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Deployment Algorithm Using Fluid Dynamics for Agriculture Sensor Networks

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Abstract

In this paper, we propose a 2D fluid dynamics algorithm for the mobile sensor network composed by agricultural robot. This algorithm regards the entire sensor network as a fluid body, regards robot node as charged particles. It will auto complete the deployment by the interaction of node to node, obstructions, borders. This algorithm is adaptive, robust, simple, and especially suitable for farmland, orchard deployment. This paper chooses coverage, uniformity and other metrics to evaluate the performance of the algorithm. It also uses mobile trolleys to simulate the deployment. The result shows that this simulation results match the algorithm expectation. This paper provides a new idea for the fluid dynamics to implement in agriculture mobile sensor networks.

Key words

Agricultural engineering, agricultural robot, fluid dynamics, node deployment, sensor networks

1. Introduction

Noguchi et al. mentioned that agricultural robot was special robot used for agricultural production [1], was new multifunctional agriculture machinery. The advent of agricultural robot was the result of the modern agricultural machinery development. It was also the product of robotics and automation technology progress. The emergence and applying of agricultural robot, had changed the traditional way of agricultural labor, and promoted the development of modern agriculture. In the 21st century, new multifunctional agriculture increasingly widely applied robotics; intelligent robots will more and more replace farm work done by hand in the vast field. Second agricultural revolution will be in-depth development. Agricultural robot will be the future direction of agricultural development.

Abbasi et al. mentioned Sensor network apply in agriculture increasingly widespread, and its combination with agricultural robot can play a greater advantage [2-3]. Shinghal et al. presented the flow field deployment algorithm combined with agricultural robot can perform a variety of agricultural activities [4], for example, multi-robot cooperation can achieve the best sprayed coverage of spraying of pesticides to achieve the spraying effect; picking robot cooperate to pick fruit, transplanting robot cooperate to plant and so on.

There are many literatures on sensor network applications in agriculture [5-13]. Wang put their main discussion in recent technologies and standards of wireless sensor networks, especially the communications as applied to wireless sensors [5]. Furthermore, they also discussed agriculture and food industry and their future development trend of wireless sensor technology. Díaz proposed a scheme which can guide agricultural applications for wireless sensor networks [6]. They thought that there exist commonalities among these applications; unfortunately, no methodology proposed can be used in the general case. Liu proposed a random deployment method [7], which can achieve better both coverage and co connectivity by using three popular regular patterns-equilateral triangle, square and hexagon.

In the above papers mentioned, although some literature has done the research on agriculture sensor node network deployment, but these studies are not enough. In this paper, we propose a 2D fluid dynamics algorithm about the mobile sensor network composed by agricultural robot. This algorithm regards the entire sensor network as a fluid, regard robot node as charged particles. It will auto complete the deployment by the interaction of node to node, obstructions, borders. This algorithm is adaptive, robust, simple, and especially suitable for farmland, orchard deployment.

The paper is organized as follows: Sect. 2 constructs a deployment model using fluid dynamics for mobile robot sensor networks; Sect. 3 proposes the deployment scheme of fluid dynamics; Sect. 4 presents computer simulation results and discussions; finally, Sect. 5 draws conclusions from these results.

2. Fluid Dynamics Model of Mobile Robots

2.1 Model Analysis

Fluid is gas and liquids in general. In people's lives and production activities we can encounter fluid anytime and anywhere, so the fluid mechanics is closely related to the human life and production, agricultural production is inseparable from the fluid. Computational fluid dynamics (CFD) is based on the basic governing equations of fluid dynamics, i.e., continuity equation, momentum equation and energy equation. In this paper, the concept of fluid dynamics and the derivation of control equations are discussed in detail. We regard the entire sensor network as a fluid, and the mobile node will be regarded as the infinitesimal fluid unit. In CFD, the governing equations are divided into two types, namely, conservative and non-conservative. Because of the infinitesimal fluid units (nodes) can be moved, the non-conservative type equation would be adopted. Besides, the fluid itself includes viscous and non-viscous fluids, friction and other effects can also affect the deployment process. In this paper, we mainly consider the viscous fluid. We use the governing equations for viscous and non-conservative Neville-Stokes equations as follows:

$$\begin{cases} \rho \dfrac{Du}{Dt} = -\dfrac{\partial p}{\partial x} + \dfrac{\partial \tau_{xx}}{\partial x} + \dfrac{\partial \tau_{yx}}{\partial y} + \rho f_x \\ \rho \dfrac{Dv}{Dt} = -\dfrac{\partial p}{\partial y} + \dfrac{\partial \tau_{xy}}{\partial x} + \dfrac{\partial \tau_{yy}}{\partial y} + \rho f_y \end{cases} \quad (1)$$

The robots move in a two-dimensional plane, so the equations include two directions of x and y. Here ρ is the density of the fluid, D/Dt is the material derivative, p is the fluid pressure, f_x and f_y are X and Y direction of the unit mass of physical components, u and v are two direction infinitesimal element of fluid velocity components. According to the convention, τ_{ij} denotes j direction stress applied perpendicular to the plane and on the i axis. This equation is the governing equation of the fluid, in order to make it more applicable to the deployment of mobile sensor networks, so we need to simplify the equation. The stress is divided into two parts: one is related to the friction; the other is related to the coefficient of viscosity, so the problem is simplified, and is more conform to practice. The friction force is only related to the positive pressure. Located along the X direction of the positive pressure is F_x, the friction coefficient is μ_x, so the friction force along the X direction of the node is $\mu_x F_x$. The viscous resistance is positively related to the node velocity, i.e., the faster the speed, the greater the viscous resistance. The coefficient of viscosity is λ, and the coefficients in different directions are the same, so the viscous resistance along the X direction is λu. In the same way, the friction force and viscous resistance in Y directions are $\mu_y F_y$, λv.

$$
\begin{cases}
\dfrac{Du}{Dt} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} + \mu_x N_x + \lambda u + f_x \\
\dfrac{Dv}{Dt} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial y} + \mu_y N_y + \lambda v + f_y
\end{cases} \tag{2}
$$

Then we analyze the physical meaning of the equation and the relationship between the equation and the mobile sensor networks. The left side of the equation is the change rate of the fluid velocity, namely the acceleration. ρ is the local density, which can be given as follows:

$$
\rho_i = \frac{R_s n_i^2 + \sum_{j \in N_i} r_{ij}}{\sum_{j \in N_i} r_{ij}} \tag{3}
$$

What can we get in actual deployment is the distance or location information of nodes which can obtain by communication signal strength and GPS devices respectively. Nodes may be considered as charged particles, and its pressure comes from the field stress imposed from other nodes. As for this, we may acquire:

$$
F_{ij} = k \frac{Q_i Q_j}{{d_{ij}}^2} \tag{4}
$$

The equation mentioned above is Coulomb's law, where F_{ij} is the electric force node i subject to node j; k is Coulomb's constant; d_{ij} denotes the Euclidean distance between the node i and node j; Q_i and Q_j represents the charges of the node i and node j.

Considering the momentum of X direction. Now only f_x left, which is called physical force. Physical force directly acts on the volume mass of the fluid unit, but forces are not directly generated by the contact, such as the gravitational force, the electric field force, and the magnetic force. Therefore, we can merge the f_{ije} and f_x, because they are both the electric field force in the mobile robot network. The combined equations are as follows:

$$
\begin{cases}
f_x - \mu_x N_x - \lambda u = \dfrac{Du}{Dt} \\
f_y - \mu_y N_y - \lambda v = \dfrac{Dv}{Dt}
\end{cases} \tag{5}
$$

For the X direction of the momentum, Du/Dt is the change rate of movement of a fluid unit along the X direction. $\mu_x N_x$ is the friction force, λu is the viscous resistance, and f_x is the net gravitational force and the net electric field force. This equation is the governing equation, and then we discuss the boundary condition of the equation.

2.2 Boundary Condition

The area of farmland and orchards is limited, and the deployment of robot nodes should not exceed this range. The boundaries can be real (such as mountains, rivers), but they can also be assumed (such as latitude and longitude). When the node moves to the boundary, it should not exceed the boundary, that is, the boundary condition (Fig. 1).

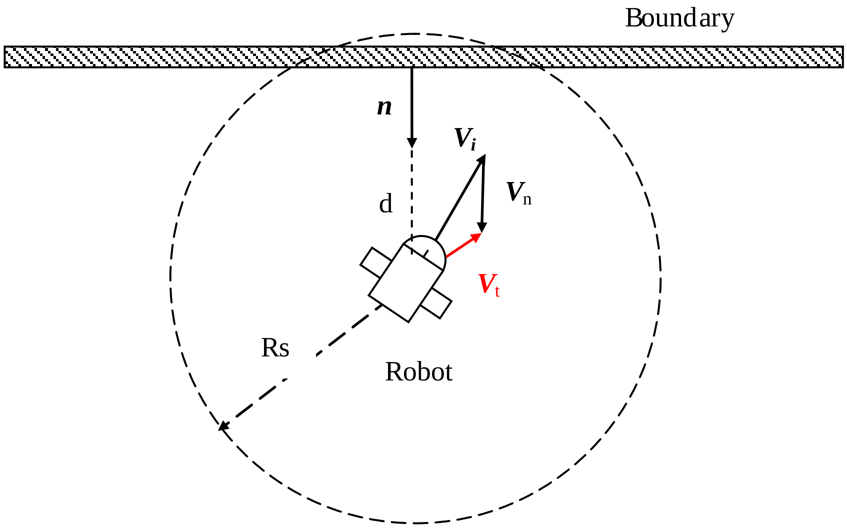

Fig.1. Illustration of the boundary condition

Here Rs denotes the sensing radius of node, when the distance d between the node and the boundary is less than the Rs, the node will change its direction due to the Coulomb force exerted by the boundary. In addition, due to the superposition of the original velocity $\boldsymbol{V}_i$, and the vertical boundary velocity $\boldsymbol{V}_n$, creating a new velocity $\boldsymbol{V}_t$. The change of $\boldsymbol{V}_t$ direction makes the node leave the boundary. Therefore, there is always a safe distance between the nodes and the boundary.

3 Deployment Algorithm for Agricultural Robots

3.1 Model of Deployment Area

The shape of farmland and orchards are varied, and their terrains are complex. It is our first need solved issue that how these areas become digital information computer capable handling. As computer technology and information science develop highly today, only relying on paper maps to provide information has been unable to meet the needs, digital map has changed this situation, the digital map is the digital presence and digital forms of paper map, can be very convenient for combination of elements in any form, stitching, forming a new map, you can also carry out any scale, any range of graphics output. It is easy to modify, can greatly shorten the mapping time; can be easily to combine with satellite images, aerial photographs and other information sources, generate new graph types. This paper make Google digital map as the source of the deployment of regional modeling.

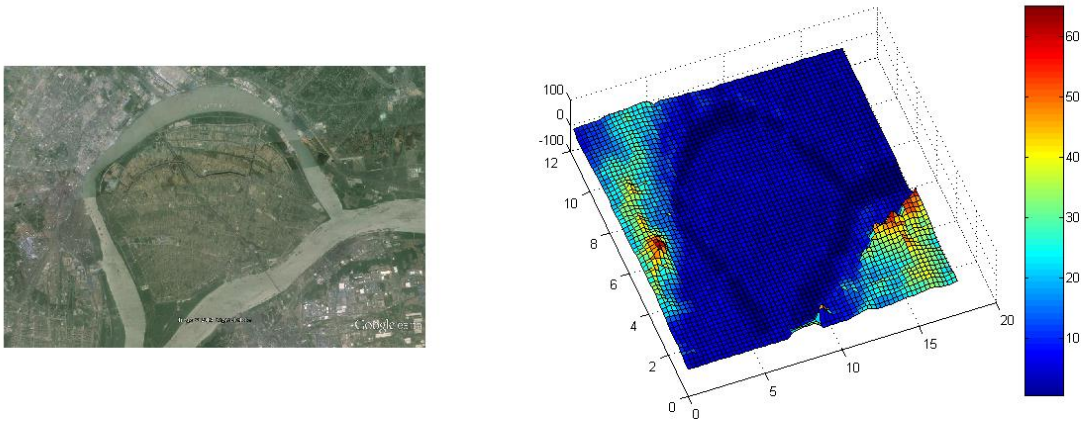

Fig.2. Satellite map (left plot) and results of modeling (right plot)

Left plot is the plane photo of large areas of farmland in China Yangtze River intercepted with the Google satellite map, of which the central area is surrounded by the Yangtze River and its DC. We choose these satellite map photos to model 3D elevation map (right), we can clearly see that the central region is a large flat terrain. In the use of a satellite map we get 3D elevation map, and also obtain corresponding height and terrain information, which will help us to construct the boundary conditions. On the right plot the highlands and rivers can be regarded as boundary which need to be considered when node deploying.

3.2 Deployment Algorithm

Assuming the area A requires the deployment of sensor nodes for the detection of this region, then how should the sensor nodes be deployed to achieve the expected results? We propose a concept, namely Coverage Ratio as follows:

$$C = \frac{\pi R_c^{\ 2} N}{A} \tag{6}$$

In the above formula, N is the total number of nodes; A is the area of the deployment area; R_c is the communication radius of the sensor nodes; C is the Coverage Ratio of the area. C denotes the ratio of the area of the communication coverage area of all nodes (the total number of

N) and the area of the deployment area A. Its value reflects the communication coverage of the area. The greater the C value, the better the connectivity of sensor networks, the higher the quality of service. The sensor radius of the node is R_S.

4. Simulation Results

In order to verify the correctness and feasibility of the algorithm proposed, we choose many experimental sites in Google definition digital map near Yangtze River, and specific coordinates will be given below. Parameter settings of our simulations are indicated in Table 1 with reference to the related figure number.

Table 1. Simulation settings by figure number

Parameter	*Fig. 3*	*Fig. 4*	*Fig. 5*
Deployment Area (A)	1150×850 (m)	1000×900 (m)	1100×950 (m)
Node number (NN)	20	20	20
$\boldsymbol{a}_{th}$, $\boldsymbol{v}_{th}$	2.5; 1.5	2.5; 1.5	2.5; 1.5
Damping factor (Df)	0.7	0.8	0.8
Time (T)	20	20	20
Charges (Q)	1e-9	1e-9	1e-9
Rs, Rc	2; 4	2; 4	2; 4
Δt	0.2	0.2	0.2
Number of obstacles	0	1	0
Number of ROI	0	0	1

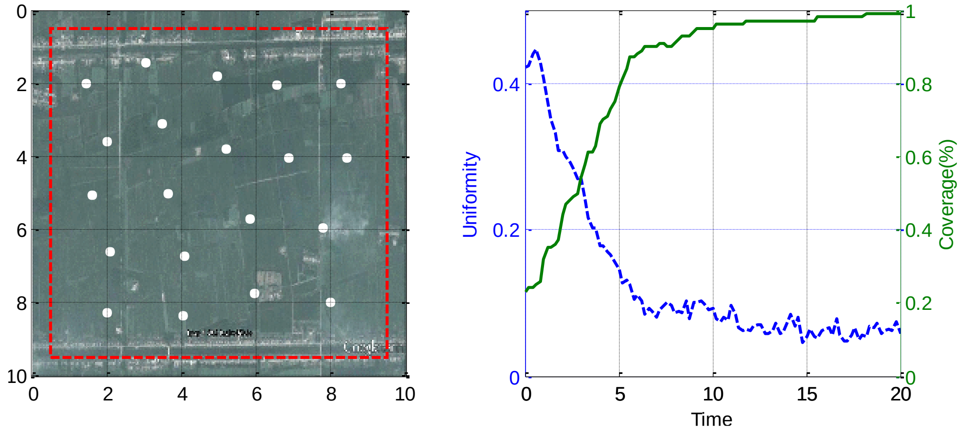

Fig. 3. Normal Deployment

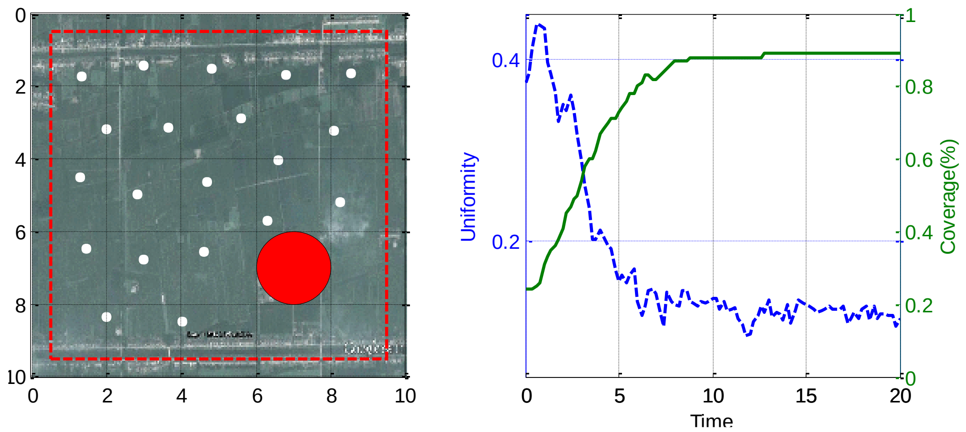

Fig.4. Deployment with obstacle

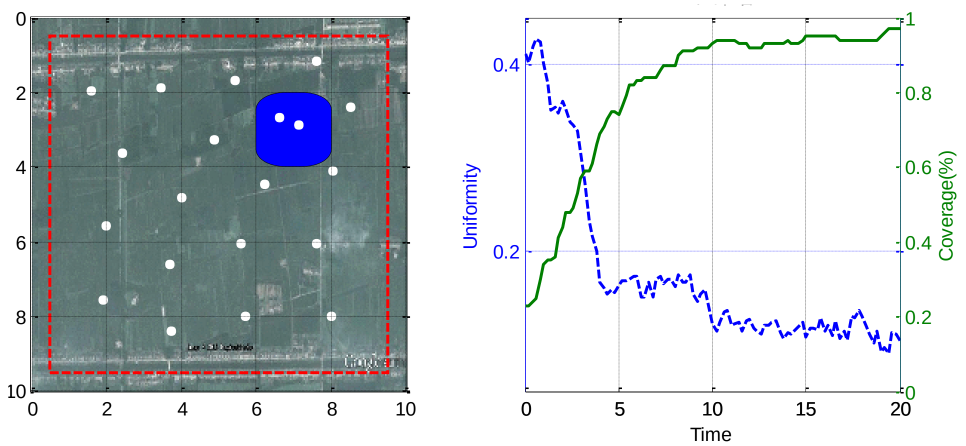

Fig.5. Deployment with Region of Interest (ROI)

5. Discussion

In Figure 3, the red rectangle indicates the simulation area (area A). Tiny white dots represent the nodes location. Start position is at the upper left corner (close to [1,1]). The right figure shows the deployment change in Coverage and Uniformity in accordance with the left figure. We can see from the chart, in the initial time, nodes cover only a small part of the region, and the coverage rate is below 28%. As the nodes move, the Coverage Rate starts to rise, and at the end of a certain time to reach a balance (T=15). At this time the coverage is the maximum (about 100%). Uniformity is 0.4 at the start of the simulation. At the beginning of the deployment, it rise rapidly, reaching a maximum value, and then begins to decline. It tends to close to 0.1 at the end of this simulation. Uniformity is expressed as the standard deviation of the network, so the smaller the uniformity is, the more uniform the network is.

In left Figure 4 the solid red circle represents obstacle and there only one in this region. By adjusting the amount of charges carried by the obstacle, we can adjust the distance between the nodes and the obstacle. Due to the repulsive force, nodes keep a certain distance from the obstacle, which is very significative in practical application. To keep a certain distance from the nodes to the danger or the non-reachable region, we can reduce the damage to the nodes, and it also indicates that the algorithm is adaptive. The right figure shows the change of uniformity and coverage during the deployment process. We can see that due to the exits of obstacle, the area is not completely covered by the nodes. The maximum coverage is less than 100% (about 90%). In comparison with figure 3, when the node reaches the equilibrium state, the uniformity value is higher, which is because of the existence of obstacle.

In left figure 5, the blue region stands for region of interest (ROI). ROI is the emphasis region where nodes need to be deployed densely. There is only one ROI located on upper right corner, judging from the figure. From the previous sections of this paper, we consider ROI's as stationary charges with the opposite signs in this paper. The amount of charges it carries determines the attraction to the nodes. The ROI here contains a negative charge. It can be seen that after the deployment, ROI gathers more nodes, indicating a higher density of nodes in ROI, so the coverage of ROI is higher. In the right plot, the Coverage and Uniformity curve illustrates the changes in coverage and uniformity. When the node reaches equilibrium state, the coverage rate is slightly lower than the normal deployment, which is caused by the attraction of ROI.

The simulation results show that the coverage and uniformity are in agreement with the proposed theory model. Finally, we can draw the conclusion that our proposed algorithm is suitable for varies deployment scene, which includes normal deployment scene, obstacle deployment and ROI deployment. And, we can also predict that our proposed algorithm will work well in mobile sensor networks.

Conclusion

The algorithm proposed in this paper does not need to explore the deployment area in advance, and it has the characteristics of self adaptation, robustness and simplicity. Therefore, the proposed algorithm is suitable for the deployment of the unexplored area. In the simulation experiment, we choose the coverage and uniformity as the performance indices of the algorithm. According to the simulation results, the results of the algorithm are in agreement with the predicted results. This paper provides reference for the field deployment of mobile sensor networks.

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