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The Study on Autonomous Agricultural Machinery Modeling and Control Method

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Abstract: This paper presents a unified framework that will facilitate the implementation of future autonomous farming systems. It describes the coordination of information flow between what is called precision autonomous farming and Precision Agriculture. Precision Agriculture aims to fulfill the agronomical needs of the crop growth. Precision autonomous farming addresses the operation, guidance and control of autonomous machines to carry out agricultural tasks to satisfy agronomical needs. The paper also proposes the integration of various subsystems to form the entire autonomous farming system. In the area of autonomous farm machinery it will present the development of an experimental system based on a John Deere tractor and the robust control of the tractor that is subjected to side slip. In addition, it addresses the mathematical modeling of farm vehicle systems, especially for seeding in broad acre farming. Such vehicle systems include a tractor, an implement and a seed/fertilizer carrier. Results will be presented showing the effects of disturbances on a model that takes into account the lateral slip. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Precision farming, Precision agriculture, Autonomous agricultural vehicles.

1. Introduction

Developing autonomous systems for the agricultural industry is becoming an ever so important task, especially due to rising demand on quality agricultural produce and the continuously declining labour availability in rural farming areas. It is a well known fact that, for the deployment of fully autonomous machines, the farming systems must be far more structured than they currently are. A structured farming system substantially simplifies the application of robotic machinery, while ensuring greater reliability and productivity of operations. In particular, as applied to broad acre farming, all operations such as seeding, weeding, fertilizing, crop sensing and harvesting can be automated with unmanned machinery, if the farm land layout and the crop plantation can be structured. Primarily the aim is to achieve a desirable crop plantation pattern with respect to a global coordinate frame. Determining the crop plantation pattern is not a trivial task. It involves the land geometry its contour map, the geometric parameters of the available machinery and the crop being planted. In addition, a number of agronomical constraints will play a role. Nevertheless, this task can be carried out off-line before crop plantation is started. It is obvious that, to ensure a structured crop layout, seeding must be carried out as specified to ensure precision crop plantation. The complexity of the operation and the sub-inch precision required, rules out the human operators. Especially in broad acre farming, operating massive machinery generally rated around 200 to 400 horsepower, to maintain sub-inch seeding accuracy over often vast distances is impractical. Such accuracy essentially requires autonomous agricultural vehicles.

At the research level, there are a number of fronts progressing. Work in Precision Agriculture is, among other things, constantly evolving to provide better and more information about the agronomic requirements of the crop in order to produce maximum yield. In the development of precision autonomous machinery much work has been carried out in several areas. These include tractor guidance, whether it is laser-based [1], or GPS-based [2-4]. For agricultural tasks, precision guidance of the tractor is necessary, but not sufficient, as the tasks themselves are generally carried out by some form of trailing implement. As a result, research has been carried out in order to precisely control a tractor-implement combination. More specifically, dynamic modeling has been carried out in [5], and [6], while advanced control techniques are being developed to accurately guide tractor-implement (and similar) systems, [7, 8]. Finally, trajectory planning and control of articulated vehicles and farming machinery remains a central issue in the development of precision farming. A number of studies have taken advantage of the structure of the underlying dynamics of the vehicles for path planning and control [9-14].

2. Farming as a System-of-systems

The farming system can be in fact viewed and described as a more complex system-of-systems. It is driven by a set of inputs to produce a set of outputs, often via a complex and inter-related set of sub-systems. A high level architectural depiction is shown in Fig. 1 below, and briefly described following.

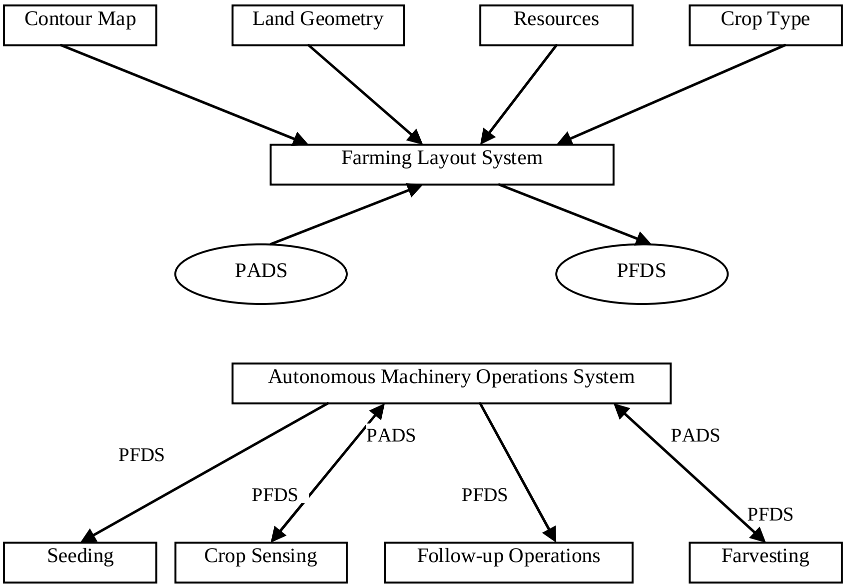

Fig. 1. The Farming System Architecture

2.1. Farming Layout

Various inputs, including information about land geometry, contour maps, available resources, and crop type are considered in order to determine the best or optimal crop layout and thus optimal traffic directions for the machinery. This will improve the crop laying accuracy as well as the efficiency of the machines being operated.

2.2. PFDS and PADS

It is proposed that the farm or crop layout process produces a Precision Farming Data Set (PFDS) which describes the crop layout. Such a set will describe the navigation and spatial accuracy requirements for the crop and provide a basis for other farming machinery sub-systems where spatial accuracy is required. In the case of broad acre farming, the PFDS will take the form of a route map for the tractors. This will aid in the required precision seeding, which in turn will aid in the precision and efficiency of follow-up operations.

A Precision Agriculture Data Set (PADS) will work in conjunction with the PFDS to ensure the agronomy requirements of the crop are satisfied. The PADS is a continually evolving entity developing as the crop growth continues and when crop sensing and other follow-up operations are taking place. It specifies such information as fertilizer type for a specific crop, application rates, herbicide and pesticide formulas and dosages, as well as ongoing monitoring information such as crop growth rates and soil conditions, all with respect to the spatial data.

2.3. Automated Machinery Operations

This system encompasses the operation of all farming machinery, whether partially or completely automated. Such operations include crop seeding, crop sensing, follow-up operations, and harvesting, and must of course be governed and operated in a coordinated fashion. The following briefly describes the machinery operations, however the reader is referred to [16] for more detailed descriptions.

1) Seeding System: Arguably one of the most important operations, the seeding systems must adhere to the PFDS in positioning each plant. All subsequent machinery-based operations on the crop will be then based on the seeding placement accuracy. In farming situations, it can be difficult to achieve implement accuracy due to several factors, the most pronounced being significant disturbance forces which act on it. These disturbance forces are predominantly due to either significant ground engagement, or gravitational effects, and can cause the implement to deviate from its desired course.

2) Crop Sensing System: Various parameters can be measured, such as foliage growth soil moisture content, and weed prevalence, type, and growth. These measured parameters are then fed into the continually evolving PADS, to ensure the efficient and accurate utilization of the machinery used for follow-up operations. So, delivery of inputs such as fertilizer, herbicides, and pesticides for example, can be done more accurately from a dosage point of view as well as spatially. Crop sensing can be done with the aid of the PFDS for ground based vehicles, or alternatively, sensing may take place via aerial means to detect such parameters as foliage growth.

3) Follow-up Operations: Follow-up operations include such operations as fertilizing, and application of herbicides and pesticides. These operations are controlled by the PADS which are updated via crop sensing data, as well as the PFDS originally constructed for spatial guidance. Autonomous machinery can be used to undertake these tasks, possibly consisting of a mobile platform such as a tractor, and a means to perform the specific operation.

4) Harvesting: In the final stage of the crop cycle, harvesting lends itself also to autonomous operation. Harvesting machinery can traverse the crop field once again guided by the PFDS, and may include the use of autonomous grain collecting vehicles operating adjacent to, and coordinated with the harvester. Importantly also, the harvesting stage should accommodate on-the-fly crop yield and quality measurement, input into the PADS.

3. Progress in Automating Farming Machinery

The employment of autonomous and unmanned farm vehicles can yield numerous benefits to the operation of the farm. It is hoped that such vehicles will afford a greater level of precision, on a consistent basis, and over more extended periods of continuous operation. This will result in a more productive and efficient farm, leading to economic gains. Arguably, being able to remove the operator from the vehicle itself will also lead to a decrease in safety hazards associated with manned operation.

As outlined in Section II, the scope of required precision tasks are varied and numerous. Such variation includes the level of precision, the type (if any) of mechanical attachments required, the amount of sensing required, and the level of intelligence employed to carry out the operation. It is proposed that at the heart of all farming operations is an autonomous vehicle, or Precision Autonomous Farming (PAF) unit. Despite the variation in the required tasks, each unit will typically be dedicated to be multi-functional. So, for example, a unit configured for crop sensing, can be easily and quickly (in real-time) re-configured and re-programmed for crop seeding. Further, for increased production and efficiency, and where practical, multiple PAF units may be used simultaneously, requiring increased intelligence and coordination.

At the heart of each autonomous vehicle or unit, is the ability to guide it in a precise and robust fashion. The requirement of its robust performance cannot be understated due to the uncertain and challenging environment that the farming landscape provides.

3.1. Robust Precision Guidance of an Agricultural Tractor

Ongoing work by the authors involves autonomous guidance of a retro-fitted John Deere tractor, introduced in [15], and shown in Fig. 2. A feature of the retro-fitted tractor is its ability to operate in either manned or un-manned modes.

1) The Autonomous Tractor Testbed: A platform is located at the rear of the tractor, and used to mount most necessary equipment, including the on-board computer, motor amplifier, watchdog circuitry for safety remote start-up circuitry Intertial Measurement Unit (IMU), modems for all navigation, encoder circuitry and connector boxes.

Navigation is achieved through the use of dual Differential RTK GPS aided by a tilt sensor and IMU system. Two GPS receivers are located on top of, and either side of, the tractor roll bar, with accuracies of 2 cFm and 20 cFm respectively. Differential GPS data is obtained via the use of a third base station receiver. The dual GPS data allows the accurate (to within 2 cm) position as well as roll and yaw to be determined. Determining the pitch of the tractor is only possible with the additional information obtained from the tilt sensor. The IMU is precisely mounted on the platform also, and provides acceleration information. It is primarily used for short term position tracking in between GPS measurements and as a back-up to the dual differential GPS. Orientation information becomes a more significant issue in an agricultural setting where there are real conditions to contend with, such as ground undulation and uncertainty sloping terrain, and type slippage.

In addition to the above instrumentation, wheel encoders are installed, one on each rear wheel, and enable a back-up measurement of the velocity of the tractor, but more importantly, can be used to provide information about rear wheel slippage when its data is compared to data from the navigation system.

Fig. 2. John Deere compact agricultural tractor.

In order to ensure precise navigation of the tractor, a high-level path tracking controller has to be designed and implemented, which is responsible for determining appropriate actuation for the tractor, including the desired steering angle and desired wheel speed. Low-level feedback controllers to control the actual steering angle and wheel speed have been designed and implemented.

2) Kinematic Model: Robust and precise guidance of the tractor is achieved by considering its kinematic model. In turn, the kinematic model of the tractor is derived by considering the model of Fig. 3. In this model, the front wheels are represented by a single wheel along the longitudinal axis of the tractor. Steering is via the front wheel, while the drive is via the rear wheels. A similar model may be noted in [13] where a more detailed derivation may also be seen. Importantly, the model includes the effects of vehicle slip, which is realistic in an agricultural setting where the ground conditions are uncertain and undulating.

A suitable kinematic model description of the vehicle in Fig. 3 is given by the following equations:

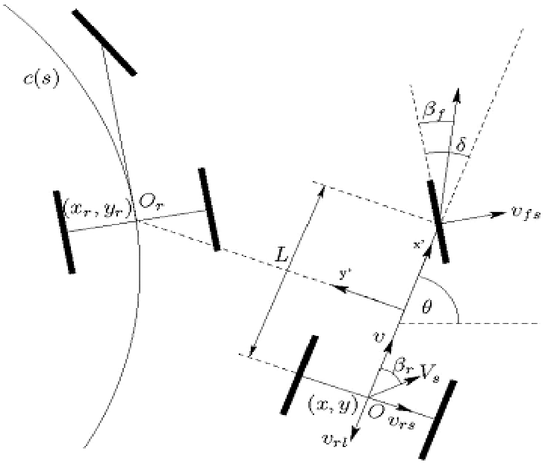

Fig. 3. Tractor system showing reference trajectory.

$$\begin{aligned}
\dot{x} &= v\cos\theta - v_{rl}\cos\theta - v_{rs}\sin\theta \\
\dot{y} &= v\sin\theta - v_{rl}\sin\theta - v_{rs}\cos\theta \\
\dot{\theta} &= \frac{v - v_{rl}}{L}\left[\tan\beta_r + \tan\left(\delta - \beta_f\right)\right], \\
&= \frac{v - v_{rl}}{L}\tan\left(\delta - \beta_f\right) + \frac{v_{rs}}{L} \\
\dot{\delta} &= u
\end{aligned} \qquad (1)$$

where (x, y) represents the position of the center point O, of the rear axle, θ is the orientation of the tractor's longitudinal axis, and δ is the angle of the front steered wheel with respect to the longitudinal axis. The inputs are the steering angle rate u, and the drive speed v. The wheelbase is represented by L. Importantly, in this model; the vehicle slip is represented by several parameters. In the longitudinal direction, the slip velocity v_{rl} acts in opposition to the drive speed, and the slip velocity v_{rs} acts in the lateral direction. Note, the effects of the slip generated at each of the rear wheels is combined and applied at the center point of the rear axle, O. At the front of the tractor, slip is described by the angle β_f. The slip angle at the rear axle is described by β_f. The coordinate (x_r, y_r) and curvature c(s) denote the parameterization of the reference, or desired, trajectory.

3) Sliding-Mode Trajectory Tracking Control: The robust and precise guidance of the tractor is achieved by utilizing a combination of sliding mode control and the now widely used back stepping technique. The controller is derived in [14], and constitutes a modification/improvement of the work in [13]. The design philosophy is briefly outlined below.

Using traditional first order sliding mode control, a control law is designed to force the system state onto a manifold, or sliding surface. Such a control law is typically designed to be discontinuous, thus ensuring it remains on the surface, even in the presence of certain disturbances. While on the surface, the dynamics governing the motion of the state are of order one less than that of the state, and are thus often referred to as the reduced order dynamics. The problem then becomes one of ensuring that the reduced order dynamics are stable, allowing the system state to slide along the surface towards its ultimate and desired destination on the surface.

In the presence of other disturbances such as those present in the tractor model of (1) and represented by the slip velocities, true and ideal sliding does not occur for a first order design. In this case, one can hope that the design forces the state to be bounded and to remain sufficiently close to the sliding surface.

In this design a sliding surface is defined first, and a discontinuous control law is designed to force the state towards the surface. To ensure the appropriate and stable sliding behavior while on the surface, the backstopping technique is used on the reduced order dynamics. The backstopping design is once again based on that used in [16]. In this design however, a robust damping design is employed, rather than parameter adaption, which although may produce a more conservative control law, also allows for slip velocity disturbances which are time varying but bounded. Experimental results demonstrating the performance of the controller are not yet available, as tuning and hardware modifications are still being undertaken on the existing John Deere tractor platform.

However, simulation results are promising and are shown below in Fig. 4. The figure shows the simulation of the tractor under sliding mode control with disturbance or slip velocities acting on it. As can be seen the tractor is attempting to track a trajectory made up of straight lines and semi-circular paths. The initial position of the tractor is in error and thus the control has to bring it into line with the desired trajectory. In the absence of experimental validation, slip velocities are applied and assumed to be at a level up to approximately 10 % of the velocity of the tractor. This level is to be confirmed once experiments can be undertaken completely.

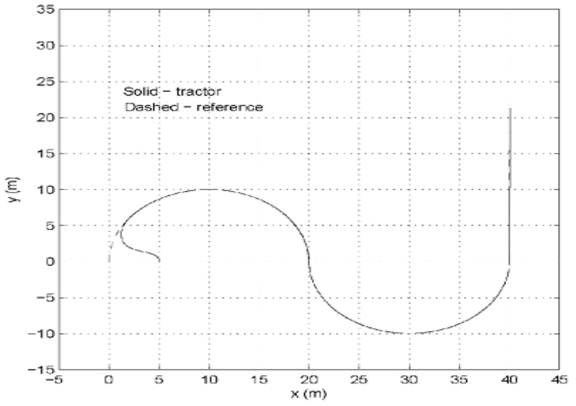

Fig. 4. Robust trajectory tracking using sliding-mode control.

3.2. Precision Seeding Machinery

As already established, the operation of seeding takes place is via the use of a seeding implement being pulled by a tractor. As can be seen the operation of precise and autonomous seeding builds upon the foundation of having an autonomous farm vehicle capable of precise navigation. To achieve the required and strict precision in seed placement, precise guidance of the tractor alone is not sufficient. Some means has to be devised to guide the implement precisely, which not only requires control of the implement, but also the coordination of both the tractor and implement. A particular avenue of research by the authors is focusing on the design and precise guidance of an active (rather than passive) seeding implement, pulled by the autonomous tractor. Design of a prototype active implement has been carried out, with construction now being undertaken.

For the seeding system precise and autonomous seeding is considerably challenging due to the level of precision required, but also the complex and significant ground contact forces disturbing the whole unit. The unit will consist of the tractor and the seeding implement minimally, but may also include a third trailing element for carrying the necessary seed and fertilizer. This further adds to the challenge of precise control.

A vital part of being able to control such a complex system is developing comprehensive models which describe their dynamic behavior as a whole, and how their constituent parts interact. Only then can one be confident of designing an appropriate control to achieve the precise guidance. Recent work in [17] has reported the detailed dynamic model development of a tractor-implement-trailer combination. This model accounts for both non-slip and slip conditions, where the non-slip model is representative of ideal conditions, and the slip model represents conditions likely to be encountered in real farming situations. The model is based on the John Deere tractor already retro-fitted by the authors. Of note, the inputs to the model include those of the tractor (propulsion of the rear tractor wheel and steering), and in addition, steering of the implement wheels. Steering of the implement provides active implement control and is necessary for its precise robust guidance.

Fig. 5 shows simulation results for the tractor-implement-trailer model under varying conditions. Specifically, the tractor is subjected to constant propulsion inputs, and the steering is varied. After steering the tractor straight for a time, the front wheel steering is actuated to the right for a short period, and then actuated to the left again to straighten the tractor wheel up.

In the figure, the trajectory of the implement is plotted, comparing both the no-slip condition as well as the slip condition with differing lateral disturbance levels. The disturbance forces applied simulate the effect of traversing across ground with a grade of 2 % and 6 % respectively, sloping from top to bottom in the plot. This demonstrates the need for a steering and propulsion controller for the tractor and implement to maintain accurate path tracking while subjected to disturbances.

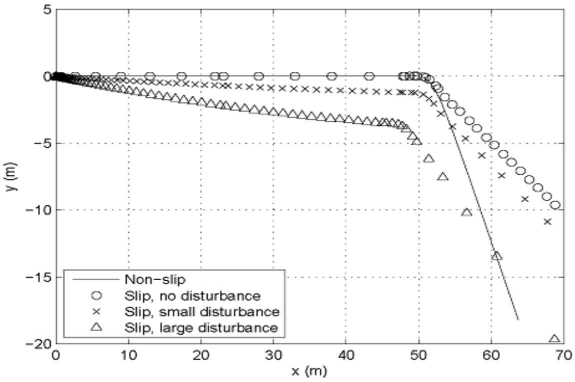

Fig. 5. The implement trajectory for all four cases: (i) Non-slip; (ii) Slip, no disturbance; (iii) Slip, small disturbance; (iv) Slip, large disturbance.

3.3. Non-Herbicidal Weeding Machinery

Weed eradication requires the two stages of weed detection and weed destruction, and generally takes places two to three weeks into most of the broad acre crop growth. Weed detection is an area that has already received significant research attention. And there are systems that are currently operating employing crude means of detecting weeds. That is, any plants that appear to absorb more nitrogen are considered a weed. Weed destruction on the other hand is mostly carried out by spraying an herbicide. The current practices do not allow the herbicide treatments to be optimized to suit the weeds to be eradicated as there are no means of identifying the individual weed types. Hence there is a need to develop methodologies to detect the prevalence and the individual weed types so that the correct treatment and dosage can be applied to individual weed types.

A more advantageous approach is to find non-herbicidal methods. Methodologies such as electrocution, electro-ration, microwaving, heating and cooling, to name a few, should be considered as alternatives. This immediately eliminates the need to determine the herbicide formula and dosage and therefore, the need to identify the weed type. These methods are particularly suitable for crop that is planted according to a PFDS. The weeds that grow in the crop row itself will compete with the crop for vital nutrients, and in general be defeated. This reduces the need for in-row intervention to eradicate weeds. However, all plants, weeds or otherwise, that grow in the inter-row space will absorb nutrients that were meant for the crop and will cause growth retardation of the crop.

The authors have completed preliminary developments of a non-herbicidal weedier that has PFDS/laser/vision guided crop tracking capability with high voltage plasma arcs targeting all plants in the inter-row space. The small foot print (0.75 m × 0.50 m × 0.45 m) robot shown in Fig. 6 has motorized Ackermann steering, electronically geared rear wheel drive and differential, a pair of stereo cameras, a laser range finder, GPS and a long range communication system. For the destruction of weeds, a five electrode plasma arc generation system is attached to a well insulated cradle that extends out at the back of the robot.

Similar to the operation of crop seeding, the autonomous weeding vehicle forms the basis for the operation of autonomous non-herbicidal weeding, and is required to be accurately guided. Similar methods of robust tracking control can be employed as those described above.

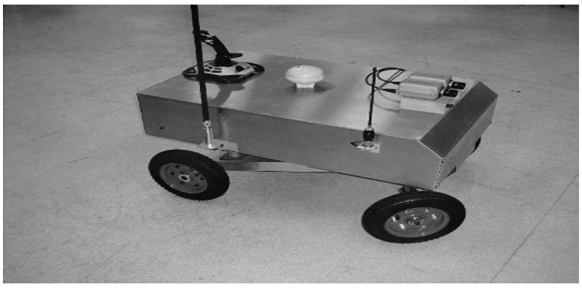

Fig. 6. Weeding robot.

4. Conclusion

This paper has presented the requirements and progress made towards achieving a future precision autonomous farming system. The system proposed is a relatively complex, although structured and hierarchical one, consisting of systems within systems. Importantly, there is a need to introduce strict structure into the system, aiding in autonomous operation. In turn autonomous operation further strengthens and maintains such structure. Another issue emphasized is the importance of integrating farm system, or Precision Agriculture, requirements, with robotic solutions for autonomous farming. Central to this idea was the proposal of the implementation of the PFDS and PADS, and their strong interaction. The PFDS is primarily used for relaying spatial accuracy information for machinery navigation, while the PADS are used to communicate the agronomy information about, and requirements of, the crop.

The additional main theme of the paper centered around the design and use of robust trajectory tracking farm vehicles, with emphasis on a retro-fitted John Deere tractor and small-footprint weeding vehicle, both capable of being used as a stand alone autonomous vehicle or as a foundation for precise seeding and weeding operations. Design and simulation of a robust trajectory tracking controller is certainly promising, however experimental validation is necessary to prove its worth. Similarly, simulation of a complex seeding system comprising a tractor, implement, and trailer has allowed some insight to be gained about the challenge and complexity waiting when designing seeding system controllers.

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