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A Robust Adaptive Controller for a Seed Refilling System on a Moving Platform ⋆

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Abstract: This paper considers an opportunity for robotic automation in the seeding of field crops. It reports on progress in designing a partially automated seed refilling system that transfers seeds to a centralized tank on a tractor-pulled planter during travel, while the tractor continues to follow a trajectory determined by a desired seeding strategy. The paper describes challenges associated with accommodating variability among commercial planters, as well as with formulating a control strategy for a robotic manipulator that compensates for time-dependent uncertainty and unknown disturbance loads due to travel of a mounting platform across uneven terrain. To address such challenges, the paper reviews theoretical predictions for a recently proposed adaptive control framework regarding the existence of transient performance bounds in the presence of fast uncertainty, as well as robustness to unmodeled dynamics in the form of time delays in the control signals. In particular, the theoretical treatment guarantees the existence of a positive time-delay margin, below which stable operation can be expected. Several experimental designs involving one or multiple robotic manipulators are considered in order to validate the theoretical results and to explore possible seed transfer strategies.

Keywords: Seeding, adaptive control, delay robustness, moving platforms, rough terrain, uncertainties.

1. INTRODUCTION

A potential target for robotic automation in agriculture is seeding of field crops. This task is time-consuming and sensitive to environmental conditions and crop properties, may involve complicated processes with multiple steps, and is clearly labor intensive if not automated properly. Efficient automation enables timely and systematic dispersal and planting according to seeding strategies that account for year-to-year changes in climate (He et al., 2012; Iizumi and Ramankutty, 2015), varying weather patterns during a growing season (McKenzie et al., 2005), as well as farm size and financial constraints (DuPont, 2012).

Opportunities for automation of seeding include development of autonomous or semi-autonomous vehicles that traverse a field based on predefined seeding patterns and information about current soil conditions, as well as mechanical apparatuses that plant individual seeds according to desired depth and spacing. Seeding vehicles may be guided by software algorithms that regulate the speed and direction of travel in order to provide optimal coverage of a field (Eaton et al., 2008; Li et al., 2009). Seed delivery mechanisms may be designed in order to decouple the speed of travel from the forward speed with which seeds enter the furrow (Garner et al., 2013), potentially reducing the time required for planting.

Common commercial seeding systems consist of a tractor pulling a frame (toolbar) to which individual seeding row units are attached. Each such row unit includes mechanical elements for opening and closing a furrow, as well as for metering seeds from a corresponding hopper or from a central tank situated on the frame. With a unit-to-unit spacing of 30 in, and as many as 48 parallel row units, commercial planters may be as wide as 120 ft.

When all the seeds in a hopper have been planted, the hopper must be refilled before operation can resume (see Fig. 1). Refilling may be performed entirely manually or using dedicated machinery. To our knowledge, no such machinery exists on the market or has been documented in the research literature. In current practice, the planter is returned to a seed storage building for refilling, interrupting the seeding operation for some period of time.

In this paper, we report on our progress in designing a partially automated refilling system, with dedicated machinery, that allows for continuous operation of a planter, without interruption and extraneous travel. Specifically, we propose the use of a semi-autonomous or fully autonomous refilling vehicle that includes a robotic manipulator arm for transferring seeds from an onboard tank to a central tank on a planter. Importantly, we envision this task being performed during travel, while the tractor continues to follow a trajectory determined by the desired seeding strategy.

To achieve this goal, it is necessary to design vehicle maneuvering strategies that allow a refilling vehicle to

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move into position relative to the planter and remain in formation even as both vehicles traverse an uncertain terrain. It is also necessary to design the kinematics of the transfer apparatus, including the robotic arm and, for example, a vacuum-based system for delivering the seeds to the planter. The control of the robot dynamics must account for variable alignment of the two vehicles, as well as unmodeled disturbances. On a higher level, it is desirable to develop planning strategies that allocate refilling vehicles in time and space to ensure continuous and simultaneous operation of one or several planters.

The remainder of this paper is organized as follows. Design challenges associated with the proposed system are discussed in Section 2. These challenges motivate a careful analysis of adaptive control strategies for multi-degree-of-freedom robotic manipulators on moving platforms. In Section 3, we review such a candidate strategy and describe recent results on its sensitivity to actuator time delay as an indicator of robustness to unmodeled dynamics. Several preliminary scaled experimental setups that validate the control strategy and explore key aspects of the refilling system are described in Section 4. Section 5 gives concluding remarks.

2. DESIGN CHALLENGES

The design of the proposed refilling system is a highly coupled problem. The maneuvering and positioning of the refilling vehicle depend on the shape and size of the tractor and planter system. These also constrain the choice of transfer strategy, as well as the mechanical design of the seed transfer system. The robotic control algorithm must be able to account for unmodeled dynamics of the refilling platform, excited by the variable terrain profile, and the uncertain alignment of the two vehicles.

There is great variability in the geometry of commercial planters. Widths range from 15 ft up to extreme widths of 120 ft. In some commercial systems, each row unit is equipped with an individual seed hopper, whereas the larger systems often rely on one or several centralized tanks. In the latter case, the tanks may be positioned either in front of the toolbar (relative to the direction of travel) or behind the toolbar, as shown in Fig. 1. In all instances, no load-bearing wheels traverse the parts of the terrain in which seeds have already been planted. For example, the wheels that hold the centralized tanks in the case where these are positioned behind the toolbar travel between the furrows.

Given such variability, there exists no general solution to the problem of identifying a relative configuration of the tractor/planter system and the refilling vehicle that allows for successful seed transfer during travel. Even if an approach from behind is the optimal choice, a maneuvering strategy that brings the refilling vehicle into position must avoid crossing planted furrows, and remain between the furrows until the edge of the field is reached. For an autonomous or semi-autonomous refilling vehicle, this may require sophisticated computer vision algorithms and communication with the planter when in close proximity.

Possible seed transfer strategies include the wholesale substitution of a full hopper for an empty one, or the delivery

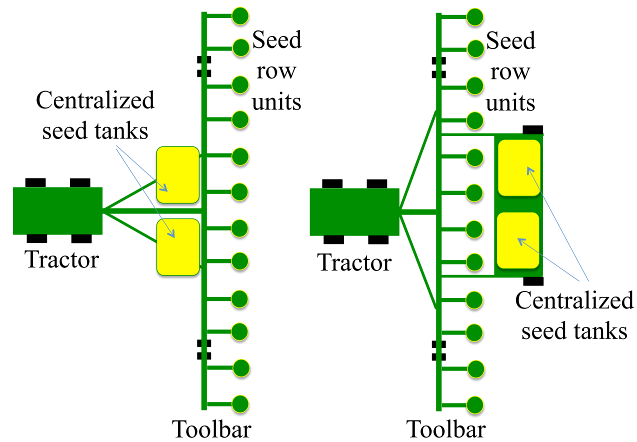

Fig. 1. Seeding tractors with centralized tanks mounted in front of (left) and behind (right) the toolbar.

of individual seeds from the refilling vehicle to the planter. Although it may be possible to replace individual hoppers during travel, it is unlikely that such a strategy would be deployed for a centralized tank, given the significant weight and size. While gravity may offer a possible physical mechanism for achieving transfer of individual seeds in a non-moving application, it is an unlikely candidate in the final design of a moving system, given the resulting raised center of gravity of the refilling vehicle. A more likely alternative is a pump-based system in which seeds are transferred through a flexible hose, modeled on those used to transfer seeds from a central tank to the individual row units (Shoup et al., 2008).

The mechanical design of the transfer system has to be able to accommodate different planter geometries, as well as time-dependent changes in the relative orientation of the two vehicles. It may be necessary to reconfigure the planter, including the design of a docking mechanism on a centralized tank. Transfer mechanisms with few degrees of freedom allow for simple control strategies, but may fail to engage and sustain the transfer connection in the presence of large disturbances. Additional degrees of freedom afford greater flexibility, but introduce challenges in the control design.

The design of a control framework for the seed transfer system may be decomposed into three stages. In the first stage, a specification of a desired task-space trajectory of the manipulator end effector is arrived at that also ensures the stability of the refilling vehicle to tip-over. In the second stage, the corresponding joint-space trajectories for the manipulator degrees of freedom are computed using sensor feedback that describes the relative motion of the two vehicles. Finally, in the third stage, an adaptive control framework is implemented to achieves stable performance of the system. This is designed to accommodate uncertainty and disturbances due to travel across a rough terrain and interactions with the planter, as well as unmodeled dynamics in the motor control system.

3. ADAPTIVE CONTROL FRAMEWORK

In the seeding application, the dynamics of the robotic manipulator are coupled to *a priori* unknown motions