論文の内容の要旨

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論 文 題 目　Study on Localization System for Agricultural Vehicle Navigation Using Omnidirectional Vision
（全方位カメラによる農業用車両のナビゲーションのためのロカライゼーションシステムに関する研究）

With the problem dwindling in numbers of farm labor force and satisfying with precision agriculture necessary, agricultural vehicle automation is becoming more important. GPS is the most popular method for agricultural vehicle navigation. However, there are some limitations. First, its accuracy depends on the position of the satellites. In rural environments, especially in valley, hills or trees can obscure the microwave beams from satellites, resulting in a considerable drop in accuracy. To overcome this problem, the GPS sensor must be fused with other sensors, such as dead-reckoning sensors and machine vision sensors. Second, kinematic GPS for agricultural application is very expensive. Machine vision is also a popular method and other methods like GDS are not matured for application. Machine vision is a kind of cheaper and passive sensor, which has some excellent computer algorithms and matured success researches to support. GPS guidance system provides an absolute guidance system based on GPS base station on the ground, which is not affected by environments varying. The best solution on technology is a guidance system fusing with the technologies of GPS and machine vision.

Recently, omnidirectional vision sensors are very attractive for autonomous navigation system. An omnidirectional vision sensor is cheap and simply composed of a digital camera aiming at a catadioptric mirror. The images (obtained without rotating the robot) are 360° view of the environment and therefore are not sensitive to wheel slippage and small vibrations. Although it is not straightforward to obtain distance estimations from an omnidirectional image due to shape of the mirror, the apparent angles of objects from the robot are relatively accurate and easy to derive from the image.

In order to compensate for GPS that can use in the places where hills or trees obscure the microwave beams from satellites, resulting in a considerable drop in accuracy and develop a localization system substitute for GPS is used in the forage production, in greenhouse and apply for precision agriculture. We developed a new localization system based on low-cost omnidirectional vision and artificial landmarks which estimates an absolute position relative to the landmark-based coordinate system on the ground. In this work, we used an integrated-type omnidirectional vision consisting of a conventional USB camera and a hyperbolic mirror.

The field localization system for agricultural vehicle indoor and outdoor environments consists of four artificial landmarks, an omnidirectional vision sensor, PC and operating vehicle (as shown in Fig. 1). The system sets four red artificial landmarks as a rectangle in the corners of an operating spot and estimates an absolute position relative to the landmark-based coordinate system on the ground. The principle of localization is that the omnidirectional vision sensor takes the image of the landmarks and estimates the directional angles of landmarks in the image. Camera location is estimated based on the directional angles. The system is not only a potential substitute for the GPS guidance system to localize agricultural vehicles, but it can also operate common computer vision functions to support localization and obstacle avoidance. Based on the analysis of system features, we know that agricultural vehicles equipped with the localization system will likely carry out navigation using their “eyes” in the same way that mammals move around in the world.

The recognition of landmarks and extraction of features is pivotal to realizing localization. In farm fields, the same crop usually shows a homologous color pattern, which makes it very difficult to utilize natural crop landmarks as features for processing images. Omnidirectional vision having a 360° view can capture landmark images in different directions. In order to ensure that images are captured in all directions and provide the same results, the landmarks were designed as a right circular red cone. Furthermore, to distinguish the landmarks from environmental interferences, we proposed a color model with red and blue patches.

One algorithm is about landmark tracking extraction in which red landmark pixels beyond the threshold were extracted as a small area and the center of gravity was calculated for the extracted small area representing the candidate of one landmark. Generally, providing the blue patch as compensation to further distinguish the landmark from other objects in a complex environment, blue patch pixels beyond the threshold were extracted as a small area and the center of gravity was calculated and judged the candidate of landmark by the distance between the two centers of gravity. Then the positions of four representative landmarks were obtained.

One image processing is about noise smoothness, which the classic low-pass filter (LPF) was employed to remove high spatial frequency noise from digital images. We multiplied convolution kernel elements by the least common multiple to compute the weighted sum and then divide the summation with the least common multiple to obtain the real results to improve computational speed.

The second algorithm is about estimation of the position of vehicle installed with camera. Based on the obtained positions of four landmarks via the landmark tracking extraction algorithm, and then estimated the four directional angles of the landmarks centered by camera principal point using only one omnidirectional image. Vehicle location was estimated using the center of gravity of the four intersections formed by four arcs according to geometric transformation based on the four directional angles of the landmarks. If only find three landmarks, we also utilized the directional angles to estimate the vehicle location.

In the test, if we used PC (Intel Core 2, 2.33GHz) to process a piece of image resolution 1024×768, it took only about 0.1~0.2 s. The tracking extraction, position estimation algorithms and image processing (LPF) are robustness.

In the localization algorithm, the principal point in the image is pivotal position and other calibration parameters are useful for improving the accuracy of locating. The calibration method utilized a 2D calibration pattern that can be freely moved. Without a priori knowledge of the motion, the boundary ellipse of the catadioptric image and field of view (FOV) were used to obtain principal point and focal length. Then, the explicit homography between the calibration pattern and its virtual image was used to initialize the extrinsic parameters. Last, the intrinsic and extrinsic parameters were refined by nonlinear optimization. Experimental results are proved to the calibration method which is feasible and effective. Localization application experimental results show that calibration can provide with the principal point value and improve the accuracy of localization about 1.6 cm in a 0.9×1.8-m area. The role of calibration is very obvious.

For the fast and accurate self-localization applying for agriculture, artificial landmarks can be used very efficiently in the natural environment. Based on the proposed artificial color landmark model, balancing distance between landmark and camera, landmark height and camera height to enlarge the application area was considered. We theoretically analyzed the necessary to balance camera height and landmark height to enlarge application area. Experimental results show that adjusting camera height and landmark height can enlarge application area for agricultural vehicle localization and we can decide the landmark size by the relations about landmark image size with distance between landmark and camera, landmark height and camera height, respectively.

In order to prove the localization system, we have done indoor experiments and outdoor experiments to verify the feasibility and effectiveness for indoor and outdoor field. The agricultural vehicle often operates on uneven ground and vibrates, camera tilt experiments also have done to test the errors caused by tilt angle. Indoor experiments were conducted under daylight lamps in a 5.8×3.53-m rectangular area of the laboratory, and outdoor experiments were conducted under natural sunlight in a 50×50-m square area to verify the system. Indoor experimental results showed that the maximum and mean position errors were less than 8 cm in an illuminated and small environment (as shown in Tab. 1). Outdoor experimental results (as shown in Tab. 2) showed that the maximum and mean position errors were about 46.96 and 31.99 cm, respectively; camera tilt experiments (as shown in Tab. 3) showed that the tilt angle had some effect on errors, but not to an obvious level, and it was not necessary to compensate for the errors caused by camera tilt. In conclusion, the system is feasible and a potential compensation or substitute for GPS in agricultural vehicle navigation required for indoor and outdoor environments for our purpose.

We introduced a new localization method on road for agricultural field utilizing omnidirectional camera with two landmarks. Image process extracted landmark candidate in the image and estimated the image distance between landmark and camera. The localization algorithm estimated the absolute location of vehicle based on the distance computational model between landmark image distance and spatial distance. Experimental results (as shown in Tab. 4) show that the mean distance error is about 20 cm on a 20 m distance road test. The proposed localization method is feasible and effective for agricultural vehicles field road navigation.

In a whole, we divide agricultural vehicles localization into two solutions to realize navigation: Field localization and Field road localization. This study mainly developed a localization system for agricultural vehicle in the indoor and outdoor field. We also developed a localization system for agricultural vehicle in the field road. Both of them use an omnidirectional vision sensor and artificial landmarks with simple construction and easy operation.

Tab. 1 Errors in x, y and distance (D) in indoor experiment

	RMS error (cm)	Mean error (cm)	Max. error (cm)	Min. error (cm)
x	2.94	2.59	4.85	0.55
y	4.40	3.84	6.99	0.19
D	5.30	4.98	7.80	2.43

Tab. 2 Errors in x, y and distance (D) in outdoor experiment

	RMS error (cm)	Mean error (cm)	Max. error (cm)	Min. error (cm)
x	29.57	25.47	45.60	0.20
y	17.32	14.53	35.40	1.40
D	34.24	31.99	46.96	2.05

Tab. 3 Errors in distance (D) relative to zero degree position with varying tilt angle

Tilt angle (°)	RMS error (cm)	Mean error (cm)	Max. error (cm)	Min. error (cm)
±1	10.89	8.77	16.95	4.75
±2	12.46	11.59	15.54	7.33
±3	13.56	13.06	17.54	10.12
±4	16.60	14.90	18.11	10.32
±5	18.65	17.16	21.77	12.99

Tab. 4 Errors in x, y and distance (D) on 20m distance road experiment

	RMS error (cm)	Mean error (cm)	Max. error (cm)	Min. error (cm)
x	20.94	16.24	43.00	0.40
y	10.85	8.45	25.60	0.40
D	23.58	20.01	50.04	2.53