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Application of Robot Formation Scheme for Screening Solar Energy in a Greenhouse

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***Abstract*—**Many agricultural and especially greenhouse applications like plant inspection, data gathering, spraying and selective harvesting could be performed by robots. In this paper multiple nonholonomic robots are used in order to create a desired formation scheme for screening solar energy in a greenhouse through data gathering. The formation consists from a leader and a team member equipped with appropriate sensors. Each robot is dedicated to its mission in the greenhouse that is predefined by the requirements of the application. The feasibility of the proposed application includes experimental results with three unmanned ground vehicles (UGV).

***Keywords*—**Greenhouses application, robot formation, solar energy.

I. INTRODUCTION

THE increasing demand for quality products as well as augmentation of the productivity necessitate the use of advanced and innovative technologies in all stages of the productive process. These are the facts that make the applications of automation and especially robotics useful. Automation allows the reduction of production costs while the use of robots may substitute human activities in repetitive operations as well as in hazard environments where chemical and toxic products are used. A typical example of such applications is in agriculture and particularly in its rapid developing sector of greenhouses.

Greenhouses are facilities characterized by structured environment for hastening the growth of plants. Automated procedures and robotized activities have an advantage over that environment and can increase the productivity despite the higher investments. Many operations like plant inspection, temperature measurement, selective harvesting, spraying and screening solar energy could be performed by robots [2], [8], [19].

The field of cooperative control, control of multi-agent formations and flocking [15], has recently gained increasing attention [3], [5], [11]. The main interest is in real-world applications such as inspection, surveillance, scientific data gathering etc. The main feature of formation control is the cooperative nature of the system components.

In this paper multiple nonholonomic robots are used in order to create a desired formation scheme for screening solar energy in a greenhouse.

The problem definition is discussed in section II. Section III presents the application of robot formation in a greenhouse while in section IV experimental results are shown. Conclusion and future work are presented in section V.

II. PROBLEM DEFINITION

In this work the problem can be defined as follows: given a greenhouse, a multi robots team should moves from an initial location (starting waypoint) to a final location (goal waypoint), in order to screen solar energy in the whole structure. In particular we are interested for the photosynthetically active radiation (PAR) that is the part of the incoming global radiation, which it has bandwidth from 400 to 700 nm [16]. This type of radiation is used for the photosynthesis by the plants.

The multi robot team consists from three robots. The first (named A) is the base robot which gather the transmitted data from the other two robots (named B and C) that form the robot formation. The robots B and C in this paper are mechanical similar, moreover in the case of simulation they are identical, and the base robot is a Pioneer 3-AT.

The task for each robot of the formation is to simultaneously move to a goal location, avoid colliding between each other and maintain a formation position. In the proposed application since the greenhouses are facilities presenting a structure environment, the robots track their computed trajectories.

A. Formation Model

In our work we consider a column formation for a team of two robots [1]. According that formation the robots travel one after other, keeping a constant distance each other. Each robot of the formation has a specific position defined by its identification number, fig. 1.

Fig. 1. Column formation for two UGV robots.

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Concerning the formation maintenance it is accomplished in two steps as described below [1]:

i. Define-formation position: is the process which figure out the actual position (i.e. the starting waypoint) of each robot in formation, based on current structures data.
ii. Maintain-formation: is the process which generates motor commands to direct each robot toward to the correct location.

In order that each robot determines its position in the formation we use the technique of leader-referenced [1]. According to that technique each robot determines its formation position in relation to the leader robot (robot B). The leader does not attempt to maintain formation, only the following robot (robot C) is responsible for formation maintenance.

In this paper we assume that each robot of the formation is modeled as unicycle, so we have the following equations:

$$\dot{x}_i = u_i \cos\theta_i \tag{1}$$

$$\dot{y}_i = u_i \sin\theta_i, \qquad i = 1, 2 \tag{2}$$

$$\dot{\theta}_i = \omega_i \tag{3}$$

where u_i, ω_i denotes the translational and rotational velocity respectively and are considered as the control inputs, fig. 2.

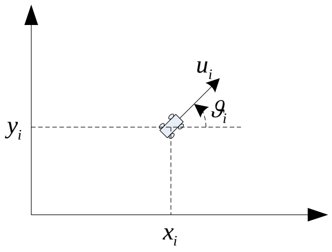

Fig. 2. Nonholonomic robot.

In our approach since the greenhouse is a well defined environment we use waypoints to get to a goal ($W_1 \rightarrow W_8$), fig. 3 [13].

Each robot starts it’s moving from the starting waypoint and moves towards the next waypoint until the desired position (goal).

B. Greenhouse Requirements

Greenhouse cultivation is a steadily growing agricultural sector all over the world [6], [7]. Climate parameters like temperature and humidity are properly controlled in the greenhouse, in order to ensure the maximum growth of the culture.

Among environmental conditions, the importance of photosynthetic photon flux (PPF) that affects growth and photosynthesis of plantlets has already been demonstrated in many species [4], [12], [14]. However, light quality alsoplays an important role in morphogenesis and photosynthesis [9], [18], influencing the way in which light is absorbed by the chlorophyll [21], [22]. Both light intensity and quality are used in growth models in order to predict the production of the crop.

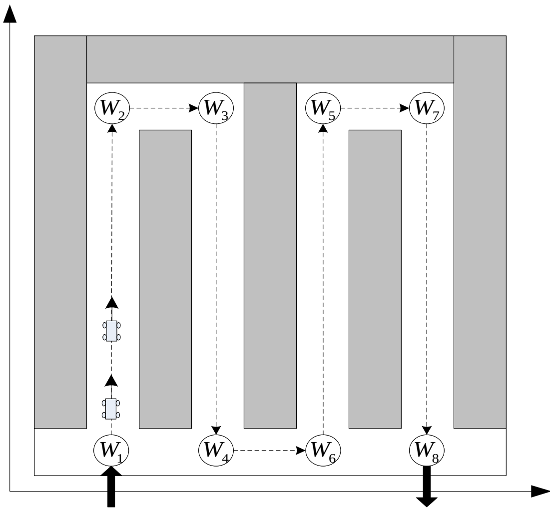

Fig. 3. Greenhouse ground plan.

In addition the most common and simple method used until now for scheduling irrigation in greenhouses consists in estimating the crop transpiration by means of the radiation-based method [20]. A solar integrator gives a starting signal to a water supply system after a previously set level of radiation is reached. An irrigation system controlled by a solar radiation method can appropriately supply water to plants without unnecessary water and nutrient emissions [17].

According to the above there is a grate necessity for accurate measurements on light intensity and quality in order to control the irrigation of the crop and to predict plan’s growth and production.

III. APPLICATION OF ROBOT FORMATION IN A GREENHOUSE

The system under investigation consists of a greenhouse and three nonholonomic UGV robots.

The greenhouse is constructed by translucent plastic as shown in figure 4. The interior consists from an alternation of double rows of plants and corridors for operations. The corridors length is 40m and its width is 0,90m.

Given that the greenhouse is a structure environment, it implies that the different objects populating the greenhouse area are carefully organized in order to leave free space for the robots movements. As consequence in our application we assume that no obstacles are present during the robots travel.

As aforementioned the multi robot team consists by three robots. At the beginning of the application the Pioneer 3-AT robot it is located outside the greenhouse, in front of the main entrance, while the other two robots are located at the starting waypoint (W_1). The desired distance among the robots of the formation is $0,5m$. Each one of them determines its position by dead reckoning having on board the pre-computed trajectory. At the starting way point we assume that robots have the correct orientation. The control algorithm on each robot take into consideration, the distance between the robot and the goal waypoint D_{w1}, and the difference angle ϑ_d between the goal angle ϑ_{w1} and the robot steering angle ϑ_i (fig. 5).

Fig. 4. Greenhouse structures.

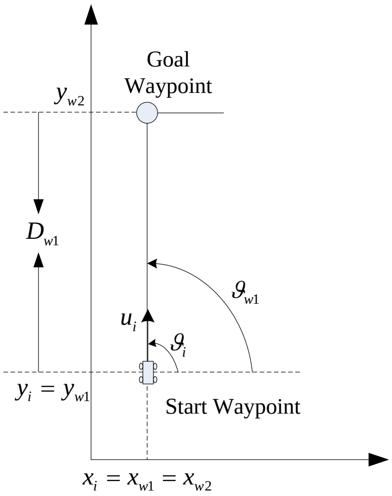

Fig. 5. Robot position and goal waypoint.

In fig. 5 is depicted the position of a robot, where x_i, y_i are robot Cartesian coordinates specifying its location and ϑ_i is the angle of the robot with respect to the horizontal axis. D_{w1} is the distance between the robot and the goal waypoint. As consequence we have the following equations:

$$D_{w1} = \sqrt{\left(x_{w1} - x_i\right)^2 + \left(y_{w1} - y_i\right)^2} \tag{4}$$

$$\vartheta_d = \vartheta_{w1} - \vartheta_i \tag{5}$$

and

$$\vartheta_{w1} = \tan^{-1}\left(\frac{y_{w1} - y_i}{x_{w1} - x_i}\right) \tag{6}$$

The two UGV robots of the formation are equipped with appropriate sensors as well as ZigBee modules (explained afterwards), in order to continuously communicate among them and with the base robot. Fig. 6 depicts the robot formation as the robots travels along a corridor.

Fig. 6. UGV robot formation in a greenhouse corridor.

In experimental runs the robot B start travelling, and after a specified time interval, and when it has covered the desired formation distance D_f, the robot C starts its travel. As above mentioned the robot C is responsible for formation maintenance. It receives the distance D_B that the leader has covered and in combination with its covered distance D_C, calculates the distance D_f among them:

$$D_f = D_B - D_C \tag{7}$$

If this distance became greater than a given threshold $D_{f_{H\lim}}$, the robot C increase its velocity, while if this distance became smaller than a given threshold $D_{f_{L\lim}}$, the robot C decrease its velocity, i.e.

$$D_{f_{H\lim}} < D_f < D_{f_{L\lim}} \tag{8}$$

Regarding communication, we used ZigBee/IEEE 802.15.4 protocol [10]. This protocol is selected for the following reasons:

1) One ZigBee network can contain more than 65,000 nodes (active devices). The network they form in cooperation with each other may take the shape of a star, a branching tree or a net (mesh). The ZigBee protocol does not require a host/slave configuration like many similar technologies, allowing for more flexibility in networking topologies such as mesh networking, broadcast mode, and packet rerouting. For this reason we can add via ad-hoc function

more robots in formation system and more sensors for different measurements.

2) The low-power model of ZigBee, offers a wireless transmission range of 100 meters. The maximum length of corridors in our application was 40m.
3) There were many transmission lines of high voltage around the greenhouses area. As consequence they produced powerful electromagnetic fields. Zigbee protocol offers low transmission bandwidth, high frequency transmission $2,4Ghz$ and low rate errors that are unaffected from electromagnetic fields.
4) Zigbee provides low-power electricity consumption during data transmission. For that reason we don't need extra power source for transmission module.
5) For reliable and secure data transmission in wireless networks, Zigbee offers a security toolbox including access control lists, data freshness timer and 128-bit encryption.

The block diagram of fig. 7 presents a completed ZigBee system, which contains microcontroller, MAC Layer, Network Layer, security (if needed) and the application profile with the sensors drivers that will be connected.

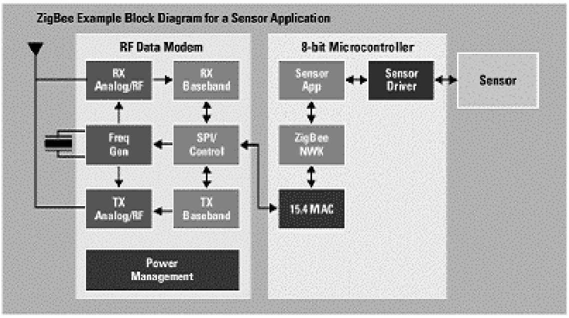

Fig. 7. ZigBee system.

IV. EXPERIMENTAL RESULTS

The experiments take place in a greenhouse at an experimental farm, during several days with different sunlight. The robot formation that was used for screening solar energy inside the greenhouse was equipped with appropriate sensors. The ground distance of each sensor is $30cm$.

During the experiments we proceed in four different scenarios:

1) Greenhouse windows closed (scenario GWC).
2) Greenhouse left window open (scenario GWLO).
3) Greenhouse windows open (scenario GWO).
4) Filter panel inside greenhouse (scenario FPG).

Every measurement was screened on front panel in LabVIEW code as shown in fig. 8.

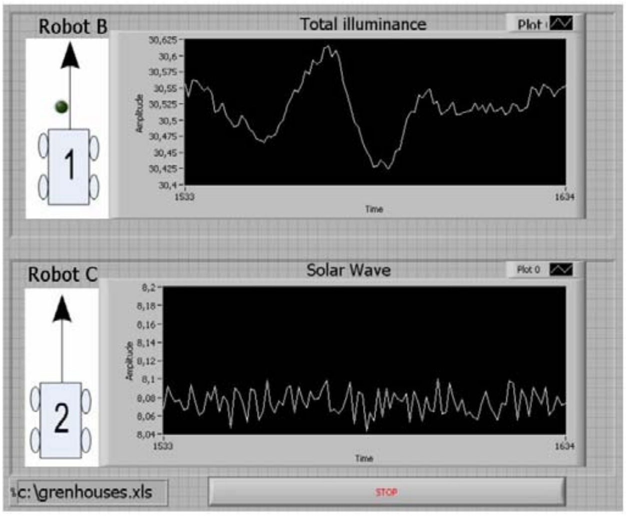

Fig. 8. Front Panel from the control in LabView.

In each experiment we measure, the photosynthetically active radiation expressed as the total luminous flux incident on a surface, per unit area (mW/cm^2) through the first robot, and the illuminance of specific wavelength at $660nm$ (in mW/cm^2 and $\mu W/cm^2$) via the second robot. The measurements concern the first row of plants, near the left window of the greenhouse. We must notice that along this row there are three fixed measurements points for each of the above magnitudes, located at $0, 20$ and 40 meters.

Each one of the following figures shows two lines. The irregular line depicts the robots measurements while the smooth line corresponds to the Gaussian distribution of the illuminance based on the fixed sensors measurements. As consequence we can compare the measurements obtained by the fixed sensors and the measurements provided from the robot formation.

A. Scenario GWC

In this scenario we measure the illuminance for the first row of plants which is near the left window of the greenhouse, while all windows are closed.

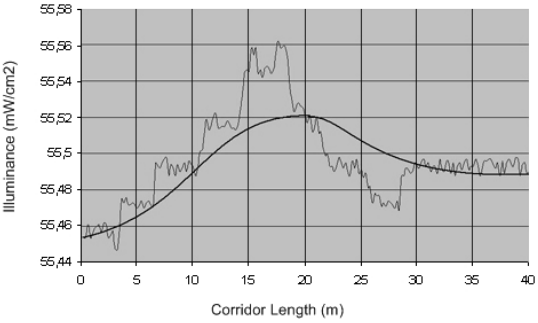

Fig. 9. Amplitude of the illuminance with closed windows.

Fig. 9 shows measurements of the illuminance along the first row of plants provided by the lead robot of the formation, while the smooth line corresponds to the Gaussian distribution of the illuminance based on the fixed sensors. Fig. 10 shows illuminance measurements for wavelength at $660nm$.

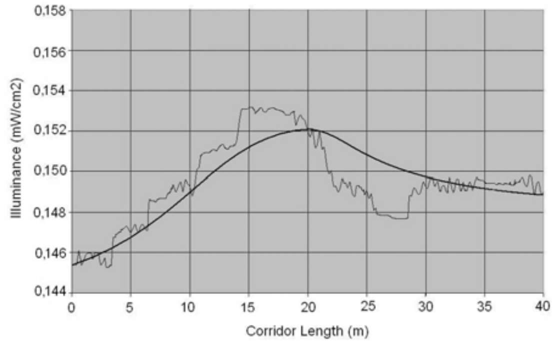

Fig. 10. Illuminance for wavelength of $660nm$ with closed windows.

B. Scenario GWLO

In this scenario we measure the illuminance for the first row of plants, while the left window is open. Fig. 11 depicts the differences peaks along that row.

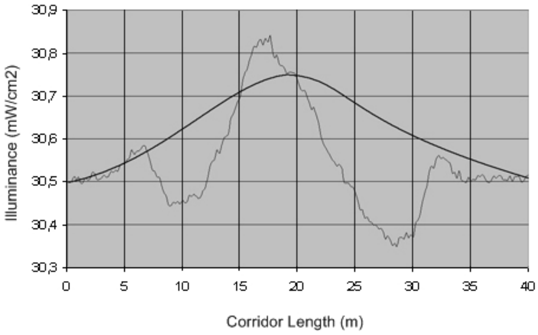

Fig. 11. Illuminance with left window open.

In fig. 12 we can observe measurements for wavelength at $660nm$, along the first row of plants.

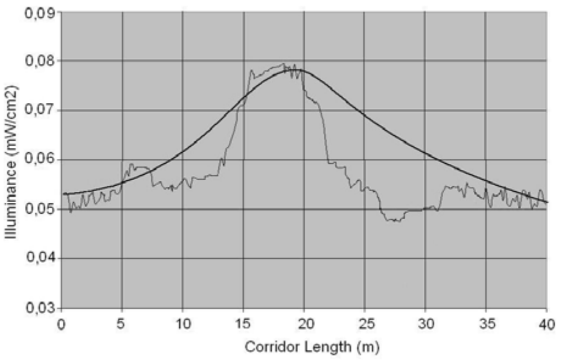

Fig. 12. Illuminance for wavelength of 660 nm with left window open.

Using the above results we can also compare the level of magnitude between the three fixed measurements points and the measurements provided by the robot formation. This information could be used to control which of the four independents parts of the left window must open for solar balance inside the greenhouse.

C. Scenario GWO

According to that scenario we measure the same variables while the left and the right window of the greenhouse are open.

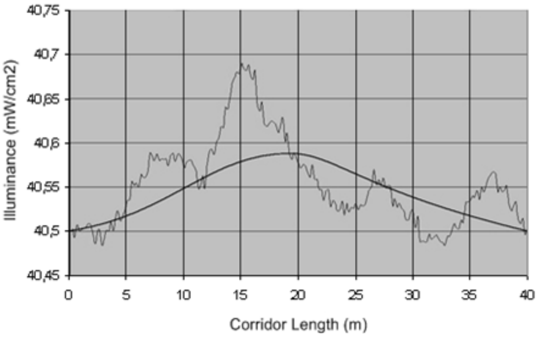

Fig. 13. Illuminance with left and right window open.

Fig. 13 shows the illuminance when both windows are open. Furthermore we can evaluate the level of magnitude between the three fixed measurements points and the measurements provided by the robot formation.

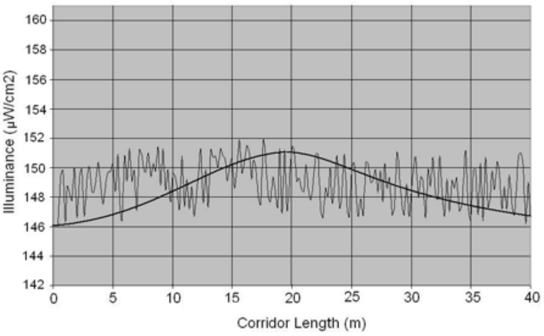

Fig. 14. Illuminance for wavelength of $660nm$ with left and right window open.

Fig. 14 presents the measurements for wavelength at $660nm$ with the same conditions.

D. Scenario FPG

In this scenario we applied a panel filter to cut the wavelength at $660nm$. This filter was set on the top of growth along the inside area of greenhouse (fig. 15).

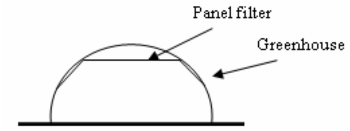

Fig. 15. Panel filter inside the greenhouse.

Fig. 16 shows measurements of the illuminance along the first row.

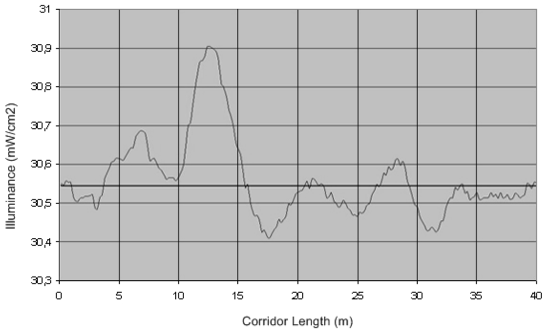

Fig. 16. Illuminance for the first row with filter panel in $\lambda = 660nm$.

Fig. 17 shows that the amplitude of the illuminance of wavelength at $660nm$ has been decreased.

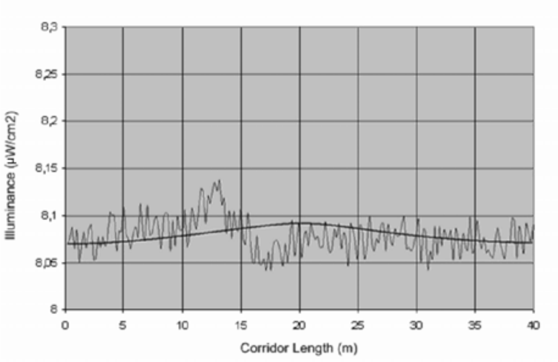

Fig. 17. Illuminance for wavelength of $660nm$ with filter panel at $660nm$.

V. CONCLUSION

The requirements of intensive agricultural processes and in particularly the structure environments of greenhouse necessitate the use of advanced and innovated technologies. The utilization of robotics in greenhouse environment is a necessary evolution of cultivation handling procedures that could result in significant benefits.

This paper presents an application of multiple nonholonomic robots which are used in order to create a desired formation scheme for screening solar energy in a greenhouse.

Solar radiation influences water requirements of agricultural cultivations and as consequence irrigation process. The proposed application provides measurements of the solar radiation that could result in more rational use of water reserves. In additional it can be used to the designing of the appropriate controller for the complete automation of greenhouses installations, as well as in sensors allocation inside the greenhouse area.

A topic of future research includes the application of the robot formation in environment with obstacles.

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