple mobile robots move the trays of seeds and plants around the different stations of the hydroponics farm (Section IV); and c) robot management system that is responsible for commanding and scheduling the robots (Section V). The developed robot system is economical to deploy, suitable specifically for hydroponic plants and a completely integrated system that can complete the entire workflow autonomously. This paper presents the novel mechanisms related to the seeding robot and logistics robot, and the algorithms and software developed to realise the required operations.

II. Overall System and Site Description

This section will describe the various operations required to be performed by the robot system and the proposed layout of the testing environment.

A. Robotic Operations for Indoor Hydroponics Centre

The indoor hydroponics farming process involves the following stages:

1) The sowing of seeds onto a wet sponge fitted within a tray (*seeding station*). A typical tray is 600 mm x 600 mm and contains approximately 560 seed locations.
2) After sowing, the tray is then placed in a dark *germination chamber* for 3-4 days to stimulate germination.
3) After germination occurs, the young plants are transferred to a specially designed rack with LED lights and a nutrient solution (*growing rack*). The LED lights provide the necessary spectrum for photosynthesis, while the nutrient solution ensures the plants receive essential minerals directly at their roots. Depending on the plant species, this growing stage can last several weeks to months.
4) When the plants reach maturity and are ready for harvesting, they are removed from the rack and transferred to a designated harvest area. Here, the plants are meticulously cut, cleaned, and prepared for either consumption or sale.

The proposed hydroponic system aims to automate the seeding and logistics of moving of trays between the different stations (seeding, germination and growing rack). To achieve this, a seeding robot arm, a system of multiple mobile robots and additional automation components located at the stations, were developed.

B. Layout of the Indoor Hydroponics Centre

Figure 2 shows the floor plan of the robot test site, the Controlled Environment Hydroponic Research and Development Centre (CEHRDC) at the Vegetable Marketing Organisation (VMO) in Hong Kong. Although the developed system can be applied at different hydroponic setups, as described in Section V, the tight-spaced like at the CEHRDC is common in Hong Kong. With the lack of space, it would be difficult to install complete mechatronic automated racks.

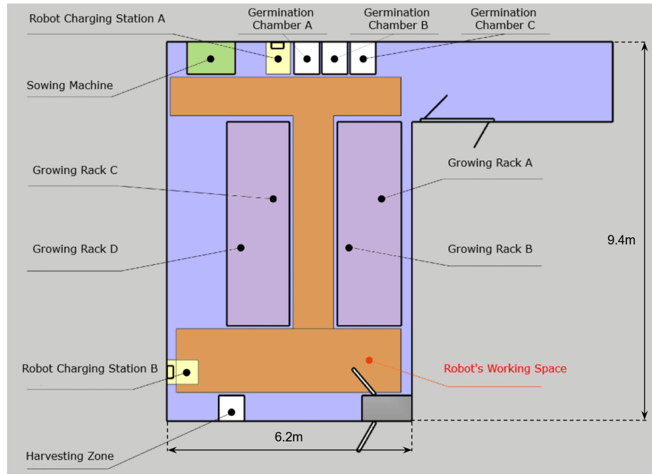

Fig. 2. Floor plan within the CEHRDC

At the CEHRDC, the approximately 36 m^2 area is designed to house one seeding station, three germination chambers, four growing racks and two mobile robot charging stations. This leaves a limited pathway remaining for the mobile robots to operate within. Figure 3 shows the arrangement of the CEHRDC in isometric view.

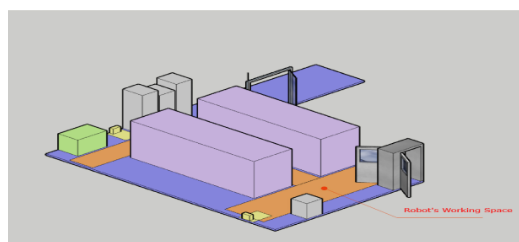

Fig. 3. 3D view schematic of the indoor hydroponics setup

III. Seeding Robot System

As described in Section II, plants are grown on trays within growing racks. As such, the first step of the growing process is to place the small seeds within a tray. To facilitate the growing with sufficient space, the seeds must be accurately placed within evenly spaced locations on a piece of wet sponge within the tray. An important challenge within the seeding process to deal with smaller seeds, such as those 1 - 2mm in diameter.

As existing tray seeding machines typically place much larger seeds of approximately 5mm, they cannot be used for smaller seeds. As such, the seeding process at the CEHRDC was performed completely manually with human workers using assistive equipment. However, the process is labour intensive and it is difficult to ensure that only 1 or 2 seeds are placed within each seeding location. This motivates the need of an automated robotic solution.

The novel developed system that can handle small seed planting, shown in Figure 4, consists of three components, a 6 degree-of-freedom robot arm, a custom designed seeding end-effector and a camera. The robot arm is responsible for moving to different specific locations above the tray for seeding the aid of the camera. The end-effector contains the seeds and is responsible for seed placement.

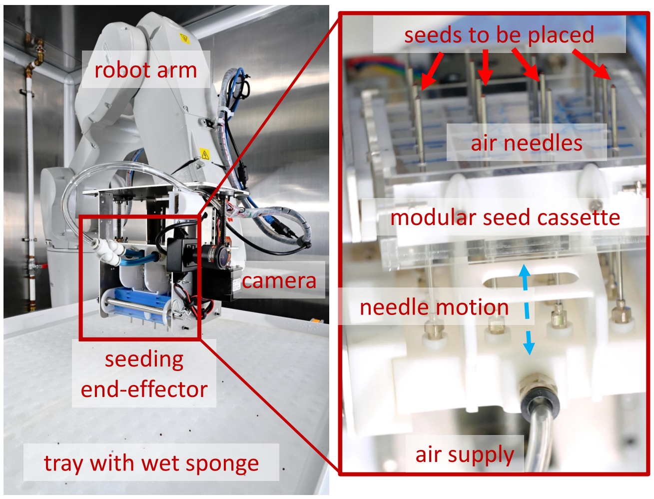

Fig. 4. Seeding robot: overall system (left) and seeding end-effector (right)

A. Modular Seeding End-Effector

As shown in the right side of Figure 4, the seeding end-effector consists of 3 components: a) modular seed cassette; b) air supply; and c) an array of needles connected to the air supply that can move up and down. The modular cassette stores the seeds to be planted, and houses an array of needs that can move in and out of the cassette. In the developed robot, each cassette contains 16 needles arranged in a 4 x 4 grid. The modular cassette allows different types of seeds to be planted to be easily interchanged during operation.

To enable the planting of small seeds, the seeding operation consists of two steps as shown in Figure 5:

1) The end-effector is initially in the upward posture, where the needle is pointing upwards and moves from inside the cassette to outside in order to push a single small seed per needle. The air supply is then enabled to ensure that every seed remains with the needles.
2) Next, the end-effector is rotated downwards by the robot arm. Subsequently, the seeds are planted onto the seed locations of the tray by turning off the air supply when the robot arm is in the correct position.

Note that the array of needles is to improve the seeding efficiency, where a larger number of needles increase efficiency, while at the same time limiting the flexibility of seeding. The distance between the needles are designed to match the interval between seeds on the tray.

B. Seeding Placement Algorithm

As the sponge within the tray is flexible and the dimensions are smaller than the tray, the sponge may deform and be displaced within the tray. As such, the developed robot uses the attached camera in order to determine the most suitable position of the robot arm for seeding.

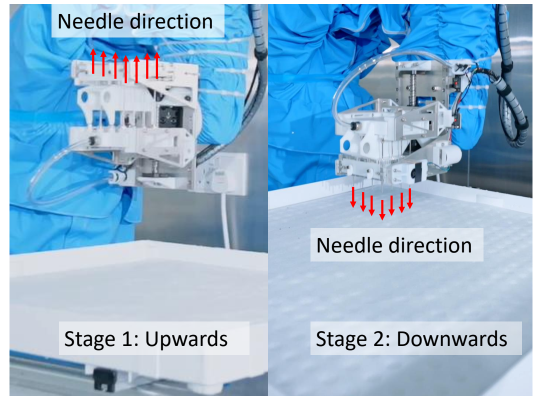

Fig. 5. Design of seeding end-effector

When initially setting up the robot arm, a transformation matrix T_0, referred to the transformation between the base of the robot arm and a reference tray image, must be determined (Figure 6). For every new tray, the system will first take an image of the tray and use Hough Circle Transform to find the hole locations. Then, the robot arm coordinate for each hole is defined as

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = T_0 T_p \begin{bmatrix} u \\ v \\ 1 \\ 1 \end{bmatrix}$$

where T_p is the transformation matrix that transforms a point from input to reference image space. Since it is a point cloud registration problem, Iterative Closest Point (ICP) [9] algorithm will be used to find T_p.

The ICP algorithm iteratively refines an initial guess of the transformation matrix T_p to align the points in input image to the points in reference image. In each iteration, the algorithm identifies the closest points between the transformed points set and reference point set, computes an error metric

$$E(T_p, \mathscr{P}_r, \mathscr{P}_t) = \frac{1}{n} \sum_{\mathbf{x} \in \mathscr{P}_t} \| T_p \cdot \mathbf{x} - n(\mathbf{x}, \mathscr{P}_r) \|^2$$

where $\mathscr{P}_r$ and $\mathscr{P}_t$ are the point set from reference image and input image, respectively, and the $n()$ function is used to find a point in reference image that is closest to a given point in input image. The error function is iteratively minimized to find the optimal transformation matrix T_p. Figure 7 shows the process and the result of ICP.

Using the seeding algorithm, our experiments show that over 95% of the seed can be placed in the sponge hole. Figure 8 shows an example result of seeding on the tray.

IV. Hydroponics Tray Logistics

As introduced in Section II, the movement of trays between the different chambers and growing racks require the development of a mobile robot to load and unload the trays.

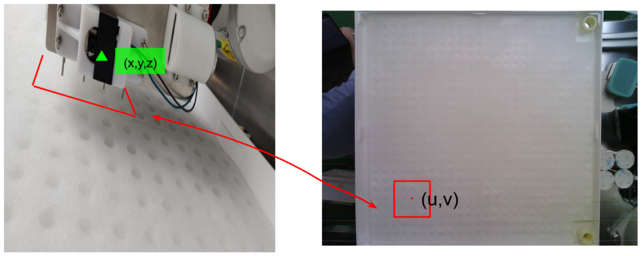

Fig. 6. Manually record robot arm's coordinate (x,y,z) and the corresponding reference image's coordinate (u,v) to compute matrix T_0

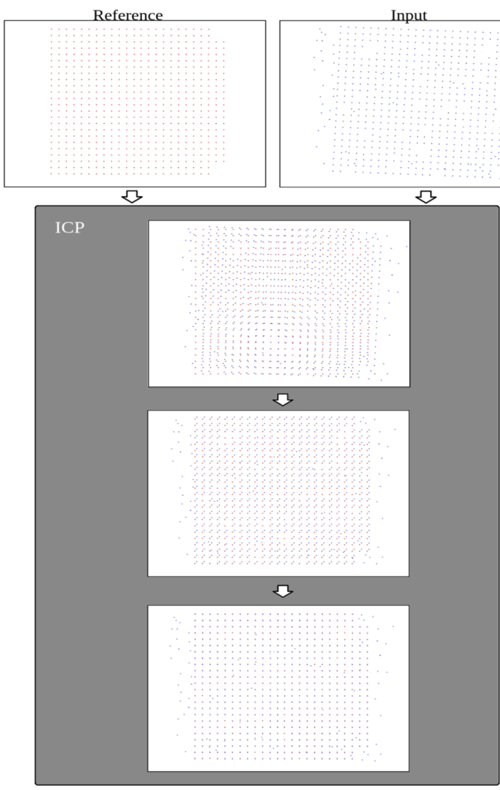

Fig. 7. ICP algorithm takes the reference point set (red dot) and the input point set (blue dot) as input. It will iteratively align the two sets to minimize the error.

As shown in Figure 9, the designed robot system must meet the following requirements:

- The mobile robot must be small in dimension (650mm x 650mm) in order to navigate within the tight indoor space with pathways of approximately 1m in width.
- The robot must be able to raise and lower trays as the growing racks are arranged to store 4 trays vertically.
- The mobile robot and growing rack is arranged such that the robot must push the tray to load on one side of the growing rack, and to pull on the tray to unload on the other side.

A. Docking Algorithm

For the mobile robots to successfully load and unload the trays from the chambers and growing racks, it must be able

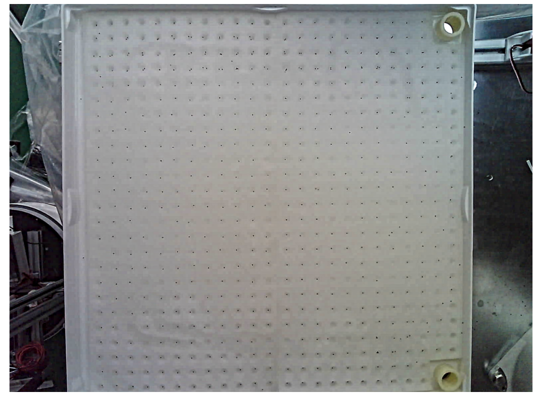

Fig. 8. Result of the seeding

Fig. 9. Logistics mobile robot for tray moving

to accurately dock in front of the rack first. To minimise the robot position offset, AprilTags Visual Fiducial System [10] is used and placed at the bottom part of every docking location. Figure 10 shows examples of the placement of the tags. AprilTag detection allows the precise relative translation and rotation between the robot and tag to be computed.

The docking process can be broken into three parts. First, the system will estimate a trajectory to align with the predefined docking point for the mobile robot. Then, the system will check whether the alignment is suitable for docking. If not, the robot will move backward to ensure enough space, generating a new trajectory. The robot will keep correcting its position until it has a good alignment. Typically, the robots can align with the docking point within one to two correction steps. When the alignment is suitable, the robot will move forward and dock. Figure 11 shows the whole docking process.

B. Multiple Robot Collision Avoidance

A centralized server is used to cooperate with the multiple mobile robots. The server will plan the robot's path and ensure there won't be any conflict between the robot's trajectories. An undirected graph is used for the path planning

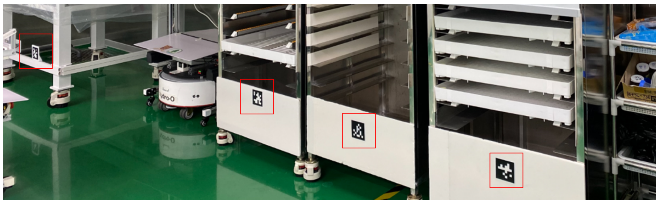

Fig. 10. The tag placement of the sowing machine and the germination chambers (red box)

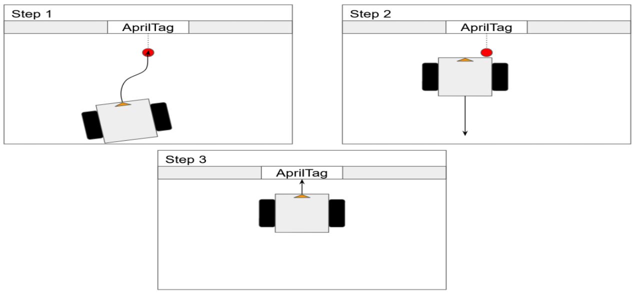

Fig. 11. Possible trajectory for every docking step. The arrow is the trajectory, and the red circle is the predefined docking point

to mimic the railroad system. Every vertex in the graph is a station, and every edge is a rail connected two station. The robot will follow the edge and pass the intermediate vertices until it reaches the destination vertex. Figure 12 shows the undirected graph used for the system.

Using a graph can reduce the search space path planning and speed up the planning process. The server only needs to find the shortest path between the starting and destination vertex. Once the path is found, all the vertex the robot will pass will be marked as occupied. The vertex will be released when the robot passes it. With the occupation mechanism, a collision can be avoided during path planning. Algorithm 1 is the pseudocode of the path planning algorithm.

Algorithm 1: PathPlanning

Data: graph G, current position P, destination D, list of occupied vertex V_o
Result: set of vertex S_v
$S_v \leftarrow \{\}$;
$temp_g \leftarrow RemoveOccupiedVertex(G, V_o)$;
$S_v \leftarrow Dijkstra(temp_g, P, D)$; `/* use Dijkstra's Algorithm to find the shortest path */`
if S_v *is not empty* **then**
  return S_v;
end
$WaitVertex()$; `/* Wait for vertex to be released */`
$V_o \leftarrow UpdateVertexList()$;
$PathPlanning(G, P, D, V_o)$

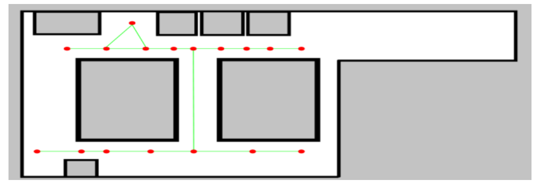

Fig. 12. The red circles and the green lines are the vertices and edges of the undirected graph respectively.

V. Robot Management and Scheduling

With the seeding and logistic robots presented above, it is important to develop an intuitive interface for the end-users, such as the Vegetable Marketing Organisation, to operate the robot system by themselves. Furthermore, rather than directly commanding the motion of the robot, a task scheduling system was developed to allow the routine for seeding, growing and harvesting, to be entered into the system.

A web-based management system was built to allow the user to operate the hydroponics system and examine the status of every plant. Figures 13, 14, and 15 show the user interface of the dashboard, data, and schedule, respectively. The functions of each page will be explained below.

The dashboard (Figure 13) shows the tasks that will be executed today. The system will keep updating the progress bar of every task to keep the user updated, and the status of the machine and mobile robots.

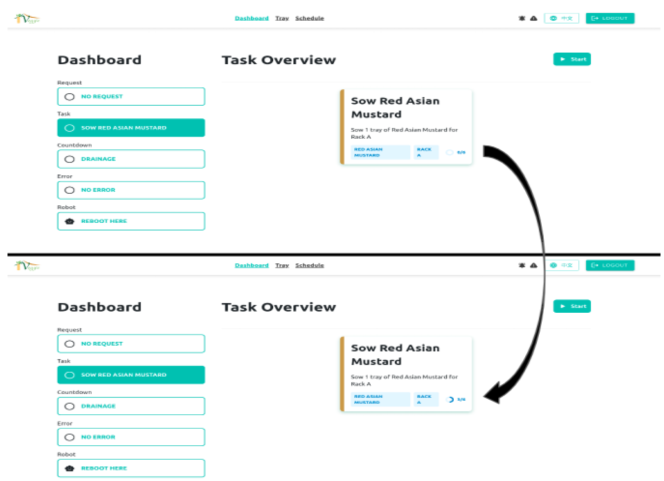

Fig. 13. The dashboard page shows the details of the tasks that will be executed today. The progress bar at the bottom right corner will be updated when a sub task is done.

The tray page (Figure 14) lists the information on every tray inside the germination chambers and racks. This information includes the tray location, plant species and growing day, which is helpful for the user to plan the daily tasks. If the user wants to review the past data, the historical harvest records are also available on the page.

The schedule page (Figure 15) shows every day's tasks, and the user can create new tasks for today or a later date. Every possible action for a task is already set as a predefined option, so typing is minimized.

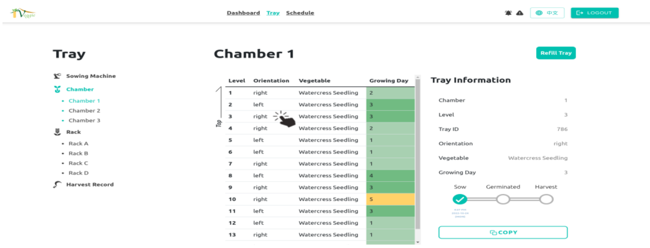

Fig. 14. Users can check the status of the trays inside the chambers and racks on the Tray page. In addition, historical harvest records can be viewed as well.

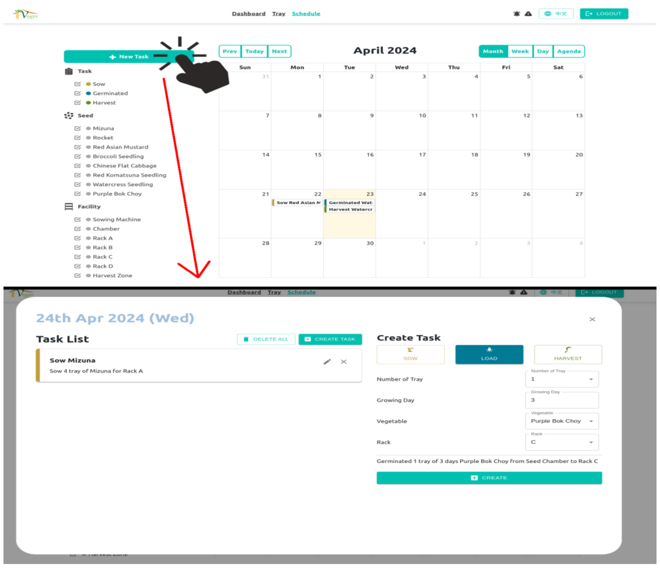

Fig. 15. On the Schedule page, the user can view and plan the daily tasks for the system to execute. When the "New Task" button is clicked, a popup box (bottom) will appear. The user can input the task requirements and create the task in that box.

To increase productivity, each task has a different priority level, and the system will schedule the task execution order based on that. Since the sowing machine can work in parallel with mobile robots, the tray transport task related to the machine has the highest priority to ensure the sowing machine is not idle. Besides that, harvest-related tasks have the second priority because the racks are always in full load.

VI. Discussion

Originally designed for the CEHRDC, the system's true strength lies in its adaptability. It can seamlessly transition to hydroponic farms of all sizes. For larger operations, the system can effortlessly scale up by adding more facilities and mobile robots. The beauty of this design is that the sowing and transplanting functions are independent modules, allowing smaller hydroponic farms to choose between the sowing machine or the mobile robot, depending on their needs.

The system has two potential areas for improvement. The first limitation is the adaptability of the shape of the seed. Currently, the sowing machine can only work on the round-shaped seeds. If the seed is in an oblong or bean shape, the seed may jam inside the seed cassette. The other limitation is the need for harvesting capability. A complex harvesting machine is needed to handle various crops, but the testing site has no free space. Future work could address these limitations to optimize the system further for broader applications.

VII. Conclusions

This paper presents a novel robot system for indoor hydroponics farming, including the planting of small seeds, movement of trays between chambers and growing racks, scheduling of robot tasks. The developed system was deployed at the VMO CEHRDC since 2021 and has been in daily operation to help in minimising human labour, increase seeding accuracy and operational efficiency. Future work will focus on expanding the range of tasks for the system, such as pollination, harvesting and packaging.

Acknowledgement

This work was supported by and conducted in collaboration with the Centre of Controlled Environment Hydroponic Research and Development Centre (CEHRDC), a joint initiative by the Vegetable Marketing Organisation (VMO) and the Agriculture, Fisheries and Conservation Department (AFCD), HKSAR Government. Moreover, robot photos in the paper were kindly provided by the VMO. Finally, acknowledgements go to James S. C. Lam, John Lau, Echo Y. F. Lam, Tim X. Hou, Roy C. C. Cheung and Ken Kwok for their contribution to the robot development.

References

[1] M. A. N. Sashika, H. W. Gammanpila, and S. V. G. N. Priyadarshani, "Exploring the evolving landscape: Urban horticulture cropping systems–trends and challenges," *Sci. Hortic.*, vol. 327, p. 112870, 2024.

[2] N. Kondo, M. Monta, and S. Arima, "Strawberry harvesting robot on hydroponic system," in *IFAC Artificial Intelligence in Agriculture*, 1998, pp. 181–185.

[3] V.-C. Pham, H.-G. Nguyen, T.-K. Doan, and G.-B. Huynh, "A computer vision based robotic harvesting system for lettuce," *Int. J. Mech. Eng. Robot. Res.*, vol. 9, no. 11, pp. 1526–1531, 2020.

[4] V. Rajendran, B. Debnath, S. Mghames, W. Mandil, S. Parsa, S. Parsons, and A. Ghalamzan-E., "Towards autonomous selective harvesting: A review of robot perception, robot design, motion planning and control," *J. Field. Robot.*, pp. 1–33, 2023.

[5] "Implementation of inverse kinematics for crop-harvesting robotic arm in vertical farming," in *IEEE Int. Conf. Cyber. Intelli. Syst. (CIS) and IEEE Conf. Robot. Autom. and Mechatron. (RAM)*, 2019, pp. 298–303.

[6] B. Li, S. Gu, Q. Chu, Y. Yang, Z. Xie, K. Fan, and X. Liu, "Development of transplanting manipulator for hydroponic leafy vegetables," *Int. J. Agric. Biol. Eng.*, vol. 12, no. 6, pp. 38–44, 2019.

[7] A. Shrivastava, C. K. Nayak, R. Dilip, S. R. Samal, S. Rout, and S. M. Ashfaque, "Automatic robotic system design and development for vertical hydroponic farming using iot and big data analysis," *Mater. Today.-Proc.*, vol. 80, pp. 3546–3553, 2023.

[8] H. Ohara, T. Hirai, K. Kouno, and Y. Nishiura, "Automatic plant cultivation system (automated plant factory)," *Environ. Control Biol.*, vol. 53, no. 2, pp. 93–99, 2015.

[9] P. Besl and N. D. McKay, "A method for registration of 3-d shapes," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 14, no. 2, pp. 239–256, 1992.

[10] E. Olson, "Apriltag: A robust and flexible visual fiducial system," in *2011 IEEE International Conference on Robotics and Automation*, 2011, pp. 3400–3407.