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Motion Planning for Autonomous Grain Carts

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Extended Abstract

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1. Introduction

1.1 Motivations

When harvesting grain crops on large farms, a combine follows a specific route to cover the field while a grain cart performs a series of supporting logistical tasks. When the combine's tank fills up, the grain cart approaches and drives alongside to unload the grain. Then the grain cart approaches and transfers the grain to a semi-trailer parked by the roadside for subsequent road transport. This work cycle is repeated throughout the harvest. There are several issues associated with human-driven grain carts including labor shortages and growing labor costs, operational imprecision and inefficiency as well as safety hazards, which could potentially be addressed if grain carts were autonomous.

1.2 Challenges

Temporal Constraints: The grain cart needs to meet the combine when the combine reaches full capacity. Otherwise, the combine may fill up and be forced to stop before the cart arrives, interrupting the harvest, or the grain cart may arrive too early and have to follow the combine before unloading starts, resulting in more fuel consumption and non-productive time. Spatial Constraints: Harvested areas traversable for the grain cart are constantly changing, and only the track to the left of the combine's path can be used for unloading. Unpredictability: Unexpected obstacles or events may occur during harvesting such as varying yield of different field areas and another vehicle's passing through. Numerous Parameters: the combine's dimensions, pose, speed, capacity, the field’s geometry and yield, and the grain cart's dimensions, pose, speed, unloading rate, and kinematic constraints.

1.3 Research Gaps

In industry, numerous farming equipment manufacturers have ongoing projects or products related to autonomous agricultural vehicles (AAVs). However, these AAV systems (e.g., remote control, leader-follower, driving assistance) are better described as semi-autonomous, as human supervision and control is still required. In academia, the majority of studies involving planning for AAVs solve simplified generic problems without focusing on specific farming operations that are often of higher complexity. The interactions between combines and automated grain carts have been scarcely investigated. Most production-level harvesting is still performed without detailed planning.

1.4 Objectives

The first objective of this study was to develop a motion planning algorithm for grain carts to autonomously navigate in the field and accomplish the logistical tasks in harvest operations, addressing the temporal and spatial constraints. Simulation tests were used to verify the effectiveness, robustness, efficiency and computational ease of the algorithm. The second objective was to provide a high-level software and hardware solution to building navigation systems on autonomous grain carts to implement the proposed planner. Mobile robot tests were used to first verify the effectiveness and practicality of the navigation solution and further verify the effectiveness, robustness, and efficiency of the planning algorithm.

2. Solution Procedure

2.1 Navigation Solution

Sensors: RTK-GPS features centimeter-level accuracy and broad range and was adopted for real-time global localization; 2D lidar was selected for local obstacle detection as it is accurate and robust, enabling fast detection over reasonable range with low cost; IMUs are robust, accurate and affordable and was employed for measurement of states of motion.

Communication: Both WLAN and ZigBee work as they feature low energy consumption, broad range, low cost, and simple configuration. Control: PID, simple and efficient, was sufficient for this application. Actuation Plan: Drive-by-wire powertrains (i.e., servomotors or electromechanical actuators directly controlled via electric wires) would work.

2.2 Planning Algorithm

Artificial Potential Field (APF) and Fuzzy Logic Control (FLC) were selected to form the basis of the planning algorithm. APF is known for its mathematical elegance, simplicity, computational efficiency as well as a major drawback: local minima traps. To exploit the advantages of APF and overcome its limitations, the influence range of the repulsive forces from obstacles can be set to be small, so that they are only effective when the grain cart travels dangerously close to obstacles. When the grain cart is safely away from the obstacles, another algorithm should be able to generate rational and efficient motion plans. Because a human operator can expertly navigate the grain cart in the field, their operational intelligence can be leveraged to perform efficient motion planning. Fuzzy Logic resembles the human decision-making methodology and is known for its simplicity, efficiency, and robustness in spite of uncertainty and imprecise information. Navigation in dynamic agricultural environments requires fast reactions to uncertainties, but the behaviors of agricultural vehicles are often too complex to be modeled accurately. FLC can directly leverage knowledge, experience and intuition as well as the imprecise reasoning and decision-making mechanism of human operators to provide planning solutions quite efficiently. FLC is thus a good choice for overcoming the deficiencies of APF. In this research, the attractive forces of APF always decide the heading towards the goal, but when the grain cart is safely away from the obstacles, FLC applies effective rules to generate motion plans that account for the GLOBAL efficiency of the motion. When the grain cart gets dangerously close to the obstacles that FLC has not circumvented, the repulsive forces of APF enable prompt avoidance of these LOCAL obstacles.

2.3 Test Design

The first set of simulation tests compared the proposed APF+FLC planner with a simple APF planner. A 2D virtual harvest operation was modeled and executed in MatLab. A set of actual yield monitor data from a corn field in Minnesota were used to validate the parameter specification of the simulations. The following tests were conducted: harvesting with no obstacles other than unharvested crop rows, and harvesting with random static or dynamic obstacles.

The second set of simulation tests compared the proposed APF+FLC planner with a Vector-Field-Histogram (VFH) planner. The following tests were conducted: (i) long obstacle with narrow gap; (ii) multiple obstacles close to goal; (iii) closely and (iv) sparsely spaced obstacles; (v) dynamic obstacles potentially blocking the way.

The mobile robot tests consisted of harvest operations and general collision avoidance tasks. The harvest operation tests included two robots, a Clearpath Jackal representing a grain cart and an EarthSense TerraSentia representing a combine. In addition, the following general tests were conducted, comparing the APF+FLC planner and a simple APF planner. (i) long obstacle; (ii) static obstacle close to goal; (iii) closely and (iv) sparsely spaced static obstacles; (v) numerous randomly-spaced obstacles; (vi) dynamic obstacle with no threat; (vii) dynamic obstacle blocking the way; (viii) malicious dynamic obstacle intentionally interfering.

3. Results and Conclusions

3.1 Simulation Tests

(i) Effectiveness and robustness. The grain cart was able to autonomously navigate in the field and accomplish all the logistical tasks in the harvest operations, addressing the spatial and temporal constraints. In addition, the proposed planner was effective and robust in guiding the grain cart to accomplish more general collision avoidance tasks involving different configurations of static or dynamic obstacles.

(ii) Efficiency. In the first set of simulation tests, the APF+FLC motion plans were always smoother and more rational, leading to more efficient routes with shorter trajectory length. In contrast, the simple APF planner experienced oscillations and local minima traps. In the second set of simulation tests, the APF+FLC motion plans tended to be less smooth than VFH motion plans, but they were more rational and efficient as they were much shorter. In contrast, the VFH planner was often unable to take advantage of shortcuts and easily misled by tricky obstacle configurations.

(iv) Computational ease. Running on an ordinary CPU, the APF+FLC planner consumed an average of 0.74 ms in each computation step to process the sensing information and generate updated motion plans, sufficiently fast for real-time applications.

3.2 Mobile Robot Tests

(i) Effectiveness and practicality of the navigation solution. The proposed navigation solution, featuring lidar-based local perception, IMU-based states measurement, WLAN-supported communication, APF+FLC planner, PID control, and Drive-by-wire powertrains, was implemented in the physical world and has proven effective and practical as it successfully guided the Jackal (robot representing grain cart) to navigate between the crop rows (represented by cardboard sheets) and accomplish the logistical tasks in the harvest operations.

(ii) Effectiveness and robustness of the motion planning algorithm. Dealing with a variety of navigation tasks with different configurations of static obstacles (represented by groups of cardboard sheets) and a dynamic obstacle with different threat levels (represented by another mobile robot), the proposed planner experienced no difficulty and was always able to generate intelligent motion plans for the Jackal to accomplish the tasks.

(iii) Efficiency. The simple APF planner sometimes led the Jackal into problems such as oscillations and local minima traps. Meanwhile, the APF+FLC planner was always able to generate efficient motion plans for the Jackal to accomplish the navigation tasks. Being smoother and more rational than the APF paths, the APF+FLC paths were always shorter, illustrating higher efficiency.

Final remarks concerning the competition benchmarks and strength points

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This study proposed a novel motion planning algorithm and an associated navigation solution to achieve full automation of grain carts, which no study has previously attempted. Experimental results from both simulations and actual mobile robot tests verified that the planner and navigation solution are effective, robust, efficient, and practical for potential adoption in actual autonomous grain carts, addressing the shortages and growing costs of labor while improving harvest productivity.