Investigation for Prior Path of Sweeping Robot Considering Environmental Disturbance

Keita Nakamura, Jun Ogawa and Keitaro Naruse
Revitalization Center, LICTiA, The University of Aizu
Tsuruga, Ikki-machi, Aizu-Wakamatsu City, Fukushima Pref., 965-8580, Japan
E-mail: keita-n@u-aizu.ac.jp

Abstract

The sweeping robot plans path and moves along its prior path. However, the outdoor sweeping robot cannot move as expected. The uncertain movement of the robot is caused by some environmental disturbance such as unsmooth loose soil and wind. It can be improved by removing the disturbance, however it is difficult to remove the disturbance. For this reason, we consider path planning considering robot uncertainty because of environmental disturbance. This study considers only wind blow as a disturbance. We perform the simulation for sweeping entire area to investigate the effect on the prior path by the wind blow. Simulation results shows it is difficult to turn in the tailwind for the robot, and the moving cost is large. Moreover, it needs to turn for a long time to reach in target position when the angle between the robot direction and the direction to next target position from the robot is large, and the moving cost is large.

1 Introduction

Recently, the organic agriculture has attracted for healthy life. Rice-duck farming[1] is known as one of them. This method has effects of preventing weed seeds from sprouting by duck swimming in a rice field. Ducks stir water and soil during a swimming. Therefore, weed seeds do not take root in the field because they are floated up. Moreover, weed seeds that exist below the soil surface cannot grow well because the surface is mudding and weed seeds take sunlight less. However, the cost of rice-duck farming is very expensive because rice-duck farming has many problems. For example, rice-duck farming requires only young ducks and its farmers must fence to protect them from its vermin.

From the above background, our research group has developed a weeding robot inspired from rice-duck farming. This weeding robot is called “Aigamo robot”[2][3]. This robot can stir water and soil by rotating its wheels which we have designed. This robot has effect of preventing weed seeds from sprouting as with rice-duck farming. Figure 1 shows Aigamo robot. This robot is categorized as sweeping robot like a cleaning robot[4]. The different point between other sweeping robots and Aigamo robot is working environment. Most sweeping robot works indoors and can move as planned. On the other hand, Aigamo robot works in a rice field and cannot move as planned. The uncertain movement of Aigamo robot is caused by some disturbances such as unsmooth loose soil and wind. This robot requires to sweep the whole of rice field evenly. Working area is separated into square cells to realize its sweeping. The robot is given prior path like figure 2.(a). The number written in each cell means sequential order that the robot sweeps. Edge cells have no number because the robot turns in these cells. It sweeps all cells along the prior path. However, figure 2.(b) shows an actual trajectory. It cannot move to straight like prior path. Moreover, the sweeping has unevenness because of some disturbances.

Particularly, there are some problems when the robot sweeps many times in the same cells. For example, rice plants may be uprooted, or it may not be able to rise after falling down. There is no problem when the robot sweeps a few times in the same cells. Moreover, Aigamo robot sweeps the whole of rice field even if the sweeping is less. The effect of prevention to grow weeds is enough because rice field surface is mudding. The damage to rice plants is important problem for this robot. This is caused by the uncertain movement of the robot, and the uncertain movement is caused by some disturbances. It is possible to improve by removal some disturbances, however it is difficult to remove some disturbances.

For that reason, we consider as path planning considering uncertain movement of the robot by some dis-
turbances. It is possible to reduce the damage to rice plants by giving the robot a path that the total moving cost of the trajectory which is shorter. This study considers wind only as a disturbance. The ultimate goal for this study is finding the sweeping path whose the moving cost of the robot is the smallest. We assume that the working area separated in square cells and the magnitude and the direction of the wind are known. The constraint condition is that sweep path satisfies “All cells are visited” and “Do not visit cell that is already visited”. However, we do not understand the influence to the robot moving by the wind. Therefore, we investigate the relation between the environment with wind and the prior path with simulation.

2 Related Works

The purpose of the sweeping robot is complete coverage. There are many studies about complete coverage problem for the robot. In many cases, the given map is separated into some cells, and the sweeping path is obtained by solving TSP (Traveling Salesman Problem) that the robot visits all cells [5][6][7]. TSP is the problem of finding the route that the total cost is the smallest on the condition that is given the set of cities and the moving cost between each two cities. All cities must be visited, however already visited cities must not be visited. The larger the number of cities is, the larger the number of routes is. It is difficult to find the optimal route because of computationally expensive. There are many studies to solve TSP [8][9]. These studies which obtain the sweeping path by solving TSP assumed that the robot has some uncertainty and the environment is stable.

In this study, we propose new planning that minimizes the path length for a robot under the condition that the environment is unstable.

3 Verification Experiment

Experiment is carried out to investigate traveling route considering environmental disturbance. Here, we consider this disturbance as wind blow to one direction. In this study, the robot model simulating an actual robot (Aigamo robot) are adopted. The determine method for robot action and the sweeping rule are the same as actual robot. Moreover, the robot moving during blowing the wind is calculated by the magnitude and the direction of velocity vector of the robot and the wind.

3.1 Control Model of Robot for Simulation

Figure 3 shows the robot model for simulation.

Equation (1) and (2) show the speed of right wheel $V_R(t)[m/s]$ and left wheel $V_L(t)[m/s]$ from turning speed of the both wheel $\omega_R(t)$, $\omega_L(t)$.

\[
    V_R(t) = r\omega_R(t) \quad (1) \\
    V_L(t) = r\omega_L(t) \quad (2)
\]

where $r[m]$ is radius of the wheel and $t$ is time. Equation (3) shows the turning speed $\omega(t)[rad/s]$, and (4) shows

\[
    \omega(t) = \frac{V}{r} \quad (3)
\]
Fig. 4: The relation between robot and target

Table 2: The robot state for each a

| the range of a [rad] | robot state   |
|----------------------|---------------|
| $-\frac{1}{36}\pi \leq a \leq \frac{1}{36}\pi$ | forward       |
| $-\frac{1}{12}\pi < a \leq -\frac{1}{36}\pi$ | smaller right turn |
| $a < -\frac{1}{12}\pi$          | right turn    |
| $\frac{1}{36}\pi < a \leq \frac{1}{12}\pi$ | smaller left turn |
| $\frac{1}{12}\pi < a$    | left turn     |

the speed of robot $V(t)$[m/s].

$$\omega(t) = \frac{V_R(t) - V_L(t)}{B} \quad (3)$$

$$V(t) = \frac{V_R(t) + V_L(t)}{2} \quad (4)$$

Equation (5) and (6) show the position of robot $x(t)$ and $y(t)$, and equation (7) shows the robot direction $\theta(t)$[rad].

$$x(t) = x(t-1) + V(t) \cos \theta(t) \quad (5)$$

$$y(t) = y(t-1) + V(t) \sin \theta(t) \quad (6)$$

$$\theta(t) = \theta(t-1) + \omega(t) \Delta t \quad (7)$$

where $B$[m] is distance between two wheels and $\Delta t$ is time for simulation step. The values of $r$ and $B$ are the same to actual robot. The values of $\omega_R(t)$ and $\omega_L(t)$ are decided by the robot state. Table 1 shows the values of $\omega_R(t)$ and $\omega_L(t)$ for each robot state. The robot state is five types that are forward, smaller right turn, right turn, smaller left turn, and left turn.

3.2 Determine of Robot Action

The robot state is decided by the angle between the robot direction and the direction to next target cell from the robot. This angle is defined as $a$[rad]. $a$ is calculated from the current robot position $(x_r(t), y_r(t))$, the robot position before one step $(x_r(t-1), y_r(t-1))$, and the center position of the target cell $(x_t(t), y_t(t))$. Figure 4 shows the relation among angle $a$ and each position. $P_0$ is the vector meaning the robot direction, and $P_1$ is the vector meaning the direction to the target cell from the robot. Equation (8) and (9) show the orthogonal coordinates of these vectors.

$$P_0 = (x_t(t) - x_r(t-1), y_t(t) - y_r(t-1)) \quad (8)$$

$$P_1 = (x_t(t) - x_r(t), y_t(t) - y_r(t)) \quad (9)$$

The angle $a$ is the angle between $P_0$ and $P_1$. Equation (10) shows $a$.

$$a = \cos^{-1} \frac{P_0 \cdot P_1}{\|P_0\| \|P_1\|} \quad (10)$$

It is calculated by transform the inner product formula $P_0 \cdot P_1 = \|P_0\| \|P_1\| \cos a$. However, its range is $0 \leq a \leq \pi$. The sign of $a$ is calculated by adding the cross product formula. $a$ is positive when the cross product $P_0 \times P_1$ is positive, otherwise $a$ is negative. $\frac{P_0 \times P_1}{\|P_0 \times P_1\|}$ is realized to extract only sign of $a$. Table 2 defines the robot state for each $a$.

### 3.3 Sweeping Rule

The robot visits all cells while update the target cell. Target cell is updated at around the center of target cell because the robot movement is uncertainty. Figure 5 shows in the case that the prior path for robot is A→B→C→F→E→D→G→H→I and the working area is 3×3. The area of outside 1[m] is turn area for the robot as shown in figure 6. The robot may become immovable in the way if there is not turning area. Moreover, a cell is a square with a side of 1 [m]. The inside of the
obtained from adding \( \hat{V} \) to \( V \). Equation (11) shows the velocity vector of the robot by wind blow. The robot moving is given by calculation the sum of the velocity vector of the robot and the wind. Figure 7 shows the relation between the velocity vector of the robot and the wind. The robot moving is given by calculation the sum of the velocity vector of the robot and the wind.

3.4 Robot Moving during Blowing Wind

The robot moving is different by the wind when the wind blows. The robot moving is given by calculation the sum of the velocity vector of the robot and the wind during blowing the wind. Figure 7 shows the relation between the velocity vector of the robot and the wind. Each velocity vector is expressed in the polar coordinates. In this study, the right direction is defined as \( \theta = 0 \) [rad]. Equation (11) shows the velocity vector \( \hat{V} \) given to the robot, equation (12) shows the velocity vector \( V_e \) of the wind, and equation (13) shows the velocity vector \( V \) of the robot by the wind. \( V \) are obtained from adding \( \hat{V} \) and \( V_e \).

\[
\begin{align*}
\hat{V} &= (||V||, \hat{\theta}) \\
V_e &= (||V_e||, \hat{\theta}_e) \\
V &= (||V||, \theta)
\end{align*}
\]

3.5 Experiment Conditions

Experiment is carried out to investigate traveling route considering environmental disturbance. In this experiment, the working area is 3x3. Figure shows the working area for the robot. The outside 1[m] is the turning area for the robot. In this experiment, the start position is fixed in the cell A. The number of prior paths, which satisfies that “Path is not separated” and “All cells are visited only once”, is eight. The wind direction is rightward. \( ||V|| \) and \( \theta_e \) have a little noise because the wind is not constant in real world. \( ||V|| \) adds normal random number \( N(0.03, 0.0033) \) and \( \theta_e \) adds normal random number \( N(0.0, 0.029) \).

This experiment is tried 100 times with the combinations of each prior path. In this experiment, the robot model simulating an actual robot are adopted and the determine method for the robot action and sweeping rule is same with the actual robot. Moreover, the robot moving is given by calculation the sum of the velocity vector of the robot and the wind.

3.6 Experiment Results

All prior paths are ranked in ascending order of the average of all moving costs with each prior path. The rank is “1” when the average of moving cost is the smallest. Similarly, the rank is “2” when the average of moving cost is the second smallest. In other words, the smaller the rank is, the better the prior path is. Figure 8 shows the box plot about all moving costs for each prior path. Figure 9 shows all prior paths given to the robot for each rank. Figure 10 shows all trajectories of the robot by a prior path for each rank. In fact, there are 100 trajectories of the robot. Moreover, the number of cells is 5x5 because the outside 1[m] is the turn area for the robot. The robot starts in the cell A. From figure 8, it is clarified that some prior paths are better than other prior paths. In particular, the rank of better prior path is two or less on the condition that the wind blows to rightward.

3.7 Discussion

The factor of the larger moving cost is clarified by focusing on the turn of the robot. Figure 11 shows the color map for the sub-path length of rank 1 and 8. This figure shows the prior path and the average of all moving costs for each sub-path. The line color shows the average of all moving costs. The color bar shows the relation between a color and the average of all moving costs for each rank. The line color shows the average of all moving costs. The average of all moving costs is 1.5 or less when its color is blue. The average of all moving costs is large if its color is similar to red.

Figure 12 shows one trajectory for each prior path. Some arrows show the robot direction in the start positions of each sub-path. Some arrows that the robot direction is similar to the wind direction are extracted. The arrow color is green when the moving cost is 1.5 or less. The arrow color is red when the moving cost is 1.5 or more. From figure 11, the average of all moving
Fig. 9: All prior paths given to the robot for each rank based on average of moving cost

Fig. 10: All trajectories of the robot for each rank based on the average of all moving costs

costs is large in the sub-path that is turn of the robot. From figure 12, the turn radius of the robot is different for each sub-path. Some trajectories to next target cell from the start position of each red arrow are like the larger arc. The red arrow shows the robot direction, and the robot turns in tailwind in this time. The robot tries to turn in the sub-path that is turn of the robot. However, it is difficult to turn for the robot because of the tailwind. From the above, the moving cost of the robot is large by the turn in tailwind. However, the moving cost of the robot is not always large when the robot turns in tailwind. The robot turns to next target cell from the start position of each green arrow in tailwind in figure 12.(a), however the moving cost of the robot is small compared with figure 12.(b).

Figure 13 shows the relation between the trajectory and the angle between the robot direction and the direction to next target cell from the robot. Its angle is the same to $a$ shown in equation (10). A trajectory which the moving cost is small is compared to a trajectory that the moving cost is large. From this figure, the moving cost of the robot depends on $a$. The robot can easily reach in next target cell with a little turn when $a$ is small. The moving cost of the robot is small. It needs to turn for a long time to reach in next target cell when $a$ is large. The moving cost of the robot is large. From the above, the moving cost of the robot is small on the condition that the $a$ is small even if the robot turns in tailwind. Therefore, it is clarified that the factor of the larger moving cost is the turn in tailwind and $a$. Moreover, the moving cost of the robot is large when the robot turns in tailwind and $a$ is large. This factor applies to other conditions.

Figure 14 shows the relation among the angle between the robot direction and the wind direction, the angle $a$, and the moving cost of the robot for each wind direction to verify this factor. From this figure, we do not consider about the moving state of the robot. The moving
state of the robot is estimated by $a$. The robot may turn when $a$ is large. The angle between the robot direction and the wind direction is defined as $\Delta \theta = \theta_e - \theta$. This figure shows the relation among $\cos \Delta \theta$, $\cos a$, and the moving cost of the robot for wind direction. The marker color means the moving cost. The robot direction and the wind direction is same when $\cos \Delta \theta = 1$. In this case, the robot moves in tailwind. The robot direction is against the wind direction when $\cos \Delta \theta = -1$. In this case, the robot moves in headwind. $a$ is 0 when $\cos a = 1$. In this case, the robot can easily reach in next target cell with no turn. $a$ is $\pi$ when $\cos a = -1$. In this case, it needs to turn for a long time to reach in next target cell. From this figure, the moving cost is large when $\cos \Delta \theta$ is large and $\cos a$ is small. In this case, the robot turns for a long time in tailwind. Therefore, the factor of the larger moving cost is the turn in tailwind and $a$.

4 Conclusion

In this study, we consider the sweeping path planning problem considering the robot uncertainty by the wind. The continuous robot moving is hard by the turning in tailwind and the larger angle between the robot direction and the direction to next target position from the robot. From simulation results, it is difficult to turn in tailwind for the robot, and the moving cost is large. Moreover, it needs to turn for a long time to reach in target position when the angle between the robot direction and the direction to next target position from the robot is large, and the moving cost is large.

In the future work, we would like to develop the method for planning a better path considering uncertainty disturbance from robot and environment.

Acknowledgment

This research was supported by “development of a weeding robot system in rice fields”, Adaptable and Seamless Technology Transfer Program through Target-driven R&D, Japan Science and Technology Agency. And it had been supported by Promotion Project for the Development of Agricultural Work Support Robots among Promotion Projects to facilitate Innovation Project of Agricultural, Forestry and Fisheries Area (Rice Field Weeding Robot).

References

[1] H.Asano, K.Isobe and T.Kanichira, “Changes in weed emergence in paddy fields with continuous aigamo duck farming, an example in Yabe town, Kumamoto prefecture”, Journal of Weed Science
Fig. 14: The relation among the angle between the robot direction and the wind direction, the angle $\alpha$, and the moving cost of the robot

and Technology, vol.46, vol.1, pp.19–24, 2001. (Japanese)

[2] A.Maruymama and K.Naruse, “Development of small weeding robots for rice fields”, System Integration (SII), 2014 IEEE/SICE International Symposium on, pp.99–105, 2014.

[3] K.Nakamura, M.Kimura, T.Anazawa, T.Takahashi and K.Naruse, “Investigation of weeding ability and plant damage for rice field weeding robots”, System Integration (SII), 2016 IEEE/SICE International Symposium on, pp.899–905, 2016.

[4] Y.J.Oh, Y.Watanabe, “Development of small robot for home floor cleaning”, SICE 2002. Proceedings of the 41st SICE Annual Conference, vol.5, pp.3222–3223, 2002.

[5] J.S.Oh, Y.H.Choi, J.B.Park and Y.F.Zheng, “Complete coverage navigation of cleaning robots using triangular-cell-based map”, IEEE Transactions on Industrial Electronics, vol.51, no.3, pp.718–726, 2004.

[6] Y.Gabriely and E.Rimon, “Spanning-tree based coverage of continuous areas by a mobile robot”, Annals of mathematics and artificial intelligence, vol.31, no.1-4, pp.77–98, 2001.

[7] H.Choset and P.Pignon, “Coverage path planning: The boustrophedon cellular decomposition”, Field and service robotics, pp.203–209, 1998.

[8] B.Angeniol, G.D.L.C.Vaubois and JY.Le.Texier, “Self-organizing feature maps and the travelling salesman problem”, Neural Networks, vol.1, no.4, pp.289–293, 1988.

[9] M.Dorigo and L.M.Gambardella, “Ant Colonies for the Traveling Salesman Problem”, biosystems, vol.43, no.2, pp.73–81, 1997.

[10] A.Zelinsky, R.A.Jarvis, J.C.Byrne and S.Yuta, “Planning paths of complete coverage of an unstructured environment by a mobile robot”, Proceedings of international conference on advanced robotics, vol.13, pp.533-538, 1993.

[11] W.H.Huang, “Optimal line-sweep-based decompositions for coverage algorithms”, Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on, vol.1, pp.27–32, 2001.