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Research paper

Efficient searching for grain storage container by combine robot☆

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ABSTRACT

In this study, a combine robot was equipped with an autonomous grain container searching function. In order to realize automated grain unloading, the combine robot has to search and identify the grain storage container in an outdoor environment. A planar board was attached to the container. The marker was searched for using a camera mounted on the unloading auger of the combine. An efficient marker searching procedure was proposed on the basis of a numerical analysis of the camera's field of view and was verified experimentally. The results showed that the combine robot efficiently searched for and detected the marker and positioned its spout at the target point over the container to unload the grain.

1. Introduction

In Japan, the number of workers engaged in agriculture is decreasing, and the average age of agricultural workers is rapidly increasing. Food self-sufficiency in Japan remains low compared to other developed countries. Japan must improve its agricultural productivity in order to maintain its sustainability. Field robots are expected to play an important role in improving the efficiency of agricultural operations and meeting workforce shortages. Attempts to develop automated agricultural machinery have previously been reported (Noguchi and Terao, 1997; Ishida et al., 1998; Nagasaka et al., 2004; Takai et al., 2010). In a previous study (Iida et al., 2013), we robotized a head-feeding combine harvester (hereafter referred to as a combine) and used it to harvest rice and wheat in fields. The combine robot successfully traveled along a target path and harvested rice crops autonomously.

However, a human operator is needed to manually control the combine and unload grain from its grain tank into a separate grain storage container. We aimed to automate the unloading operation as well. A pickup truck is driven and parked by a human driver on a farm road. The parking position of the truck is determined in advance. As the combine robot can obtain this parking position as Global Positioning Satellite (GPS) data, it autonomously travels to a position near the truck when the grain tank is full. However, the position of the combine relative to the pickup truck is not strictly fixed, because the human driver cannot perfectly park the pickup truck without positional errors. Thus, the combine robot has to find the pickup truck by an image processing technique and then correct its relative position to unload grain into the truck without any loss.

Kurita et al. (2012) utilized an image processing technique to appropriately position the unloading auger to unload grain. Fig. 1 shows the assumed situation for their concept.

A planar fiducial marker (aluminum board, 400 mm × 400 mm) is placed on the roof of the pickup truck to detect the position of the grain container. The position is extracted from images captured by the camera attached to the unloading auger. On the basis of the extracted image features, the positional relation between the combine and container is determined using image processing techniques. The experimental results showed that the auger spout can be visually positioned at the target point with sufficient accuracy. In addition to this basic concept, the combine robot is required to search for and detect the fiducial marker autonomously and accurately.

Another issue with searching for the marker is work efficiency. Because work efficiency is one of the most important concerns for the automation of agricultural machinery (Buckmaster and Hilton, 2005), agricultural operations using an autonomous machine should not take much longer than the time required to perform the same operation manually. Thus, the autonomous unloading system should be designed in such a manner that the fiducial marker can be located smoothly and integrated into the autonomous unloading operation as quickly as possible.

For efficiently locating a grain container, a camera is required to smoothly capture the fiducial marker. A combine robot should search for the marker so that the camera can sweep over as wide an

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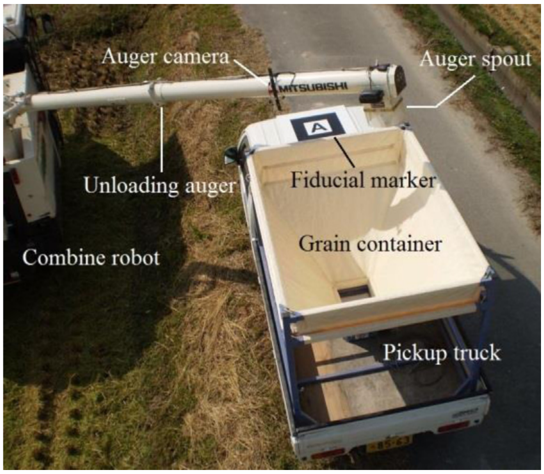

Fig. 1. Setup of autonomous unloading operation.

area as possible without overlapping. Thus, the strategy for efficient marker searching is closely linked to the camera's field of view (FOV) and its coverage. In visual servoing, the coverage of the camera's FOV is quite important for optimal control of a robot vehicle or manipulator; therefore, it has been widely studied by researchers concerned with mobile robots (Zhang and Ostrowski, 2002; Salaris et al., 2011), especially those who have developed a robot that searches for a particular object (Tsotsos and Shubina, 2007). It is difficult to actually measure the FOV of the auger camera for any set of decisive parameters, while a numerical simulation can give the FOV for any parameter with ease. Thus, the objectives of this study were as follows: to compute the FOV of the auger camera against FOV parameters based on the pinhole camera model, propose a marker searching algorithm in order to efficiently search for and accurately detect the marker and examine the actual performance of the proposed method with a combine robot.

2. Materials and methods

2.1. Kinematic modeling and mechanics of unloading auger

The test vehicle was a head-feeding combine harvester, VY50 CLAM (Mitsubishi Agricultural Machinery Co., Ltd, Shimane, Japan). The unloading auger of the combine was modeled with a two-degrees-of-freedom manipulator consisting of two joints (joints 1 and 2). As illustrated in Fig. 2, a right-handed coordinate system was assigned to the combine; the x axis of the coordinate system

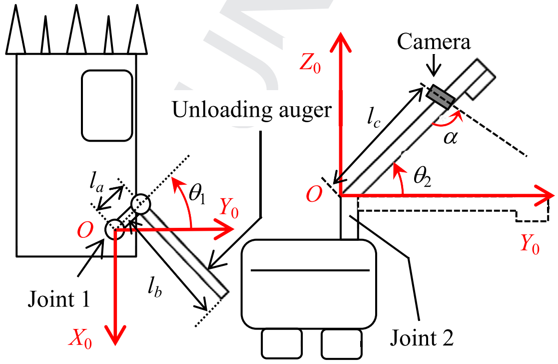

Fig. 2. Kinematic model of unloading auger.

Table 1
Camera specifications.

Model	UCAM-DLA200H (ELECOM)
Image sensor	1/4 in CMOS
Focal length	4.3 mm
F-number	1.8
Angle of view (diagonal)	60°

was along the body of the combine in the direction opposite to the direction of its motion, and the z axis pointed vertically upward. The state of the unloading auger was determined by the two joint angles (hereafter θ_1 and θ_2). Joint 1 rotated at an angle of $-110° < \theta_1 < 200°$. The grain could be discharged when $-110° < \theta_1 < 90°$. However, unloading was expected to be performed when $20° < \theta_1 < 90°$. Joint 2 rotated at an angle of $0° < \theta_2 < 45°$.

Joints 1 and 2 were actuated by a DC motor and hydraulic cylinder, respectively. Each joint rotated at a constant rate: 38.3°/s for joint 1 and 20.7°/s (upward) and 10.7°/s (downward) for joint 2 with on-off control. Link lengths l_a, l_b, and l_c were defined as shown in Fig. 2. The camera's elevation angle α was set to 71°. Table 1 lists the specifications of the camera.

2.2. FOV of auger camera

A rice paddy is usually enclosed by embankments and at least one farm road (see Fig. 3).

A commercialized head-feeding combine harvester is equipped with its unloading auger on the right side of the vehicle (see Fig. 3). As is the case for manned harvesting, the combine robot harvests rice crops in an anticlockwise fashion (Iida et al., 2013). Thus, in this study, the truck was always located on the right side of the combine. Let h_{fr} be the height of the adjacent farm road from a paddy field, h_c be the height of joint 1 of the combine harvester, and h_{kt} be the height of the pickup truck.

In general, the FOV can be represented by its angle of view (AOV) and depth of field (DOF). The AOV comprises the vertical and horizontal AOV. The DOF represents the area of the visual scene that is acceptably sharp. Outside of this range, images are blurred. The DOF depends on the focal length of the camera. In this study, the focal length of the camera was kept constant so that the DOF would fall within an acceptable range of sharpness. The DOF was empirically determined; at the same time, the target plane (i.e., the roof of the truck) was experimentally confirmed to form an image with sufficient sharpness for the expected range of the height from the paddy

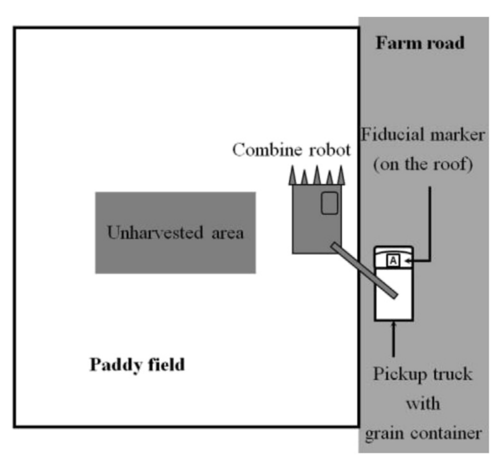

Fig. 3. Positional relation between the combine and the truck.