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Platform for simulation of automated crop production

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Abstract. During the last few decades technology used in crop production has developed noticeably. The work of farmers has decreased and continues decreasing by means of technology and automation. The aim of this research project was to find out requirements for methods and automated machines needed in automated crop production.

Agricultural machines capable of utilizing variable rate application (VRA) technology enable considering spatial variability in agricultural fields during different field operations. Agricultural field robots are the next step in technology, capable of utilizing sensor and actuating technologies, without human driven tractors. However, agricultural field robots are still under research, and commercial products do not exist. The next generation of crop farming, in the vision of authors, is based on automatic crop farming, which incorporates stationary and moving sensors systems, robots, model based decision making, automated operation planning which are adapting to spatial variability according to the measurements as well as to weather conditions.

This article presents a top-down approach of automated crop farming using simulation, trying to cover the most important pieces on a fully automatic farm and the environment is modelled. The developed simulation environment is presented as well as preliminary simulation results. The environment simulator is based on a collection of models, including models for crop and weed growth, soil water flow and generators for spatial variation and statistically varying weather.

Keywords: robots, decision making, operation planning, crop growth models, environment simulation

INTRODUCTION

Despite the remarkable developments done by today in the farming methods and the used machinery must be further developed. This will inevitably lead to increase in the amount of automation used in machines and gradually to the use of automated machines which are able to work autonomously without humans. The aim of this research project was to study problems facing during development towards automated crop production (Hakojärvi et al. 2008). Modelling and simulation were used as research methods. One of the projects aims was to develop a collection of suitable models concerning crop farming in Finland. To attain this aim the existing models were used when possible. Missing models were developed but the emphasis was on structure. The models are aimed to be as simple and transparent as possible so that they can be used as a tool for decision making e.g. in choosing machines and timing cultivation operations. Schematics of the components related to the crop growth model are presented in Fig. 1.

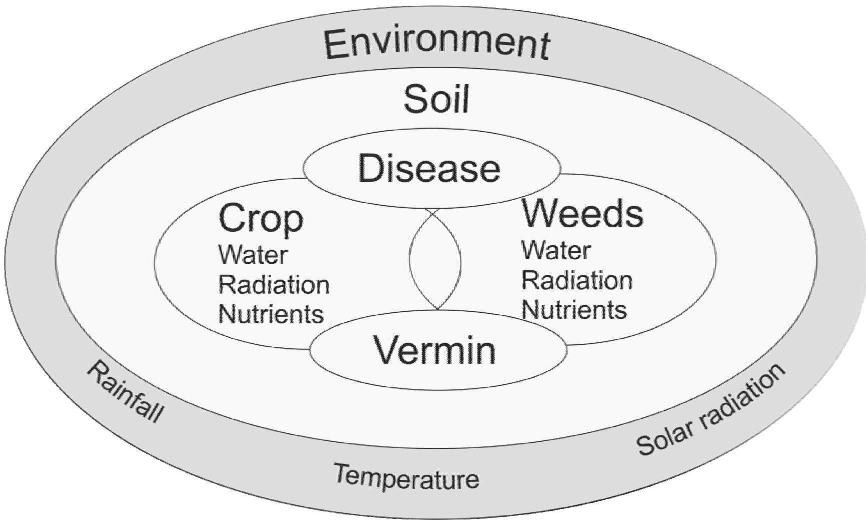

Figure 1. Schematics of the components related to the crop growth model.

The present status of crop growth models was reviewed by Hay and Porter (2006). Also Larcher (2003) gave an overview of relevant plant ecology.

Simulator structure

The structure of the developed AutoCrop simulator consists of three layers. The bottom layer contains models for soils, weather, solar, crop growth, pests, and weeds. In the simulator, the fields are split into small regular pieces. The interaction of these models is modeled in the middle layer as well as operations and actions made in the field. The top layer is modeling decision making processes, operation planning and the effects on environment.

Fields, field properties, roads, shadowing forests, sheds and storages form scenarios in AutoCrop simulator. The purpose is to create a tool for studying scenarios of a different kind related to weather, machine size and timing of different treatments, for instance. Fields, roads, forests and locations of sheds and storages are laid by user, and field spatial properties are generated automatically based on expectation values and variances for each soil property. Landscape height is generated in the same way.

In the simulator, both the spatial space and time space are discretised, and they are parameters. The default values are 5 x 5 meters (cell size in a grid) in spatial space and in the horizontal direction. In time space the step is 1 hour. A denser grid would give more accurate results but on the other hand it takes more time to compute, and the selected default values are considered a good compromise with current computer processors. The cell size in the grid also determines the smallest area of a field which can be treated separately, which is to be considered in decision making.

As in simulator both spatial and time space are simulated and models apply to both, a hybrid approach simulator is required. This means that time-dependent effects are modeled separately from spatial effects and in simulator computing they are handled one at a time. In other words, in every step in the simulator, in the first phase all the cells (field) are computed separately one time step further and in the second phase is to compute interaction between cells. These two phases are alternately repeated.

In the other simulators, the weather is either generated or measured weather station data is directly applied in the simulator. For AutoCrop simulator generated weather was selected due to requirements for different scenarios, requiring for example dry and moist seasons. Hourly simulated variables are temperature, rainfall, humidity and solar radiation. Temperature, rainfall and humidity are generated using statistical data from the weather station in Helsinki during 1971–2000, utilizing monthly expectation values and variance, and daily trend. The solar radiation is computed using an available solar simulator (ArcGIS Solar Analyst), which includes the computing of shadows from landscape, forests and buildings. In shadow areas, the decrease in solar radiation was considered but the effects of temperature, humidity and rainfall were not taken into account.

The time range in the simulator was selected to be one cultivating season, and in Finland, this was set to start from the beginning of April and last to the end of October. In the beginning, the fields are very humid and weather is cold, and when the simulator is started the temperature rises and fields start to dry, and decision making starts to analyze when the field is ready for seeding.

Plant growth and water transport models

The present status of crop growth models was reviewed by Hay and Porter (2006). Also Larcher (2003) gave an overview of relevant plant ecology. The number of parameters typically used in models is huge and their influence difficult to sort out. In the STICKS-model, for example, there are 132 parameters and tens of thousands of simulations were performed in the sensitivity analysis (Ruget et al. 2002).

This kind of approach is certainly beneficial when studying the plant growth in well-known growth conditions, like growth chambers. However in field conditions there is a lot of variation in growth conditions because of variations in e.g. altitude, soil type, soil structure and radiation. Therefore the actual growth conditions of a crop are not accurately known, which is the reason why we have chosen a different strategy. Plant growth and water transport models with varying detail were developed depending to reduce the number of parameters without loosing the main effects on crop growth. Reducing the number of parameters clarifies the structure of the models which makes the model more transparent for the user. Another benefit is the reduction of necessary measured information from the fields when utilizing the model on an actual farm.

The overview of one version of the plant growth models is presented in Fig. 2. The model contains fixed parameters and the magnitude of each may be altered by a multiplication factor in order to find out its influence on the plant growth. The model and its parameters are: mass of seed, biomass partitioning between shoot and root, sowing density and specific leaf area. In its most primitive form the model is fully analytical (Hautala and Hakojärvi 2010).

The normal values of parameters were: Mass of the seed was 45 mg and root to shoot ratio 0.3. Specific leaf area was 20 m^2/kg. The sowing density was 500 seeds/m^2, i.e. the ratio of assimilative leaf area to ground area for plant (later LAI) in the beginning was 0.021 m^2/m^2.

Biomass growth comes from the experimental facts that C3-plants produce 1.4 g CH_2O per MJ solar energy when total solar radiation is above 100 W per m^2 of leaf area when water and nutrients are not lacking (Monteith 1977). Radiation was considered effective 14 hours/day in each simulation. Root growth was 1 cm/day in depth and the maximum root depth was limited to 1.0 m. This determines the available water for plant in soil. At the beginning of simulations, the seeds were expected to be germinated and the initial root length was set to be 5 cm downwards from the depth of sown seed.

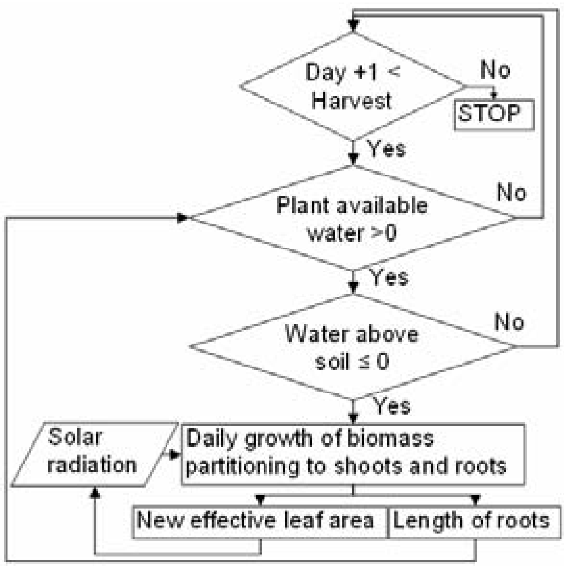

Figure 2. A flowchart of the calculations in the plant growth model.

The model for the soil water movements used here includes 10 layers (Fig. 3). At first the water flow from one layer to another was calculated according to Darcy’s law. The benefits of this approach are the changes of soil affecting the water flow in soil as a function of soil moisture content, which makes the soil moisture changes realistic. However, in larger areas the calculation of this procedure takes considerable amount of time. To reduce the time used in soil water calculations, the water movement in soil was allowed only when the water content exceeds FC. The magnitude of water flow is limited by saturated hydraulic conductivity (K), which limits the water flow between layers. Further the water content of a layer is limited by soil wet capacity (SWC), which can not be exceeded even if FC and K would allow the water flow to a layer. Also water flow away from the soil profile may always be limited by the subsurface drain, 0.00864 mm/day, which is the recommended sizing value in Finland. Water evaporation from a bare soil surface layer is 5 mm/d, when the water content of the first layer is at SWC and as the first layer of soil dries out or the leaf area of the crop grows, the evaporation is decreased. Further details of the water transport models and related phenomena are given in Hautala & Hakojärvi (2008) and Hautala & Hakojärvi (2009).

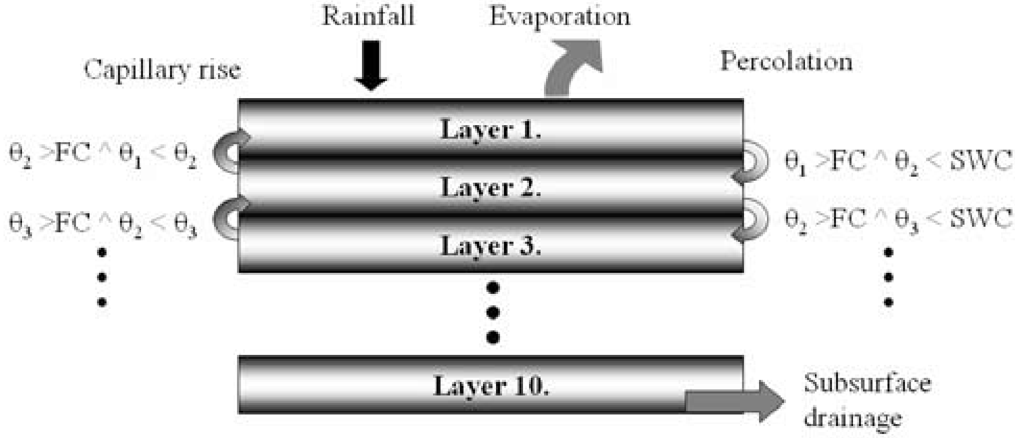

Figure 3. Effect of evaporation, transpiration, rain and drainage to water content θ_i of each layer in soil and water percolation downwards in soil.

Initially, the water content in all layers is at field capacity (FC). The crop is able to use the water in soil from FC to permanent wilting point (PWP), because the amount of water above FC is able to flow rapidly in the soil which makes the water unavailable for the crop. An experimental (and physical) fact is that about 500 moles of water becomes transpirated when 1 mole of CO_2 is used in photosynthesis (Taiz & Zeiger 1991). This water is taken from the root volume if available, otherwise the crop growth is decreased. Growth of the crop is ceased if growth conditions are not suitable, i.e. the water content of soil in the area restricted by the crop roots is less than PWP or more than SWC. Also a pond above the soil surface leads to the suspension of growth until the water has run off, infiltrated into the soil or evaporated.

The rain model

In a recent study, the statistics of 50 year summer precipitation in one location in Finland was given (Kilpeläinen et al. 2008). The cumulative distributions of rain event duration, dry spell duration and precipitation in a rain event were given as a sum of two exponentials. The yearly rain is obtained by a Monte-Carlo method. If F(x) represents one of these distributions, then a random number $0<R<1$ gives a single event x: $F(x) = R$. The weather of one summer is then obtained by random numbers, from which one obtains consecutively rain event duration, dry spell duration, precipitation in a rain event, rain event duration, and so on. The rains of one day are summed together and all the rains are built up into a table to get the rains of one year.

Three simulated rain distributions are given in Fig. 3. An average rain sum during the 90 days period was 178 mm when rains were simulated for 1000 years. Within the same simulation, the highest rain sum for the same period was 320 mm and the lowest 77 mm. Daily maximum was 51.2 mm. It is to be noted that any type of rain is easily modelled in the code. Since the distributions used in Monte-Carlo originated from experimental data, also the statistics of the simulated rainfalls corresponds the real weather statistics in Southern Finland.

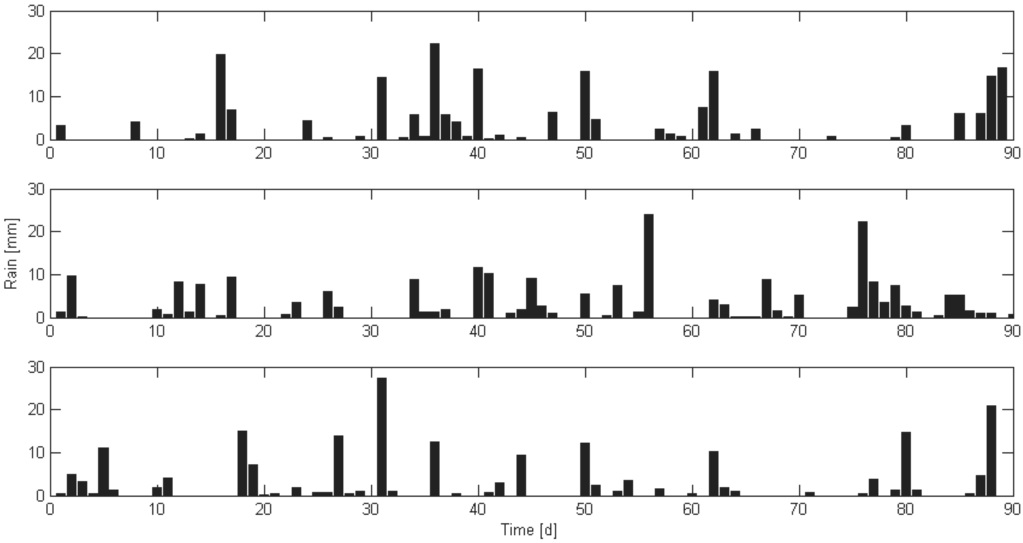

Figure 4. Examples of rain distributions, simulated rains for three sequential years.

Simulator implementation

In the implementation of the simulator, several software tools and technologies are used and integrated. The main tools used are ESRI ArcGIS/ArcInfo 9.2, Visual Studio .NET 2005, SQL Server Express 2005, Matlab R2007a, Simulink 7.0. All the used tools are found powerful in certain areas, but with none of them is solely good enough for developing the crop farming simulator therefore software integration is required. The crop farming simulator contains both spatial space and time space; Simulink is very powerful tool for time space simulation with dynamic systems, but very poor with spatial simulation purposes. On the other hand, GIS tools are powerful in spatial simulation, but time space is not considered much. These tools allow several ways of integration to other tools and therefore two different integration and implementation approaches were studied. In both approaches, ArcInfo was used as user interface and the main differences were found in the computational speed and extensibility of the simulator.

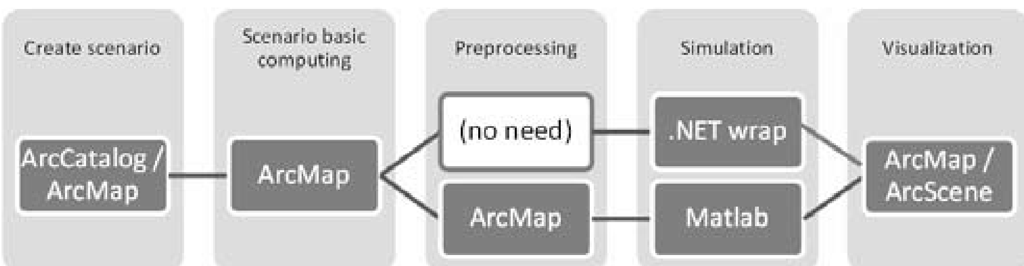

Figure 5. Work flow of AutoCrop simulator.

The workflow of AutoCrop simulator is presented in Fig. 5. In the first phase scenario is created, and it is required only once per scenario. In this phase, fields are created and it is possible to import map and road data from an external resource. Field properties are generated also in this phase so that at first a certain number of coordinates per hectare are randomly placed inside the field and values for the properties of those coordinates are generated using expectation values and their variances. After the generation of values, 3D surface is fit to generated points to get a realistic and smooth spatial variation. Spline surfaces were used in AutoCrop simulator as it produces a smooth and continuous surface. The field height variation is created in the same way.

In the basic computing phase (in Fig. 5) the scenario is converted to the simulator applicable format. This includes rasterising 3D surfaces created in the scenario using the grid size parameter. In the basic computing phase, also cloudless solar radiation is generated for the whole season beforehand (using ArcGIS Solar Analyst). In addition, other static properties of the fields are computed at this time, like an inclination rate and direction in each cell, and cell neighborhood arrays.

The preprocessing phase in the simulator workflow is required only if environment simulation is done outside GIS system. This transforms GIS data to SQL database as tables and creates empty tables where simulation results are to be placed.

The crop growth models were developed using Simulink and the modeling level is a single cell, which is assumed to be a small homogenous spatial area. In the first approach for the simulation phase (in Fig. 2), Simulink model is compiled to C++ code, wrapped with custom C++ code as a .NET component and then wrapped as ESRI compatible .NET component with C# code. In the second approach, Matlab is used in the simulation phase and it runs Simulink in a normal way. The simulator calls the crop growth model every 3600 seconds in simulation time and in the model some parts run only once a day in simulation time. One hour simulation time step is considered small enough for every model dynamics in the aspect of farming simulation.

Finally, the last step in the AutoCrop simulator is visualization, where GIS tools are used to interpret the simulation results. The selected states from the crop growth model and other models are stored as raster to SQL database in the simulation phase and these can be examined over time. In future developments, the aim is to show decision-making indices in the same way.

RESULTS

The following results are based on a fictive robotic farm in southern Finland. It was considered that modeling soils and environments is beyond of resources in our project, and on the other hand, later on more scenarios are required in the project. Therefore, a fictive farm with realistic field property variation was chosen for the preliminary testing of the simulator.

For the test, a farm with five fields was created. The locations of the fields and bounding roads and forests are based on a real map. In Fig. 6, five fields are presented with solid black boundary lines. Forests are located at the south east side of two fields on the right and in the middle of the fields. The crop model use to produce Fig. 6 was based on grain sorghum model called SORGF (Arkin et al. 1976). Here it is modified to represent a typical Finnish grain crop, barley, against variety trial yields and growth times (Kangas et al. 2006).

Figure 6. Simulated site-specific grain yield in five different fields.

The soil related parameters were generated with random numbers and thereafter fitting spline surface to the generated parameters f. Generating the soil related parameters in this way makes it possible to generate a continuous map with smooth changes which can be expected to correspond to the changes in real fields. Also surface profiles of the fields and altitudes of cells were done accordingly. The initial moisture level was FC according to the selected soil type.

In Fig. 6, the above ground results of the crop growth model are presented. Most of the variation in the grain yield comes from solar radiation variation, which is caused by the shading of forests during the day. The shadow areas produce less yield and this can be seen as dark areas in Fig. 6. The forests are modelled as non-transparent objects and the effect of decrease on solar radiation was computed using ArcGIS Solar Analyst. The solar radiation depends on the date of year as well as cell location in the field.

In Fig. 7 Monte Carlo rainfall for one growth season at one site is presented as well as consequent variations in soil moisture at five different depths. The crop root growth and water use can be seen from decreasing soil water contents as a function of time and depth of soil. In Fig. 7 the soil water model based on Darcy’s equation was used.

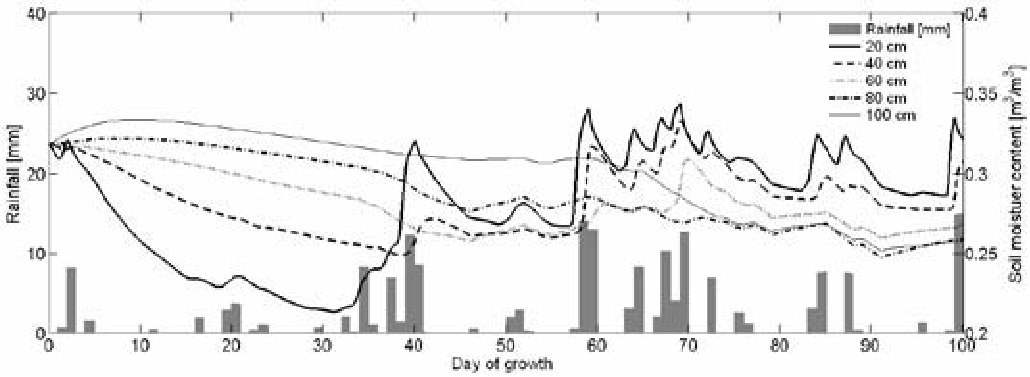

Figure 7. Simulated rainfall and soil moisture contents from several depths of soil in one cell of field.

The changes in the soil moisture content in all cells of the grid in Fig. 6 are calculated. Fig. 7 presents moisture contents in an average cell. The changes in soil moisture would be slightly different in high or low yielding zones of the field due to crop water consumption.

DISCUSSION AND CONCLUSIONS

In the developed AutoCrop simulator, software integration was used to combine the good properties of specific simulation and software tools. Two different approaches were tried to do the simulation phase, the first way was to compile Simulink model to C++ and further .NET component and run the simulation using ArcGIS; and the other way to use Matlab as a simulation engine. It was found that the first one is better even if it takes more time to develop. The computing efficiency comparison showed that the first approach took less than 2% computing time compared with Matlab approach. For the presented scenario (Fig. 6) with 9000 cells of 5 x 5 meters, using simulation time step of one hour and data store to the database every other simulated day. The simulated growth period corresponded to the actual time period from the beginning of April to the end of September and took about 10 hours to compute with P4@3.2GHz processor. This computing depends on grid and time step parameters, but also on models used in the simulation, as mentioned above.

The present models applied in the simulator can not be used to simulate winter cereal crops, because overwintering is not included in the model. However, if initial values of the crop model were entered in the model, the simulator could simulate the growth of winter crop. Cultivated as spring crops, the presented crop growth model would apply to all C3 crops.

Because of the short growth season due to location in the north, the sowing time in spring is important as it greatly affects the length of the growth season. Another important thing is water. In spring, the fields are moist and as time goes on, the moisture will evaporate from fields, which reduces the amount of water available for the crop. In some cases, this can lead to a situation, where the growth of the crop may be limited by water due to unfeasible timing of the rainfalls. In the aspect of precision farming, the timing of sowing in spring and adjusting the amount of fertilizer according to the growth conditions are the most important field operations which can be enhanced with crop and soil models. Application of fungicides or pesticides both need a separate model to simulate the growth of the weeds and spreading of the diseases.

According to the results the combination of programs for simulations in time and for simulations in space is beneficial in case of studying precision farming by means of modeling. Used GIS program was found useful and essential in the visualization of the results. However, simulation time with this combination of models is considerably high. In future developments, the time consumption is to be reduced when models for crop growth and soil moisture are to be included in the simulator.

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