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Precision Autonomous Guidance of Agricultural Vehicles for Future Autonomous Farming

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Abstract. *Due primarily to an increased emphasis on global competition, and a significant reduction in the available workforce, the agricultural industry is facing significant cultural shifts at present. These factors induce a demand for increased efficiency and productivity in farming operations, which in turn, lends itself to an increase in the need for so called Precision Autonomous Farming (PAF). This paper presents a systems engineering approach to precision autonomous farming in broad acre crops, and central to this approach, progress made in achieving precision guidance of agricultural vehicles. An overview of the farming system is presented, depicting a system-of-systems architecture, where a vital interplay between Precision Agricultural (PA) methods and precision machinery automation exists. Such autonomous machinery is assumed used for seeding, crop sensing, harvesting, weeding and other follow-up operations. The authors propose the development and ongoing management of two data sets, namely, a Precision Agricultural Data Set (PADS), used to ensure any agronomy requirements of the crop are met, and a Precision Farming Data Set (PFDS) formed off-line before crop cultivation, and used to achieve optimal performance of the farming system by specifying the spatial precision required for agricultural operations. Preliminary results are shown, highlighting the development and use of a fully instrumented tractor, as well as initial research into developing high level path tracking controller for such machinery.*

Keywords. Precision Farming, Precision Agriculture, Autonomous Navigation.

1 Introduction

The agricultural farming industry is facing significant challenges at present. Over time, the availability of skilled and unskilled labour has declined, adding to the need an already increasing level of mechanization. In addition to this, it is increasingly more difficult for communities to sustain the farming industry in a time when it is more globally competitive.

One of the consequences of a reduced labour workforce and a more competitive environment, has been the need to develop autonomous farming systems, capable of deploying autonomous sensors and farming machinery, under centralized tele-supervision. It is the belief of the authors that such autonomous machinery will in the future form the backbone of precision autonomous farming systems. For most optimal efficiency and productivity, these autonomous farming systems will also oversee the use of precision agricultural and environmental information and ensure its interaction with the autonomous farming machinery.

In shifting towards autonomous farming, arguably one of the biggest challenges is in developing and integrating robotic solutions into the farming landscape. The more unstructured and uncertain the environment is, the more machine intelligence is required to achieve the required precision operation. A further challenge will then be to introduce as much structure as possible into the environment in the pre-crop cultivation stage.

At the research level, there are a number of fronts progressing. Work in Precision Agriculture (PA) 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, including tractor guidance, whether it be laser- or GPS-based (Ryo et al., 2004; Bell, 2000). 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, some research has been carried out in order to precisely control a tractor-implement combination. More specifically, work has been carried out in dynamic modeling of tractor-implement systems, the development of advanced control techniques, and trajectory planning and control (see Eaton et al. (2008) and references therein for further details). Unfortunately, a major shortcoming of research thus far, is the inability to deal with real agricultural conditions, giving rise to physical slip of the tractor and implement due to significant disturbance forces. Achieving precision and autonomous guidance of a tractor and implement is thus a significant component of the author’s research agenda.

The paper is organized as follows: A brief overview of the farming system is presented in Section 2 including a system-of-systems description. In Section 3, progress made in the development of precise and automated agricultural machinery is described, including a tractor-implement set-up for precision seeding, and an autonomous vehicle test bed for precision and non-herbicidal crop weeding. Results will be presented in this section, including those obtained from work done on the advanced modeling of a tractor-implement system with an additional attached trailer, the physical testing of the instrumentation on board a John Deere tractor, and preliminary trajectory planning and control simulations.

2 The Farming System

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 Figure 1 below, and briefly described following.

2.1 Farming Layout System

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.

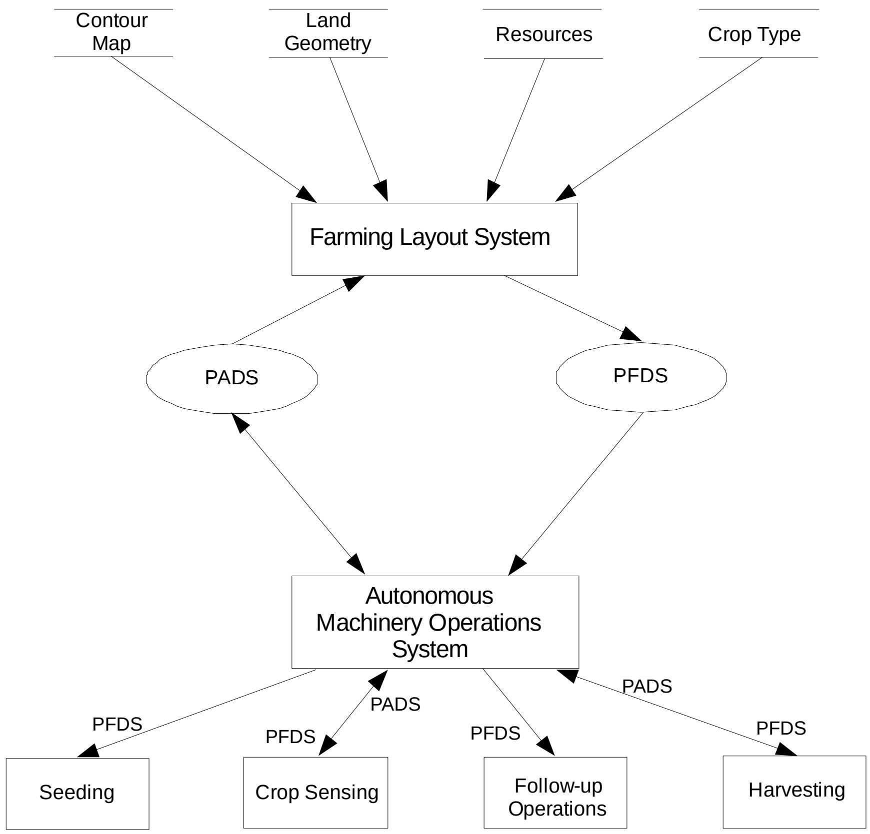

Figure 1. The Farming System Architecture.

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 operation.

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 Katupitiya et al. (2007) for more detailed descriptions.

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.

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.

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 is 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.

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

As proposed in Katupitiya et al., (2007), each farming machine is typically dedicated to one task, but may be multi-functional. For increased production and efficiency, and where practical, multiple machines may be used simultaneously, requiring increased intelligence and coordination.

Work by the authors in the area of automated farm machinery is progressing on several fronts, related to precision seeding on the one hand, and follow-up operations, on the other, specifically the operation of weeding. This progress is reported below.

3.1 Precision Autonomous Seeding Machinery

As already established, precise guidance of the tractor alone is not sufficient to achieve the required precision, so some means has to be devised to guide the implement precisely also. One avenue of research by the authors is focusing on the design and precise guidance of an active (rather than passive) seeding implement, pulled by an autonomous tractor. Design of a prototype active implement has been carried out, with construction now being undertaken. Work with the precision guidance of the autonomous tractor continues however, with the system now fully instrumented and efforts being directed towards more complete and extended dynamic models, and designing different robust trajectory tracking nonlinear controllers.

An Autonomous Agricultural Tractor Test bed

It is fairly widely known that so called "auto-steer" tractors are already commercially available, which provide precise navigation via GPS (RTK-GPS). These tractors control the steering of the tractor, but while still requiring it to be manned as usual. The authors have been continuing work with a now retro-fitted John Deere compact agricultural tractor, as introduced in Katupitiya et al., (2007), and pictured in Figure 3, which can be operated in both manned (manual) or fully autonomous mode.

Figure 3. John Deere Compact Agricultural Tractor.

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, Inertial Measurement Unit (IMU), modems for all navigation, encoder circuitry, and connector boxes.

Apart from safety, navigation is arguably one of the most important sub-systems on the tractor, and 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 2cm and 20cm respectively. Differential GPS data is obtained via the use of a third base station receiver, fixed at a pre-determined location. The dual GPS data allows the accurate (to within 2cm) 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. It is important to stress the need for tractor orientation information as well as spatial position information. The orientation of the tractor will not only have an influence on the behaviour of the tractor, but also, and more importantly, on any attached implements. 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. 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.

Testing and confirmation of the GPS navigation system was done, yielding several sets of results, one of which is displayed in Figure 4. Here, the GPS data was obtained in real-time while the tractor was driven manually, and loaded into Google Earth® off-line. Note that real-time plotting of data is also possibly within Google Earth®. The data shows several parallel runs made across the oval, each time going around the edge of the oval to start the new run.

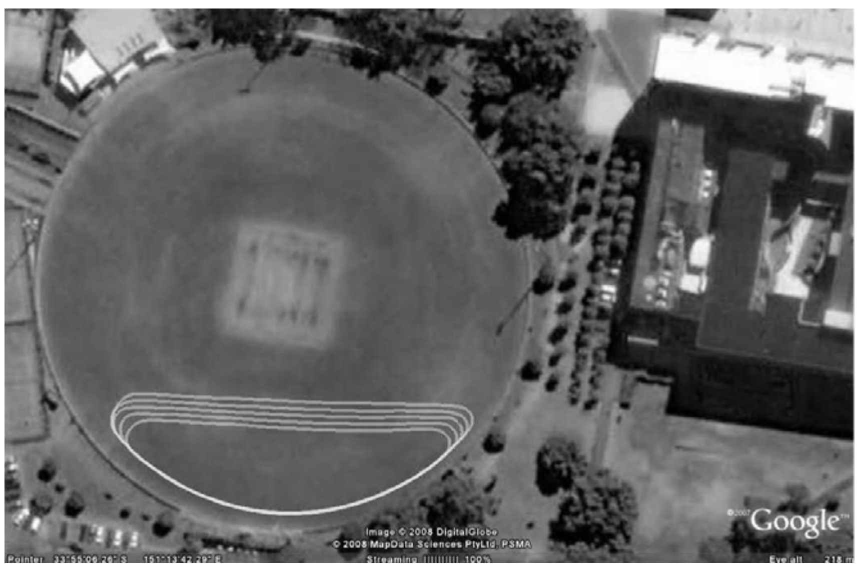

Figure 4. Testing of the GPS Navigation System, plotted with Google Earth®

A vital part of any autonomous and unmanned vehicle is safety. On the John Deere tractor, much of the safety is the responsibility of the watchdog system, which ensures safe operation of the tractor under all circumstances. In the event of any fault condition, the watchdog system is required to halt all mechanical sub-systems of the tractor, in particular, propulsion and steering. As software forms an integral part of the system, software failures contribute to most of the fault conditions. Software interacts with the watchdog system, by re-triggering a one-shot timer periodically. This re-triggering keeps the watchdog system alive. Failure to re-trigger the timer will result in a halt in tractor operations.

The software system driving the tractor element is made up of a *remote* and external *on-board* computer. The remote computer is set up with wireless access to the on-board computer. Most software tasks however, are implemented on the on-board computer, driven by Linux with a real-time kernel, RTLinux, installed, and in operation for hard real-time performance.

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 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.

Modeling of a Tractor-Implement-Trailer

A vital part of being able to accurately control such complex and challenging systems is developing comprehensive models which describe their dynamic behaviour as a whole, and how their constituent parts interact. Recent work by the authors (Siew et al., 2008; Katupitiya et al., 2007) has involved the detailed dynamic modeling of a tractor and implement unit, and extended to include an additional trailing element, such as that used for carrying seed and fertilizer for the seeding system. These models account 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 the propulsion of the rear tractor wheel and steering of **both** the tractor and implement wheels. Steering of the implement provides active implement control and is necessary for its precise guidance.

Figures 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.

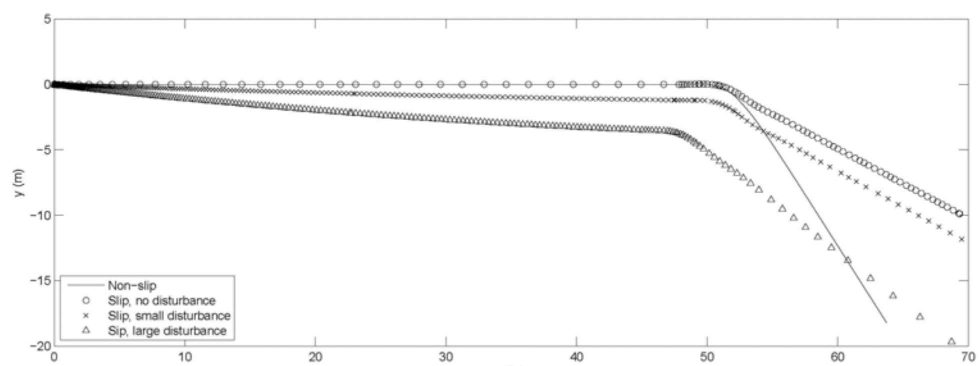

Figure 5. The implement trajectory for all four cases: (i) Non-slip; (ii) Slip, no disturbance; (iii) Slip, small disturbance; (iv) Slip, large disturbance.

Precision Guidance of a Tractor

The task of precisely controlling the tractor-implement-trailer in a practical farming situation is a substantial undertaking. Of course, the task needs to be achieved by taking a step-by-step approach. The first step in this approach is to precisely guide the tractor alone. Much work has already been done in this regard as discussed, and indeed commercially available auto-steer systems are in existence and being used. However, progress still needs to be made in being able to control them robustly and without manual propulsion, in other words, without a driver and in the presence of significant disturbance forces acting on the vehicle. These forces can manifest themselves into wheel slip, both in the longitudinal and lateral direction. Some recent work in Fang et al. (2006) and Agrawal et al. (2008) have addressed such an issue by including slip velocity disturbance components in a kinematic model. In Agrawal et al. (2008), the tractor drive is assumed to be front wheel, allowing a so called *flatness-based* approach to control design. The model in Fang et al. (2006) assumes that the drive is rear wheel, which is a more practical scenario. Here, a backstepping control approach is used while assuming the disturbance velocities are essentially time invariant, allowing adaption to be implemented.

Recent work by the authors in Eaton et al. (2008) provides an alternative control design method, which improves on the good work done in Fang et al. (2006). Once again, a kinematic model is assumed, however unlike in Fang et al. (2006) and extra integrator is in place on the steering system, also a more realistic model. Also, the design methodology allows for disturbance velocities which are bounded and time varying. The control is a mix of *sliding-mode* control and *backstepping*. The sliding-mode control allows us to push the kinematic state trajectory onto a surface in state space, and make it *slide* along this surface until it reaches its ultimate and desired destination. It is a technique which can be robust to certain bounded disturbances by also using a switching control law.

Work is still being undertaken to execute this controller and others on the existing John Deere tractor, and results are immanent, however simulation results are promising and are shown below in Figure 6. 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. Slip velocities are applied and assumed to be at a level up to approximately 10% of the velocity of the tractor.

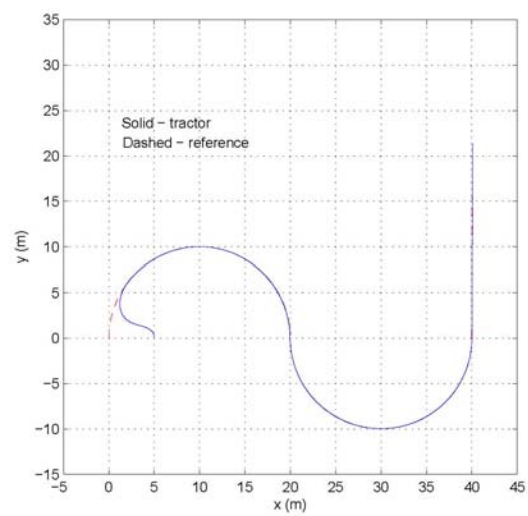

Figure 6. Robust trajectory tracking using sliding-mode control.

The next step after verification of successful practical control is to extend the results to include the steerable implement to help counter the large disturbance forces.

3.2 Non-Herbicidal Weeding Machinery

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 plants that appear to absorb more nitrogen are 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.

A more advantageous approach is to find non-herbicidal methods. Methodologies such as electrocution, electroporation, microwaving, heating and cooling etc 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. All plants, weeds or otherwise, that grow in the inter-row space will absorb nutrients that were meant for the crop and can cause growth retardation of the crop. The authors have completed preliminary developments of a non-herbicidal weeder 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 (0.75m x 0.50m x 0.45m) robot shown in Figure 7 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. A five electrode plasma arc generation system will be attached to a well insulated cradle that will be extending out at the back of the robot.

Research and development of this system is currently progressing.

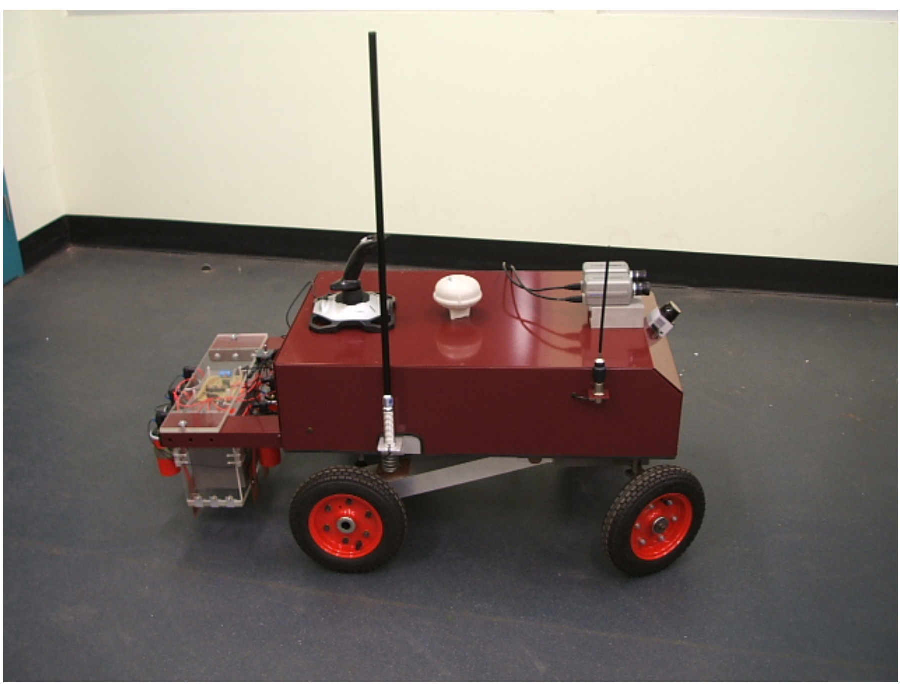

Figure 7. Weeding robot.

4 Conclusion

This paper has presented the requirements and progress made towards achieving a future precision autonomous farming system with emphasis on work done in precision autonomous tractor-implement guidance. The system proposed is a relatively complex, although structured and hierarchical one, consisting of systems within systems. The systems described include a mix of precision agriculture and autonomous, robotic farming machinery. Such a mix is increasingly important for the successful future operation of the farming industry. For an autonomous farming system, precision agriculture is most important for setting guidelines for the precision machinery to follow, such as the most appropriate and efficient farm layout, as well as dosage types and levels for fertilizer, herbicides and pesticides. Such guidelines are inherent in the proposed PADS and PFDS. It is these data sets which tend to provide the link between the different sub-systems within the complete autonomous farming system. The PADS provides information of a precision agriculture or agronomic nature, while the PFDS provides spatial information necessary for precision operation of the farming units.

Highlighted in the paper was progress made by the authors on several fronts, specifically in the implementation of autonomous farming machinery. Work continues in the precise navigation of an autonomous seeding unit consisting of a tractor and implement, while autonomous and non-herbicidal weeding is also being addressed via the construction of a small footprint weeder unit.

Acknowledgement

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