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Systems Engineering Approach to Agricultural Automation: New Developments

Jayantha Katupitiya†, Ray Eaton‡ and Tahir Yaqub†
ARC Centre of Excellence for Autonomous Systems
†School of Mechanical and Manufacturing Engineering
‡School of Electrical Engineering and Telecommunications
The University of New South Wales
Sydney, NSW 2052, Australia
Email:J.Katupitiya,R.Eaton@unsw.edu.au

Abstract— **This paper presents the Systems Engineering approach to future Precision Autonomous Farming (PAF). It focuses on the preferred specification of the farming systems including the farming system layout, sensing systems and actuation units such as tractors-implement combinations. The authors propose the development of the Precision Farming Data Set (PFDS) which is formed off-line before the commencement of the crop cultivation and discusses its use in accomplishing reliable, cost effective and efficient farming systems. The work currently in progress towards the development of autonomous farming vehicles and the results obtained through detailed mathematical analysis of example actuation units will also be presented.**

Keywords: Precision Farming, Precision Agriculture, Autonomous Agricultural vehicles.

I. INTRODUCTION

This paper discusses the Systems Engineering Approach that will lead to the development of future Precision Autonomous Farming Systems. Over the years, the agricultural industry underwent gradual changes by shifting from a labor intensive industry to a highly mechanized industry. This was essential due to the vast expanses of land that needed crop cultivation to meet the demands on agricultural goods. As the land utilization increased, the labor availability in rural areas declined, thereby emphasizing the need for large scale operator driven machines.

Today the agricultural industry faces a new set of challenges. Due to the inability of the farming communities to sustain continuation of farming, the corporate world has emerged as the new caretaker of the agricultural industry. This has led to new directions in agriculture.

Given these changes, the agricultural industry is becoming ever so dependent on the machinery usage with the minimum availability of a workforce. Hence the need to develop autonomous farming systems that deploy unmanned sensing and machinery systems with the possibility of centralized tele-supervision has been on the increase. Autonomous machinery will form the backbone of future precision autonomous farming systems.

It is a well known fact that the robotic solutions are sought to replace tasks that were traditionally carried out by human operators. Human operators have the remarkable ability to deal with unstructured environments and unexpected events. To match the capability of human operators, robotic systems require an unprecedented level of machine intelligence. While these are realizable as complex algorithmic developments at research level, and might perhaps be usable in the distant future, they are yet to be tested and qualified for commercial use.

At research level, however, there are a number of fronts progressing. On the tractor guidance front extensive work is presented in [1] and [2]. Laser based tractor guidance is reported in [3]. John Deere's Green Star precision farming system [4] is a commercial realization of a RTK-GPS based system. On the tractor implement guidance front, advanced control methodologies are proposed in [5], [6]. Dynamic models for tractor-trailer systems have been considered in [7] while the authors are currently working on a complete dynamic model. A direct implement guidance system using laser to sense crop rows is described in [8].

The authors take the approach that the farming systems must be well structured at the farming systems layout level for new farms and at the seeding stage for existing farms. The aim is to minimize the complexity of mechanical operations with an an absolute minimum number of human operators while ensuring sub-inch spatial precision in all mechanical operations. In order to achieve this it is proposed that a Precision Farming Data Set must be generated that ensures the maximum structure in the land.

II. The Farming System

As with many systems, the farming system is a complex entity which functions via the operation of several sub-systems, coordinated together to achieve common goals. For the farming system, such goals, or outputs, typically include crop yield quantity, crop yield quality, and the efficiency of farming operations. Maximizing these variables ultimately results in maximizing financial, or economic, gains. The system is also excited by various inputs, including the type and amount of seed, fertilizer, pesticide, and herbicide, as well as fuel to drive the equipment. Along with these inputs, it is a complex mix of Precision Agricultural and Precision Farming methods, executed by the various farming sub-systems, that drive the farming system outputs. These sub-systems are described in Section III.

III. Sub-Systems of a Farming System

The farming system described above have a number of sub-systems that operate at a lower level.As of now, the farming land mass of the world is fully allocated and developed. Most of the time only minor changes takes place to the boundaries of the farm although major restructuring can still take place within the allocated land. Thus, the emphasis is on the restructuring of the existing farms so that they become amenable to autonomous farming. The following sub sections describe some of the sub-systems and their requirements.

A. Farming system layout

Farming system layout is a major task that needs to be undertaken with the sole view of facilitating and simplifying the autonomous machinery usage while maximizing the outputs. It is a well known fact that, the more structured the farm is, the easier and more reliable is the machinery usage. Following factors must be taken into account in determining the optimum layout for the farm.

The contour map of the farm must be considered in determining the traffic directions for the machinery. If the traffic directions can be laid out to minimize the gravitational effects on the equipment such as seeding systems, one of the most unwanted disturbance forces can be eliminated, thereby improving the crop laying accuracy. Land geometry plays an important role in determining the length of traffic runs. The proportion of straight line traffic to headland traffic must be maximized. Thus, the geometry of the land can be used to chose the traffic directions in such a manner that longest possible straight runs are ensured. The soil type data and other precision agricultural data that may be readily available can be used to carve out areas of the land that are deemed to be unprofitable. These areas has to be taken into account with respect to the traffic directions, either by deciding to avoid traveling in these areas or by deciding to incorporate them into the traffic direction with the agricultural operations turned off within these regions. This decision has to be made depending on the cost of 'travel avoidance' on the control of heavy machinery. Other factors to be considered are the delivery of inputs such as fuel for the machines, seeds, fertilizer, herbicides and pesticides and the extraction of outputs, namely the crop. These goods need to be transported in and out of the farm and thus requires additional vehicular traffic which can also be optimized.

With these in mind, software packages can be developed so that for a given set of machinery, crop, land geometry and soil data, optimized traffic layout can be determined.

B. Seeding System

Once a good farming system has been laid out, the next most important stage is the seeding stage. As seeding positions each plant, all follow up operations such as weeding and fertilizing has to follow the seeding pattern. It is therefore important to carry out seeding so that the machinery usage for all follow up operations is simplified. Hence, it is important to use the Precision Farming Data Set (PFDS) in conjunction with the farm system layout that has been already drawn out. Initially, PFDS must contain navigational data for the machinery that will carry out seeding. In the case of broad acre farming, this would be a route map for the tractors. Today's tractor guidance technology is well developed and it is an easy matter for a tractor to follow a specified trajectory with sub inch precision[1]. However, the actual agricultural task is not carried out by the tractors; they are carried out by the implement that is being passively dragged behind. The implements however fail to follow the exact path due to a number of reasons. While geometry of the articulated vehicle system plays some role, the most pronounced reason for the implements to deviate from the desired path are the disturbance forces acting on them.

Unlike all other agricultural operations, seeding requires significant ground engagement. In broad acre farming, seeding implements can be over 10m wide and are pulled by tractors of over 200 HP. The seeding implements have a large number of tines that dig up to 12 cm into the ground to open the ground for seed placement. Depending on the ground undulations in the lateral direction, some of the tines may dig deeper into the ground than the others. Moreover, the seeding implements also place some fertilizer next to the seeding points. Thus the seeding implement must carry with it a seed container and a fertilizer container. These units are generally dragged behind the seeding implement. In addition to these, there may be some gravitational forces acting on the implements. All these forces, and the possible tine interaction with stubble from the last season form a substantial amount of disturbances.

Given these disturbance forces, controlling an implement to follow a certain desired path is not an easy matter. The implement's inability to follow the exact path often leads to over-cropping or under-cropping along the overlapping areas of adjacent seeding runs. Poor implement behavior also limits the inter-row cropping in alternating seasons. Inter-row cropping requires the seeds to be planted exactly in the middle of two crop rows that were planted last season. The typical gap between two crop rows is about 23 cm. Sub-inch precision of the implement motion is essential in achieving inter-row cropping. Note that, ensuring inter-row cropping also avoid the stubble interference. Precision guidance of implements also aids the strict enforcement of *Controlled Traffic* conditions [9], [10]. Under controlled traffic, the wheels of the tractors and the implements are restricted to follow fixed, narrow straight tracks. Thus the amount of steering permitted is minimum. This approach ensures the preservation of soil structure from compaction due to traffic. See Section IV for currently ongoing work by the authors. Their studies will lead to the development of new generation tractor-implement combinations that will deliver the requirements set by the PFDS with sub-inch precision, while overcoming all forms of disturbances.

If the crop is planted exactly according to the PFDS, then the need to localize crop through sophisticated sensing can be eliminated. This enhances the speed and the cost effectiveness of follow-up operations.

C. Crop sensing System

During the growth of the crop a variety of sensing have to be carried out. The data gathered during the growth of the crop feeds into the Precision Agriculture Data Set (PADS). The basic difference between the PFDS and PADS is that PFDS specifies the spatial data and their accuracy for all on-field mechanical manipulations such as seeding and fertilizing, while PADS contains agronomy data such as foliage growth and soil moisture content with respect to the spatial data. Crop sensing forms an important part of the entire farming system in that it enriches the PADS so that required inputs such as fertilizer, herbicides and pesticides can be delivered with greater accuracy in dosage and spatial precision. As these inputs are to be delivered using precision autonomous farming machinery, the already available PFDS can be used to guide a mobile platform such as a tractor while the PADS can be used to actuate the implement such as a variable rate fertilizer applicator. This process, in the form of a control loop continues until the objective of maximum possible growth is achieved uniformly across the field.

Foliage growth monitoring can be used to detect the affected areas of the farm. Spectral imaging, either ground vehicle mounted or airborne may be used to detect the reflectance variations across the crop. The growth monitoring data will directly feed into the PADS and based on the agronomy needs, a map to apply fertilizer can be drawn up.

In general, weed eradication takes places two to three weeks into most of the broad acre crop growth. Weed eradication requires the two stages of weed detection and weed destruction. The systems that are currently operating have crude means of detecting weeds. Any plant that appear to absorb more nitrogen is considered a weed. Weed destruction is mostly by spraying a 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.

The weed destruction itself can be improved by avoiding the use of herbicides. Methodologies such as electrocution, electroporation, microwaving, heating and cooling etc should be considered as alternatives.

D. Follow Up Operations

The follow up operations take place during the entire crop growth period. Among the follow up operations are; fertilizer, pesticide and herbicide applications.

Based on the sensing described earlier, the variable rate applicators must be controlled to deliver the correct type and amount of inputs to the crop so that the detected condition, let it be nutrient, weed or pest, can be rectified. Especially in broad care farming to carry out all these tasks, intelligent machinery must be developed. The PFDS that was originally used to lay the crop can now be used with greater ease to navigate all autonomous vehicles that will carry out follow up operations. Note that, all follow up operations do not have any ground contact and as such adhering to the controlled traffic conditions is much easier in the follow up operations. Unlike at the seeding stage, the implement operation will be controlled by the PADS that will determine, in the case of fertilizing the application rate and in the case of weeding the treatment and the dosage. This information is entirely based on the agronomy needs of the crop.

E. Harvesting System

The final stage of the farming cycle is the harvesting stage. Note that no precision implement operation is necessary at this stage. However, bearing in mind that the controlled traffic conditions may not be violated, it is still important that the harvesting machinery follow the PFDS. As the harvested grain is to be collected by a vehicle traveling alongside the harvester, autonomous systems can be developed through the application of cooperative control of ground vehicles, so that despite the absence of a mechanical link, the grain collecting vehicle can track the path of the harvester in a manner that does not violate the controlled traffic conditions.

Of extreme importance is the on-the-fly grain quality measurement so that as the grain travels from the harvester to the collecting vehicle grain quality and quantity is measured and fed into the PADS. This information is vital for sorting out the grain into different categories based on quality.

Other proposed work in the area includes the destruction of weed seeds that exits the harvester together with the chaff. In effect, the harvester actually acts as a weed seed sawing machine. New research is necessary to address this issue.

IV. NEW DEVELOPMENTS

A. Autonomous Farm Vehicles

Farming systems that can employ autonomous operation can be of great benefit when precision is required, as it is predominantly true that autonomously controlled and unmanned agents will achieve a significantly superior level of precision on a consistent basis. Autonomous and unmanned agents yield additional benefits as well. From an economic point of view, significant increases in productivity are afforded by the flexibility of operating the autonomous systems for far greater periods of time than would otherwise be possible using manned operations. From a safety perspective, it can also be argued that utilising autonomous farming systems can reduce or eliminate hazards that are inherently present in manned systems.

As outlined previously in Section III, the scope of precision tasks that are required are varied and numerous. It is proposed that each precision farming task be carried out by an autonomous system, or Precision Autonomous Farming (PAF) unit. Each autonomous unit will typically be dedicated to one precision task, with some units being developed to be multi-function units. Where possible and realistic, it is proposed that multiple autonomous units operate simultaneously, whether performing the same task or not. Intelligent coordination is required in this scenario, and should be implemented from a centralized control telesupervision location. From this centralized location, monitoring, planning, and command generation for each autonomous unit can be implemented.

Predominantly, each farming unit consists of a tractor, responsible for navigation throughout the crop, and an attached implement which is designed to carry out the assigned agricultural task. The tractor and implement tend to be attached via an off axle hitch point, allowing for the relative movement or misalignment of the implement with respect to the tractor. The implication of such relative movement is that not only must the tractor be navigated precisely, but also, and more importantly, so must the implement. Active agricultural implement control is an area identified by the farming community as important, and is one of the major areas of focus of research for the authors.

To date, much work has been undertaken in tractor control. Indeed, commercially available tractors exist, so called "auto-steer" tractors, which provide precise navigation. Via the use of Real-Time Kinematic GPS (RTK-GPS), these tractors control the steering and propulsion of the tractor, in order for it to precisely track a pre-defined and structured path. Such precision guidance of the prime-mover is vital, but is not sufficient for precise implement control. In addition, all commercially available "autosteer" tractors are not completely autonomous, or unmanned, thus not taking advantage of some of the benefits of autonomous operation.

Work already undertaken by the authors has involved the retro-fitting of an existing tractor, such that it can operates in either manned, or unmanned and autonomous modes. The tractor is a John Deere, compact agricultural tractor, pictured in Fig. 1.

Fig. 1. John Deere Compact Agricultural Tractor

Mounted at the rear of the tractor, a platform houses most of the necessary equipment to automate the tractor, such as the on-board embedded computer, remote start-up circuitry, power amplifiers, safety (watchdog) circuit, and most navigation equipment.

In developing autonomous and unmanned vehicles for farming operations, emphasis is placed on safety. A *watchdog* circuit is implemented such that in the event of any fault conditions, the watchdog system halts all mechanical sub-systems of the tractor, including its propulsion and steering. Much of the possible fault conditions are associated with the software that controls the tractor. The various parts of the software are responsible for regularly communicating "still alive" signals to each other and externally to the watchdog circuit. Failure to receive such signals will result in a halt to tractor operations.

Navigation of the tractor is achieved through the use of a dual differential GPS supplemented with a tilt sensor and Inertial Measurement Unit (IMU). Mounted on top of, and to one side of, the tractor roll bar, a GPS receiver has an accuracy of 2 cm. Differential GPS data is obtained via the use of a third base station receiver, also with 2 cm accuracy, fixed at a pre-determined location. This differential GPS data allows the determination of the spatial position of the tractor with the required precision. GPS data from a second GPS receiver located on the other side of the tractor roll bar, allows roll and yaw orientation information to be obtained. 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, and provides acceleration information. It is primarily used for short term position tracking 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 tyre slippage, as discussed in Section III.

The on-board computer is driven by a real-time operating system, with the designed software responsible for monitoring and controlling the various sub-systems of the tractor in real-time, including the safety, steering, and traction (propulsion) subsystems. An external, and remote PC is also used, linked to the on-board computer via a wireless network. This allows remote supervision of the autonomous tractor system, with commands able to be sent from, and monitoring information received to, the remote computer.

In order to ensure precise navigation, a high-level path tracking controller is to be designed which determines appropriate actuations 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. See [11] and [12] for further details.

It should be stated that the advantage of retrofitting the tractor not only lies in the ability to easily switch between autonomous and manual operation, but also in it being a more economically viable and realistic solutions for farmers who do not want to, or cannot afford to, invest additional finances in new machinery.

B. Modeling and Control of Complex Systems

The autonomous tractor provides a vital infrastructure for building more complex systems, namely the Precision Autonomous Farming (PAF) units, capable of carrying out the various required precision tasks. For a tractor and implement unit, as discussed in Section III, the implement itself is subjected to significant disturbances, uncertainty, and ground contact forces that can prevent the implement from delivering its required precision. Ensuring the implement delivers such precision requires controlling the complex system as a whole, not just controlling its constituent parts.

Control of complex systems such as the tractor and implement unit requires significant research. Firstly the development of complete and comprehensive models which describe their behaviour is necessary in order to understand the relationship between the two components. Secondly, and only then, can a suitable autonomous control methodology be devised capable of providing the required precise operation. Thus far, significant work by the authors has been carried in modeling and simulating a tractor and implement unit, such that a complete model exists which describes the dynamic and coupled behaviour of both.

The model developed accounts for both non-slip and slip conditions. The non-slip model represents ideal performance, whereas the slip model represents what may be encountered in a real agricultural environment, where ground and tyre conditions are less than ideal. In the model, the dynamics developed for the tractor are based on the existing John Deere compact agricultural tractor already retro-fitted, with front wheel steering and four wheel or two wheel (rear) propulsion.

As a complex system, the tractor and implement unit is highly nonlinear. Inputs to drive the system include the traction, or propulsion forces of the rear and front wheels, as well as steering inputs for the tractor and implement. Allowing the implement wheels to be actuated gives active, rather than passive, implement control, which is necessary to obtain precise control under the influence of the disturbances and uncertainty already discussed. Outputs of the system include the spatial position of the implement (the position of the tractor can also be regarded as an output, but is of lesser importance), the orientation of the implement with respect to a fixed coordinate frame, and the alignment angle between the tractor and implement longitudinal axes. All outputs have to be suitably controlled for the precise agricultural tasks proposed. A feature of the model simulation is the inclusion of effects of real conditions. In particular, forces to account for rolling resistance at the rear and front tractor wheels, as well as implement wheels, were included. For implements such as seeders which have significant ground interaction, a ground contact drag force was also included. Finally, to simulate the gravitational effects of operating the machinery on sloping terrain, it was necessary to add additional, lateral disturbance forces acting on

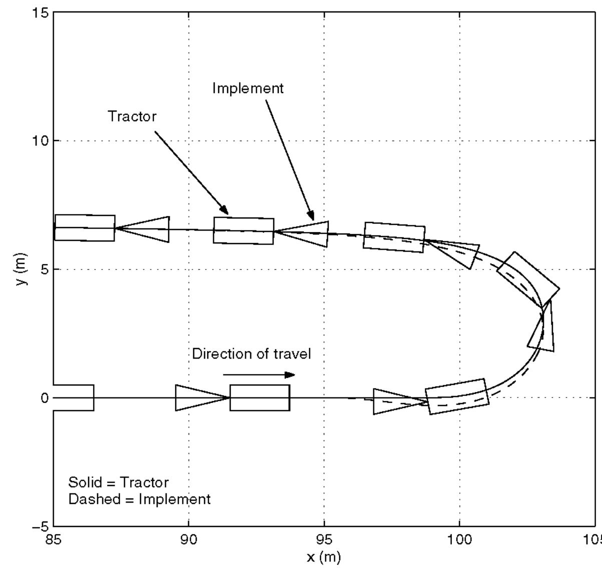

Fig. 2. Tractor-Implement trajectory under no-slip condition

both the tractor and implement.

Figures 2-4 show simulation results for the tractor/implement model under varying conditions and inputs. Specifically, the tractor is subjected to constant propulsion inputs, and the steering is varied to simulate traversing left (in the negative y direction) around a bend. In Fig. 2, part of the animated trajectory of the tractor and implement is shown under no-slip conditions. Of particular note, it can be seen that while in the bend, the trajectory of the implement (the dashed line) exhibits a “kick” outside that of the tractor, then recovers and moves inside the tractor trajectory. After the tractor straightens up again, so does the implement, and the two trajectories align themselves. For Fig. 3, the same trajectories are plotted under the same inputs and conditions, except this time allowing for the slip. A significant difference is observed. Note also that the trajectory of the implement while traversing the bend, starts to slip outside that of the tractor, indicating additional slippage of the rear of the implement. Finally, in Fig.4, the effect of applying a lateral disturbance force is seen. The forces applied effectively simulates the tractor and implement traversing across ground with a slope of approximately 10% grade downwards from top to bottom on the plot (in the negative y direction). Once again, the plot shows a marked effect that sloping terrain can have on the trajectory of both components.

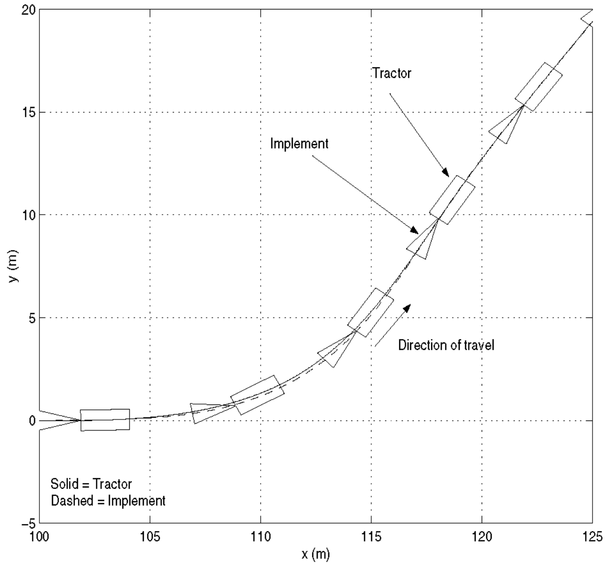

Fig. 3. Tractor-Implement trajectory with slip, no disturbances

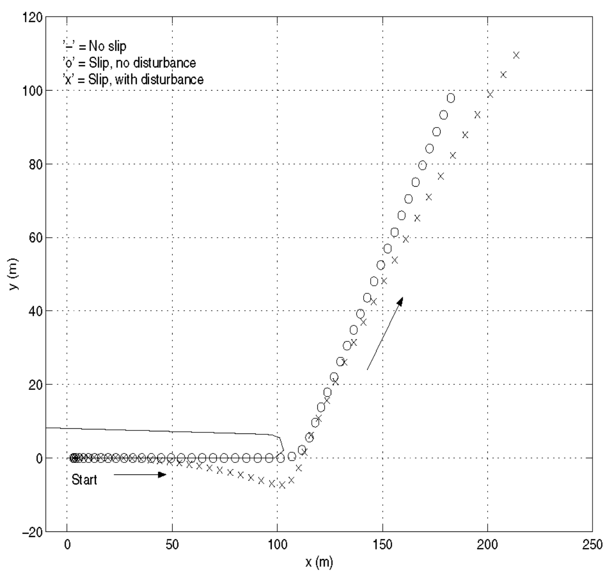

Fig. 4. Tractor trajectories for all cases

V. CONCLUSION

This paper presents the requirements of a future autonomous farming system. It emphasized the need to introduce a strict structure and the importance of taking into considerations the farm system parameters in developing an *a priori* PFDS that is continuously used by each precision autonomous farming unit. The PFDS is primarily used for machinery navigation and seeding. There exists a strong interface between the PFDS and PADS. The PADS is used to actuate the implements so that required inputs can be delivered in quantity and quality at the exact locations as desired. Autonomous farming is an ideal multi-disciplinary set up where systems engineering approach can be used to realize the successful operation of a well coordinated set of widely varying sub systems.

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