Agricultural weed control by a swarm of robots

Glenn R. Varhaug[1†], Jarle Dørum[2], Jan Tommy Gravdahl[1], Elias Prytz[2], and Henrik Vasbotten[2]
[1]Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway
(E-mail: {glenn.r.varhaug, jan.tommy.gravdahl}@ntnu.no)
[2]Kilter AS, Berghagan 3, 1405 Langhus, Viken, Norway
(E-mail: {jarle.dorum, elias.prytz, henrik.vasbotten}@kiltersystems.com)

Abstract: Herbicide application in agriculture is an effective means for combating weeds. The weed control problem can be solved with a fully autonomous precision spraying robot. In order to decrease the time spent on herbicide application, a swarm robotic solution using the AX-1 robot has been developed. The solution involves field decomposition, workload distribution, and path planning. Results show that the effect of increasing the number of robots in the swarm reduce the time spent in the field for all fields tested, regardless of size and complexity. The results do however point to distance alone being insufficient as a sole criterion for workload distribution, prompting future research to investigate how to gather a weed density distribution before performing workload distribution.

Keywords: Swarm robotics, agricultural robotics, weed control, herbicide.

1. INTRODUCTION

Herbicide usage in agriculture is necessary to combat invasive weeds which compete with the crop plants for moisture, nutrients and sunlight. The over-use of herbicides has led to some weeds evolving to become herbicide resistant [1]. Kilter's AX-1 robot (Figure 2) offers a solution to the problem by introducing a Drop-on-Demand (DoD) herbicide application system, reducing the herbicide usage by up to 95% compared to traditional methods, as well as increasing the crop yield by up to 35% [2]. The DoD system selectively applies single herbicide droplets to weed leafs only, by using machine vision to distinguish between crop plants and weeds [3].

Fig. 1 The AX-1 robot. Image courtesy of Kilter AS.

Robotic solutions are being used to solve a plethora of problems within agriculture. In [4], ten emerging technologies within the field of smart agriculture, two of them being ”swarm intelligence” and ”robots and autonomous systems” were identified.

Swarm robotic solutions, a recent overview of the state of the art is provided in [5], are already in use within agriculture [6, 7], and solutions are employed in areas such as: mapping and remote sensing, seeding, weed detection and spraying, irrigation, fertilization, phenotyping, and harvesting [6].

This paper introduces a method for solving an agricultural weeding task for row crops using a swarm of AX-1 [2] robots. The method is generalizable and can be used on fields of any size and complexity.

Fig. 2 A preliminary test of the swarm concept. Image courtesy of Kilter AS.

2. WORKLOAD DISTRIBUTION

The workload distribution consists of two parts, the initial field decomposition and the actual distribution of the field. In the following, we will introduce two real agricultural fields, for the purpose of this paper named the Simple field and the Complex field, as well as a virtual field, the Mega field. These fields will be used for demonstrating the proposed methods.

---

† Glenn R. Varhaug is the presenter of this paper.

2.1. Field decomposition

Two methods are presented in order to decompose the field into distributable sections. The first method uses the Modified Boustrophedon Cellular Decompositon (MBCD) [8] which is developed based on the Boustrophedon Cellular Decomposition (BCD) method [9]. The MBCD method allows the use of BCD on fields with predetermined row segments, i.e. row-crop fields. The method decomposes the field into separate areas that are continually traversable within two headland areas called b-cells. The headland is the area around the field where there is no crops and the robot can use for turning maneuvers. See Figure 3 where the MBCD method is demonstrated on the Simple field.

The second method decomposes the field into its constituent row segments (Figure 4). This method allows for better distribution resolution as will be seen in the following section.

2.2. Distribution of field

The purpose of distributing the workload among the robots is to reduce the total time of completion as much as possible. In order to reduce the time of completion, the robots should all complete their assigned areas within an equal amount of time. Given what is known in advance about the field, which is only the field geometry, the total distance assigned to each robot is the best criterion for distribution [10, 11]. In order to maximize the possibility of evenly distributed area, the single-row segment decomposition method is preferred over the MBCD method.

Two algorithms are proposed as methods for distributing the workload based on distance. The first algorithm is called the *Greedy* workload distribution algorithm, and it simply assigns the longest segment to the robot which currently has the shortest total area. Figures 5 and 6 show the distribution results using the *Greedy* algorithm for the Simple and Complex fields, respectively. Figure 7 shows an algorithmic description of the algorithm.

The second algorithm, called the *Ordered Absolute* workload distribution algorithm assumes a meaningful sorting of the segments. The meaningful sorting in this case is the distance from the right-most row segment to all other segments. The first robot is then assigned each row until the assigned distance is at about D/n, where D is the total distance of all rows, and n is the number of robots. For each row, a check is made which assesses whether adding a new row to the distribution of the robot will increase or decrease the absolute difference between the distribution and D/n. Once the difference increases rather than decrease, the distribution for the robot is complete, and the next robot's distribution begins. Figures 5 and 8 show the results of the *Ordered Absolute* algorithm for the Simple and Complex fields, respectively. Figure 10 shows an algorithmic description of the algorithm.

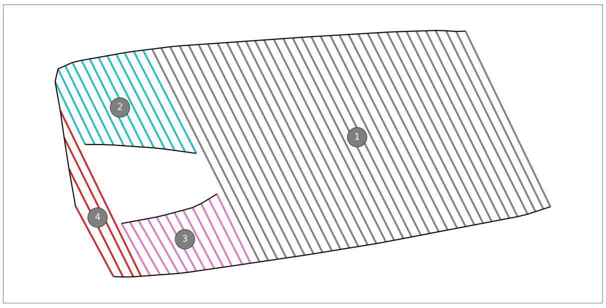

Fig. 3 The Simple field decomposed into four b-cells using the MBCD method.

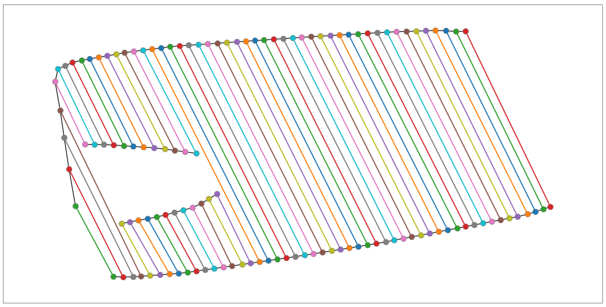

Fig. 4 The Simple field decomposed into constituent row segments.

The *Greedy* algorithm minimizes the difference in distance for the robots. However, it often leads to highly unstructured distributions. The *Ordered Absolute* algorithm however, ensures structured distribution at the cost of distance equality.

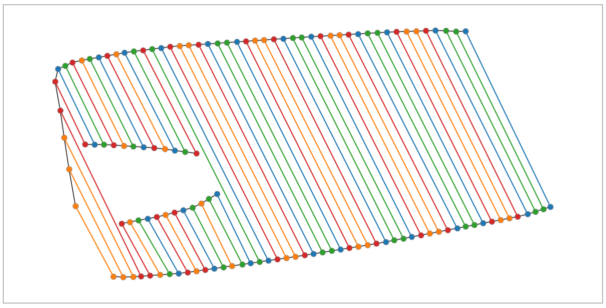

Fig. 5 The Simple field distributed among four robots using the *Greedy* workload distribution algorithm.

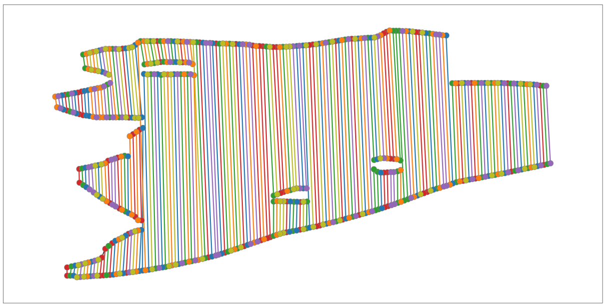

Fig. 6 The Complex field distributed among four robots using the *Greedy* workload distribution algorithm.

Algorithm 1 Modified Greedy algorithm

```
function $distribute\_greedy(rows, n)$
    $robots \leftarrow [r_1, \ldots, r_n]$                                   ▷ Initialize n robots
    $rows\_sorted \leftarrow$ SORTED($rows$, key=$length$)      ▷ Sort rows in descending order
    for $row$ in $rows\_sorted$ do
        $robots \leftarrow$ SORTED($robots$, key=$length$)        ▷ Sort robots in ascending order
        $robots[0] \leftarrow row$             ▷ Distribute longest row to robot with shortest distance
    end for
    return $robots$
end function
```

Fig. 7 Algorithmic description of the *Greedy* workload distribution algorithm. Figure reproduced from [12], which modified the algorithm from [13].

3. REDUCTION IN FIELD TIME USING MULTIPLE ROBOTS

Using three different fields, all with specific characteristics, the reduction of time used in covering the fields is assessed. The Simple and Complex fields are real-life fields, while the Mega field is fictional. For the Simple field realistically measured weed density data has been made available, while for both the Complex and Mega fields generated weed density data is used.

The data presented is a result of simulating various number of robots working in the field. For all simulations it isassumed that all robots have sufficient fuel and herbicide capacities, and the robots are not able to collide with one another. This means that any infeasibility of the paths are not considered.

3.1. Simple field

The Simple field is an example of a small and relatively simple field. The field includes a single obstacle as can be seen in Figure 11.

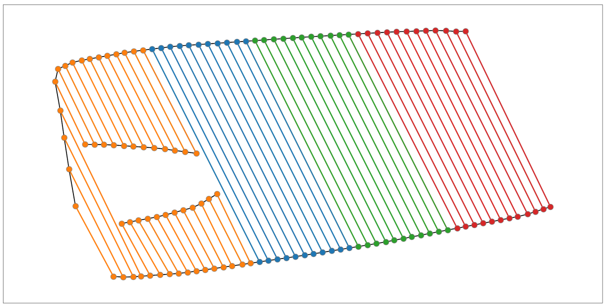

Fig. 8 The Simple field distributed among four robots using the *Ordered Absolute* workload distribution algorithm.

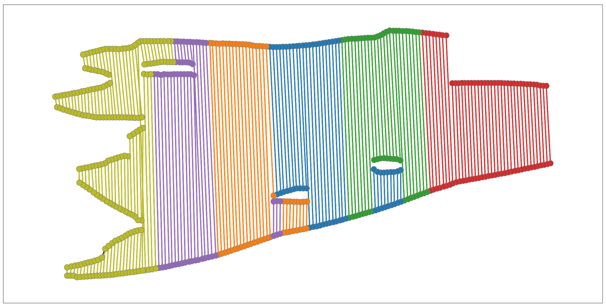

Fig. 9 The Complex field distributed among four robots using the *Ordered Absolute* workload distribution algorithm.

Algorithm 2 Ordered Absolute algorithm

```
function $distribute\_ordered\_abs(rows, n)$
    $robots \leftarrow [r_1, \ldots, r_n]$                                          ▷ Initialize n robots
    for $robot$ in $robots$ do
        $total\_length \leftarrow$ GET_TOTAL_LENGTH($rows$)   ▷ Get total length of remaining rows
        $goal\_length \leftarrow total\_length/n$        ▷ Get goal length based on $n$ remaining robots
        while LEN($rows$)$> 0$ do
            $current\_length \leftarrow robot.length$
            $next\_length \leftarrow robot.length + rows[0].length$
            $lower\_diff \leftarrow$ ABS($goal\_length - current\_length$)
            $upper\_diff \leftarrow$ ABS($goal\_length - next\_length$)
            if $lower\_diff < upper\_diff$ then
                break                                                    ▷ Move to next robot
            else
                $robot \leftarrow rows[0]$
                $rows.pop(0)$                              ▷ Remove row from rows when distributed
            end if
        end while
        $n \leftarrow n - 1$                                  ▷ Reduce remaining number of robots
    end for
    return $robots$
end function
```

Fig. 10 Algorithmic description of the *Ordered Absolute* workload distribution algorithm. Figure reproduced from [12], which modified the algorithm from [13].

The left graph in Figure 12 show the total time for completing a full coverage spraying of the field with 1-6 robots. The time is based on the last robot to finish its path. The right graph shows the time reduction as a percentage relative to a single robot in blue, and the relative time reduction from adding a single additional robot in orange. That is, the blue bar at 3 robots shows the total time improvement relative to a single robot, while the orange show the total time improvement relative to 2 robots.

3.2. Complex field

Complex is a very convoluted field containing five obstacles, as well as irregular headland. In practice, the field is too large for a single robot to cover without refueling. The total time needed for a single robot is more than 50 hours, assuming sufficient fuel and herbicide capacity. Figure 13 shows the field, and Figure 14 shows the total time to complete the field, the percentage time improvement relative to a single robot and relative to the preceding number of robots.

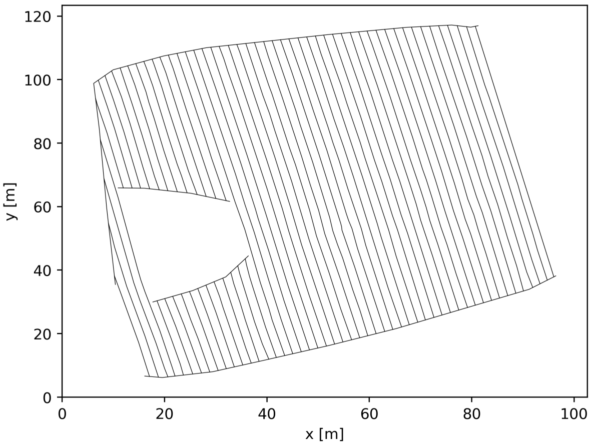

Fig. 11 The Simple field.

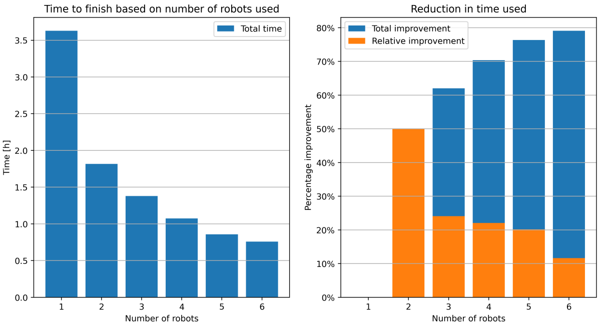

Fig. 12 The time improvement for increasing number of robots for the Simple field.

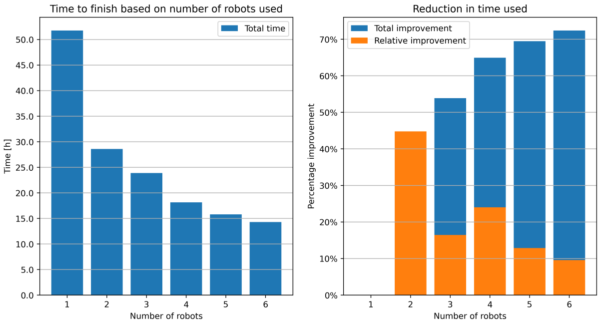

Fig. 14 The time improvement for increasing number of robots for the Complex field.

3.3. Large field

The Mega field is a fictional field generated in order to assess the system in a very large field. The field is very simple, containing no obstacles. However, the size of the field is so large that 10 robots use more than 200 hours to complete the field. Figure 15 show the field, and Figure 16 show the time improvement when increasing the number of robots by 10. The absolute time improvement graph therefore represents the percentage time improvement relative to 10 robots, while the relative time improvement represents the improvement relative to the previous multiple of 10 robots.

4. TIME AND DISTANCE DISTRIBUTION

Each area of the distribution was transformed into separate sub-fields which was then decomposed using the MBCD algorithm, before using a separate path planner for generating paths through the areas [8]. The AX-1 robot is designed to change its velocity relative to the weed density in the area it is operating. Higher weed density results in lower velocity.

4.1. Evenly distributed weed densities

The real-life weed density heatmap used for simulations of the Simple field is presented in Figure 17. The heatmap shows that the weed density is quite evenly distributed throughout the entire field, albeit some areas are slightly denser.

Using four robots, the individual paths through the field are presented in Figure 18.

Figure 19 shows the total distance and time used by all four robots. The horizontal lines indicate the total distance for each robot, while the vertical lines indicate the time of completion for each robot.

4.2. High density weed patches

As mentioned in Section 3, artificial weed density data is generated for the Complex field. As such, areas of the field contain large patches of high density weeds which drastically affect the time to complete their distributed

Fig. 13 Complex is a convoluted field.

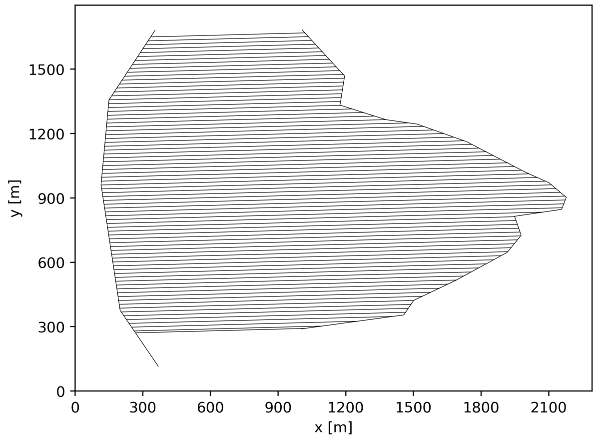

Fig. 15 Mega field is a very large field.

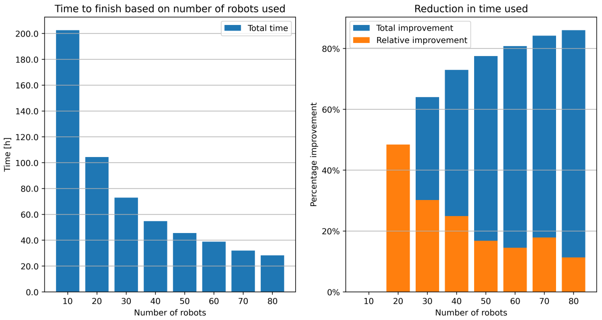

Fig. 16 The time improvement for increasing number of robots in Mega field.

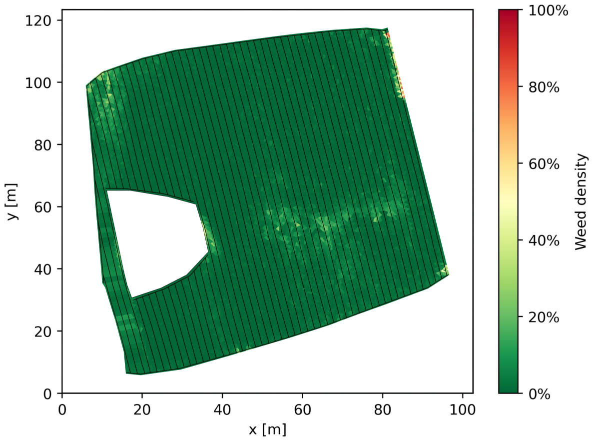

Fig. 17 Weed density heatmap for the Simple field using real-life data.

Table 1 Time and distance for each robot in an ideal simulation on Simple using four robots. Min and max values as well as the difference between them is given for both time and distance. ↑: Max value, ↓: Min value.

Robot	**Time**	**Distance**
0	1h, 12m, 45s	1040m
1	1h, 12m, 0s$^{\downarrow}$	1026m$^{\downarrow}$
2	1h, 22m, 59s	1072m
3	1h, 40m, 59s$^{\uparrow}$	1183m$^{\uparrow}$
Min	1h, 12m, 0s	1026m
Max	1h, 40m, 59s	1183m
Difference	0h, 28m, 59s	157m

areas for certain robots. Figure 20 shows the weed density heatmap for the Complex field. Notice the high density weed patches at about $(x = 100, y = 100)$ and $(x = 180, y = 120)$.

Using six robots to cover the field, the resulting path for each robot is shown in Figure 21. Notice how the high density weed patches end up within the paths of robots 1 and 3.

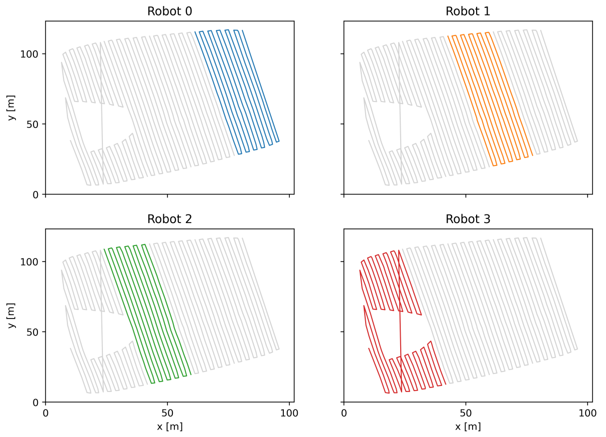

Fig. 18 The resulting paths for each of the four robots through Simple field after using the *Ordered Absolute* workload distribution algorithm.

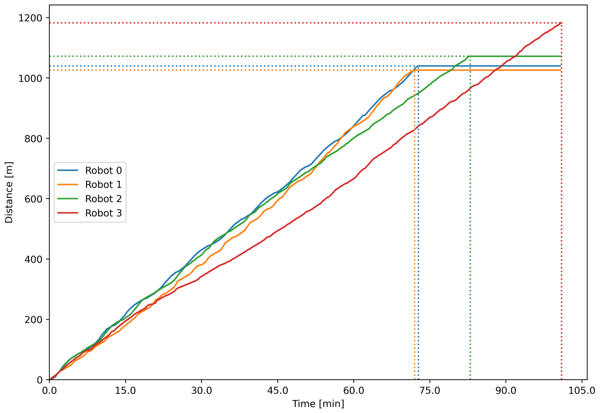

Fig. 19 The distance over time for all robots in the Simple field. The horizontal lines show the total distance for each robot, and the vertical lines show the time of completion.

Figure 22 shows the distance traveled and the time used for all robots in the simulation of the Complex field. The horizontal lines describe the total distance traveled by each robot, and the vertical lines indicate the time they used. Table 2 describes the time and distance values for all robots, the min and max values for both, and the difference between the min and max values.

5. DISCUSSION

Field decomposition using both an MBCD method and a single row segment method was introduced in order to distribute the field workload among n robots. The workload distribution presented two algorithms, the *Greedy* and the *Ordered Absolute*, for distributing based on equal distribution of field area.

5.1. Main Findings

The results of Sections 3 and 4 can be summarized into three main findings.

The single-row segment-wise field decomposition offer greater resolution for the workload distribution algo-

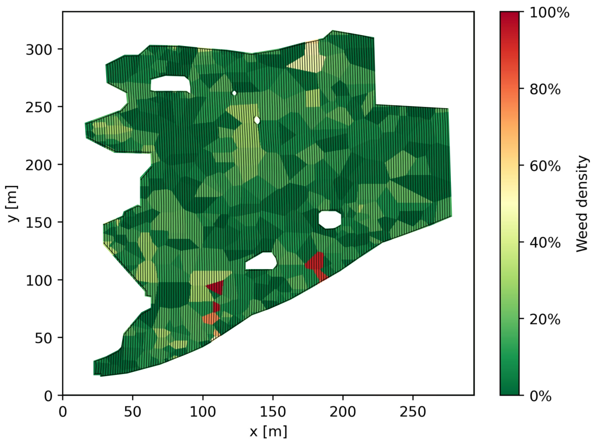

Fig. 20 Weed density heatmap for the Complex field using generated data.

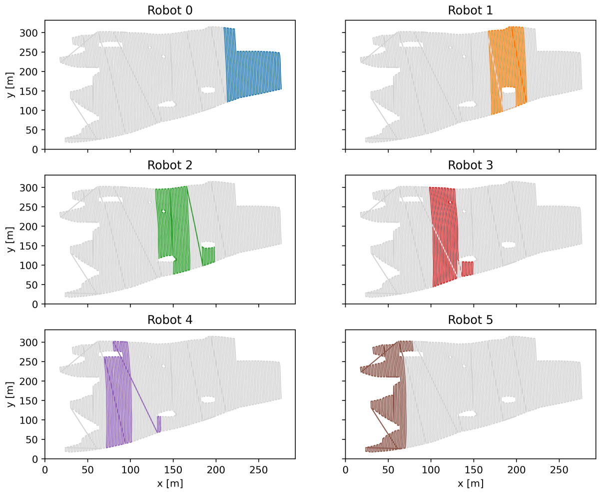

Fig. 21 The resulting paths for each of the six robots through Complex field after using the *Ordered Absolute* workload distribution algorithm.

Table 2 Time and distance for each robot in an ideal simulation on Complex using six robots. Min and max values as well as the difference between them is given for both time and distance. ↑: Max value, ↓: Min value.

Robot	**Time**	**Distance**
0	5h, 53m, 15s$^{\downarrow}$	4780m
1	9h, 49m, 15s	4900m
2	9h, 1m, 30s	5151m
3	14h, 17m, 15s$^{\uparrow}$	4692m$^{\downarrow}$
4	6h, 41m, 15s	5064m
5	7h, 37m, 15s	5238m$^{\uparrow}$
Min	5h, 53m, 15s	4692m
Max	14h, 17m, 15s	5238m
Difference	8h, 24m, 0s	546m

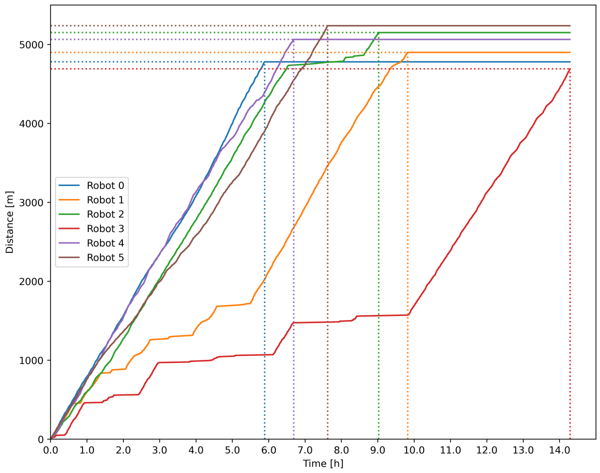

Fig. 22 The distance over time for all robots in the Complex field. The horizontal lines show the total distance for each robot, and the vertical lines show the time of completion.

rithms, allowing for more evenly distributed field area to each robot.

The time improvement gained by utilizing more robots in the swarm follows similar trends irrespective of the size and complexity of the field. The optimal time reduction possible from doubling the number of robots is halving the time to completion. Figures 12-16 show that the presented solution is close to this ideal.

Using the lengths of the rows in the field as the only criterion for workload distribution is insufficient to minimize the total time used by the swarm to complete full coverage of a field. This statement does not hold true to all swarm systems, for example for a seeding task where velocity remains unchanged [10], and for a weeding task using a classical weed spray boom [11]. This becomes an issue when using Kilter's precision spraying system which adjust the robot's velocity based on weed density.

5.2. Future Work

The presented system has essentially converted an existing single-robot problem into a multi-robot problem. The sub-fields resulting from the workload distribution present clear boundaries in which each robot will operate. With the exception of increased risk of collision at the borders of the areas, each distribution is equal to the larger single-robot problem. As such, the system is near ready for real-life testing, which would be a large step towards implementation of swarm robotics for the weed control task.

As described in Section 5.1, using distance alone as the criterion for workload distribution is not sufficient. Introducing methods allowing for an a priori estimate of the weed density distribution, combined with new workload distribution algorithms, could reduce the difference in time to complete the field for all robots. This problem is especially evident in Figure 22 and Table 2 where robot 3 has both the shortest total path length, and uses the longest time to complete it. Moreover, the robot uses almost triple the time as the fastest robot.

Another method for solving the problem of weed density affecting the time to completion is to add an online method for handling the issue by introducing communication between the robots, allowing robots to request help or notify when their path is taking longer than expected. In this case, other robots could take on parts of the requesting robots path, reducing the total time of completion for the swarm.

The system is designed to allow interchanging of all components. The study uses a path planning solution, however it does not include any performance assessment of the path planning solution nor test any alternative path planners. The path planner does not concern itself with the physical limits of the field, as can be seen by the path cutting across the field in order to reach its goals. Before any real-life testing of the system, a path planning solution which considers the limitations of the field should be tested.

None of the tested fields contain any curved rows. This should not be a problem as no parts of the system considers the shape of the rows, only their total length. Moreover, as long as the path planning solution considers only the endpoints of each row segment, the only limitation towards curved rows is the in-row controller for the robot. This statement should be tested using curved-row fields.

6. CONCLUSION

The study presented a method for solving the weed control problem using a swarm of AX-1 robots. The system consists of field decomposition, workload distribution, and path planning for n robots. The results showed a clear trend for all tested fields, where the time to complete the field was reduced by introducing more robots into the swarm. Moreover, the results showed that for the AX-1 robot, using distance as the only criterion for workload distribution is insufficient to reduce the total time to complete the field with a swarm. Future research should work towards implementing and testing the solution in a real-life system, how to account for weed density distribution in workload distribution, and test various path planning solutions in the system.

REFERENCES

[1] R. Ofosu, E. D. Agyemang, A. Márton, G. Pásztor, J. Taller, and G. Kazinczi, ”Herbicide Resistance: Managing Weeds in a Changing World.” *Agronomy*, Vol. 13, No. 6, 2023.

[2] T. Utstumo, F. Urdal, A. Brevik, J. Dørum, J. Netland, Ø. Overskreid, T. W. Berge, and J. T. Gravdahl, ”Robotic in-row weed control in vegetables.” *Computers and Electronics in Agriculture*, Vol. 154, pp. 36–45, 2018.

[3] F. Urdal, T. Utstumo, J.K. Vatne, S.A.Å Ellingsen and J.T. Gravdahl, ”Design and control of precision drop-on-demand herbicide application in agricultural robotics”, Proc. of the *13th International Conference on Control Automation Robotics & Vision (ICARCV)*, pp. 1689–1694, 2014.

[4] V. Sharma, A. K. Tripathi, and H. Mittal, ”Technological revolutions in smart farming: Current trends, challenges & future directions.” *Computers and Electronics in Agriculture*, Vol. 99, No. 99, pp. 107–217, 2022.

[5] M. Dorigo, G. Theraulaz, and V. Trianni, ”Swarm Robotics: Past, Present, and Future [Point of View]”, Proceedings of the IEEE, Vol. 109, pp. 1152–1165, 2021.

[6] C. Ju, J. Kim, J. Seol, and H. I. Son, ”A review on multirobot systems in agriculture.” *Computers and Electronics in Agriculture*, Vol. 202, pp. 107–336, 2022.

[7] D. Albiero, A. P. Garcia, G. K. Umezu, and R. Leme de Paulo, ”Swarm robots in mechanized agricultural operations: A review about challenges for research.” *Computers and Electronics in Agriculture*, Vol. 193, 2022.

[8] E. Prytz, ”Onboard Coverage Path Planning for Autonomous Ground Vehicles: An application in row-crop agriculture.” *Master’s Thesis at the Norwegian University of Science and Technology (NTNU)* (2024).

[9] H. Choset, ”Coverage of known spaces: The boustrophedon cellular decomposition.” *Autonomous Robots 9*, Vol. 9, pp. 247–253, 2000.

[10] T. Blender, T. Buchner, B. Fernandez, B. Pichlmaier, and C. Schlegel, ”Managing a Mobile Agricultural Robot Swarm for a seeding task” *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, pp. 6879–6886, 2016.

[11] D. Ball, P. Ross, A. English, T. Patten, B. Upcroft, R. Fitch, S. Sukkarieh, G. Wyeth, and P. Corke, ”Robotics for Sustainable Broad-Acre Agriculture” *Field and Service Robotics: Results of the 9th International Conference*, pp. 132–146, 2019.

[12] G. R. Varhaug, ”A Swarm Robotic Solution to Agricultural Weed Control with the AX-1 Robot: And a simulator to test it all.” *Master’s Thesis at the Norwegian University of Science and Technology (NTNU)* (2025).

[13] G. R. Varhaug, ”Workload distribution for swarm of agricultural autonomous ground vehicles” *Preliminary project for Master’s Thesis at the Norwegian University of Science and Technology (NTNU)* (2024).