Accuracy and performance experiences of four wheel steered autonomous agricultural tractor in sowing operation

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Abstract In agriculture, a typical task is to do a coverage operation for a field. Coverage path planning algorithms can be used to create the path for a vehicle. In case of an autonomous agricultural vehicle, the path is provided to the guidance or navigation system that steers the vehicle. In this paper, a four wheel steered tractor is used in autonomous sowing operation. The full size tractor is equipped with 2.5 m hitch mounted seed drill and the developed guidance system is used to sow about six hectares spring wheat. In this paper is presented the results of the guidance accuracy in the field tests, in four field plots. The guidance accuracy in terms of lateral and angular error to the path is typically less than 10 cm and one degree, respectively. The paper also presents real life problems happened in the field tests, including losing GPS positioning signal and tractor safety related wireless communication problems.

1 Introduction

The trend in agricultural engineering is to improve the productivity; to make one farmer to produce more food with the help of tools and technology. The improvement has been remarkable since the 19th century. Agricultural mechanization was ranked 7th in all achievements in the 20th century, leaving e.g. computers and telephone behind [1]. During the 20th century the development was also important for the industrialization as agriculture did not require so much workforce anymore. The trend to improve the productivity continues, but the mechanization and scaling up are not providing remarkable improvement any more. Electronics, automation and ICT are used together with the mechanical agricultural tools to improve systems. Some call this mechatronization, some call it automation and some call it robotization – despite the name, the main purpose is to improve productivity; to produce the food with less workforce and less effort.

Agricultural field robots or autonomous agricultural machines have been proposed for a long time [2, 3]. A remarkable step towards autonomous operations

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was the development and availability of GPS technology [4]. So far, very little commercial success is reached compared with the visions of the future, but on the other hand the same applies to autonomous road vehicles. The field robots help to improve productivity in a way; the farmer does not need to guide the vehicles on-board, but he could use his/her time to do other agricultural tasks meanwhile. Still, the story of field robots is not only improving the productivity, but also improve the precision and accuracy of agricultural production. The precision refers to naturally to spatial accuracy, but also approach towards operations-on-demand – as the price to do field operations decreases and allows more unmanned operations to care the crops and harvest site-specifically.

A roadmap towards the commercial success of agricultural field robots is needed to improve robustness. Several attempts to build autonomous field robots have proven to be accurate enough, e.g. in guidance, but not in a way that long working hours and durability in a season is paid much attention [2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. Some of the studies are related to specific application, like weed scouting or control [3, 13, 16] or planting [12], but typically the guidance studies are not related too much on the agricultural operation, but being generic [2, 5, 7, 9, 10, 11].

Looking back in the history of agricultural engineering, many early tractor prototypes with an internal combustion engine were build in 1910’s and the versatility in engineering was blooming. In 1920’s *tractor trials* were organized, e.g. in England, to make the tractor more common tool in farms [17]. In the tractor trials, the purpose was not only marketing in public demonstration, but the events also pushed the manufacturers to improve robustness, performance and usability as the machines were benchmarked and evaluated and the results were published. Perhaps ”agricultural field robot trials” are necessary one day to promote the technology and push the engineers to improve quality.

This paper presents a trial, carried out in Finland, to evaluate the developed autonomous tractor in sowing operation, in real fields, in real operation. The purpose of the trial was to evaluate performance factors in long run; the trial took one and half days, sowing 6.6 ha. This cannot be considered a season long operation, but it would reveal design flaws, e.g. in durability, robustness and temperature issues.

2 Materials

The tractor, the positioning system and navigation algorithms are reported and discussed earlier in [18], [19], [20] and [21]. In this chapter, the main functions and features of the system are presented.

2.1 *The autonomous tractor "APU-Module"*

The tractor known as "APU-Module" is shown in Fig. 1. The tractor was originally built by a Finnish company Modulaire Oy in the years 1990-1995. The four-wheel steered tractor is equipped with 123 kW diesel engine and hydrostatic transmission. The wheelbase is 2.7 m and the weight is 5900 kg. Each wheel steers maximum 22° and the control system keeps the steering angles synchronous, to realize the Ackermann steering principle. The control system (electrics, electronics, communication, software) was completely refurbished in the years 2009-2012. [18]

Fig. 1. APU-Module, the autonomous tractor

The steering is based on a dedicated hydraulic pump, a hydraulic valve block with four directional valves and four steering cylinders, one for each wheel. The control system for the synchronous steering of four wheels was developed during the refurbishment process. The maximum steering rate is limited by the hydraulic pump that needs to produce flow for four cylinders, compared with traditional tractor design where only one hydraulic cylinder or actuator is used for steering. In the closed loop control system, the identified control delay was 400 ms plus second order dynamics (time constant ~600 ms); the maximum steering rate is 8-12 °/s depending on steering directions if all the wheels are steered synchronously with 1500 RPM engine speed. Based on the field experiments, the hydraulic pump should be larger (volume per revolution) in order to do navigation in full speed, 3.0 m/s. [18, 20]

As the steering rate is limited and there is remarkable dead time delay, the guidance accuracy decreases when high driving speed is used. In first field tests, it was found that in practice with driving more than 2.0 m/s the path following accuracy decreases under tolerance. Therefore, the operating speed in navigation requiring accuracy is limited to about 2.0 m/s. In the trial presented in this paper, operating speed 1.8 m/s was used as a compromise between operational efficiency and navigation accuracy. [21]

In the sowing operation, the tractor is equipped with a mounted seed drill: Tume KL-2500; see Fig. 2. The seed drill is a combined seed and fertilizer drill, both seeds and local fertilizing are applied at the same time. Local fertilizing is applied in the middle of every other seed row by using another set of coulters (a device making a furrow for seeds/fertilizer). For seed rows the inter row width is 12.5 cm. The working width of the seed drill is 2.5 m, thus 20 seed coulters and 10 fertilizer coulters are installed. The seed drill is a 25-year-old machine without any electronic control, still in use for farming and in excellent condition. [20]

With both hoppers full, the weight is about 1450 kg, which does not cause any trouble for the tractor to lift or no counter weights are needed. The power of the tractor would be enough for much wider seed drill, but this was the only option available for the trials.

Fig. 2. APU-Module with the seed drill, Tume KL-2500 in the field trial.

2.2. Positioning system

The positioning system is based on GNSS technology. The positioning system consists of a) a RTK-GPS receiver, b) a fiber-optic gyroscope in heading and c) an inclinometer for tilt compensation. Trimble 5700 RTK-GPS receiver was used for global positioning; with the virtual base station signal provided by Trimble. The positioning accuracy is claimed to be typically better than 2 cm, but if the view to the GPS satellites is poor, the positioning accuracy is worse. There are several quality indicating values the receiver transmits besides the coordinates: Fix level, RTK correction in action, HDOP (and other DOP values), pseudorange noise statistics and the number of satellites. These values can be used to measure the quality of positioning, to trust on the coordinates the receiver transmits. [20]

For the heading estimation, a fiber-optic gyroscope (KVH DSP-3000) is used together with odometry and GPS heading information. Inertial-Link 3DM-GX2 was used for tilt compensation. All the signals were fused together in an embedded controller; the GPS positioning is corrected to ground level, heading is estimated based on GPS heading, fiber-optic gyro and odometry information and all the relevant information is transmitted to the navigation system by using CAN-bus. [20]

2.3 Guidance system

The desired route shall be given as waypoints that form a polyline. Here it is assumed that the route planner above in the system gives these waypoints 5 seconds in advance before they are passed – in order to utilize prediction. In curves, the waypoints are given frequently, typically a new waypoint is added if the angle deviates more than five degrees, so that the polyline is smooth enough to follow. It is also assumed that the route planner gives feasible waypoints, so that the vehicle kinematic constraints are not violated – for instance the minimum turning radius is considered in the route planner. The used geographic coordinate system is KKJ3/YKJ, a Finnish projection commonly used in cartography.

As the vehicle knows its position and attitude in the global coordinate system by using the sensors, and the waypoints are given in the same coordinate system, the path tracking algorithm needs to consider two error variables: lateral error and angular error.

The path tracking algorithm knows the waypoints it has passed successfully, and the path error computation is computed for the line segment that starts from the last passed waypoint to the next one. However, computing the error variables only for the current position and attitude does not provide enough information for steering controllers, as in curves this kind of vehicle would overshoot remarkably.

The guidance system computes the error variables not only for the current position all the time, but also for all the predicted positions of the vehicle based on the current position, heading, speed and steering angles. The prediction relies on the kinematic model of the vehicle and it takes the dynamics of speed and steering actuators into account in integration. The prediction horizon is a tuneable parameter; the value used in the tests was five seconds. The predicated error variables are converted to single error variables by using weighed averaging; the weighting function was an exponent function; the current state is weighted more than the predicted error five seconds ahead. The weighting factor affects on overshooting vs. cutting corners in the curves.

The structure of the path tracking algorithm is presented in Fig. 3. In the first block the path error is computed including the prediction, described above. The Approach Filter tweaks the error signals in case the lateral error is very large (over one meter): it modifies the angular error signal in order to guide the vehicle quicker to the route. This is helpful in case the automatic guidance is started after manually manoeuvring the vehicle to the field and/or after refilling the hoppers. If the lateral error is less than one meter, the error variables are passed through as is, which is the normal case during the autonomous operation.

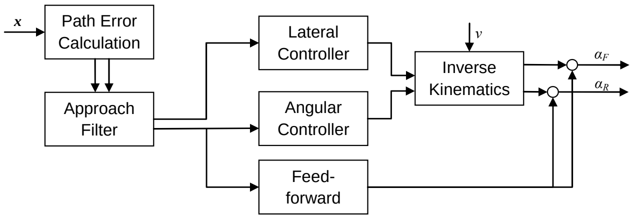

Fig. 3. Structure of path tracking algorithm; the input is the state of robot, the outputs are the steering angle setpoints for the steering servo controller

Lateral Controller and Angular Controller are controllers in the feedback loop; the structure of both is PID. The feed forward part helps to stabilize heading control. The last block is Inverse Kinematics, which translates the desired lateral speed and angular speed commands to the steering angles in front and rear. The so called feed-forward part is used to transfer the angular error to the setpoints of steering angles without dynamic filtering. The outputs are the steering angles in front and rear [20].

2.4 Path planning

The approach in coverage path planning is semiautomatic. Path planning was done in Matlab, by using two stage strategy: 1) 7 times around the field counter-clockwise to lay headlands (the turning area) and 2) swathing the mid area by following one of the edge trails of the field and using U-turns. The user may give the field boundaries as a polygon and the coverage path planning generates at first the headlands that are laid around the field. In the headland, the driving direction is always either CW or CCW, in order to sow the corners of the field by reversing. Seven times around the field is necessary for this machine in order to generate large enough headland for forward turnings. In the second step the semiautomatic path planning algorithm asks which edge of the field to follow. This was done in order to allow a user to select non-optimal path, in order to compromize with practical issues, like refilling station or stationary position of operator in the field. The path planning algorithm generates waypoints with the information whether tool is up or down (working position) and required ramps for acceleration/deceleration.

3 Results and discussion

3.1 Fields and path planning

The system was tested in four field plots in southern Finland, May 7-8, 2013. The total area of cultivated area was 6.6 ha. The autonomous sowing trial was carried out during the normal sowing season, the harrowing was made appropriately before the sowing for the seed drill. Spring wheat was sown with local fertilizing using the Tume combined fertilizer and seed drill. The hoppers of the seed drill were refilled manually, in the field, by manually guiding the vehicle next to the refilling wagon. With one refill, it was possible to sow about 0.85 ha. The operating speed 1.8 m/s was used in sowing and 1.5 m/s in turning manoeuvres.

The trial started from Field #1 to Field #4 in order. The field areas are: 1) 1.07 ha, 2) 2.40 ha, 3) 1.76 ha, and 4) 1.36 ha. The path planning is semiautomatic, the user may select from which corner of the field the operation starts. A typical rule of thumb is to follow the longest edge; this was used in this trial in ¾ of the cases. For Field #2 it was more convenient to select short swaths in order to avoid long runs in the large field; this was selected for a practical reason – the human operator needs to be all the time within 50 m distance from the tractor, otherwise the tractor safety system would kill the engine and this strategy allowed the operator to stay in place instead of continuously running behind the machine back and forth. Similarly, the first stage is driven counter-clockwise because the remote controller radio receiver/transmitter is located on the left side of the tractor, so the range is slightly better when the operator stands in the middle of the field during the operation. The fields and the planned paths are presented in Fig. 4.

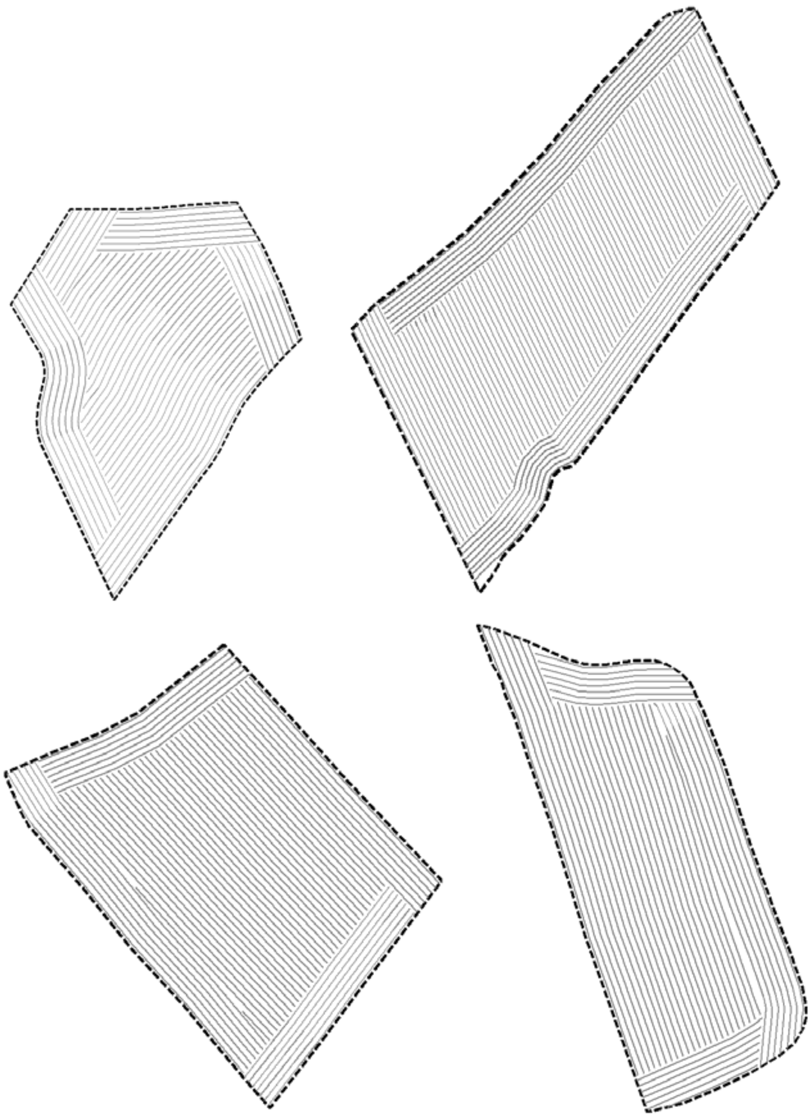

Fig. 4. The field plots used in the field trials. Top: Fields #1 and #2, Bottom: Fields #3 and #4. The planned path is presented in gray lines.

3.2 Autonomous sowing in practice

In theory, the developed system is autonomous. However, there are many practical issues why it was necessary to have at least one human in the field all the time.

First of all the hoppers of the vehicle needs to be refilled after every 0.85 ha; this is required more or less every hour with the system (Fig. 5). The other practical reason is the seed drill, which is not developed for autonomous use and in some moist places of the field the coulters were blocked by moist clay soil, which is not uncommon for this type of machines – a human operator was able to see blockages during autonomous operation (as there was nothing else to do) and by interrupting the autonomous mode, lifting the hitch and cleaning the coulters helped; and became a common practise during the trial.

Fig. 5. Autonomous operation going on in Field #2. The refilling wagon is seen on right.

The wireless radio communication between the tractor and operator is another issue. The wireless remote control system, manufactured by Technion Oy, has versatile control knobs and an integrated emergency stop feature. The manufacturer has used 2.4 GHz band in communication; the manufacturer says it is done according to IEEE 802.15.4. The manufacturer sells the remote control system for cranes and other machines in the market and in the design safety has been an important requirement. Therefore, in the wireless system continuous two way communication is alive all the time, and in case of the communication timeout, the system goes to the safe state, which can be programmed in the tractor end. In the tractor, in case of timeout, the receiver module shuts off the electricity from all safety critical ECU's; including the one controlling the diesel engine – the engine shuts down, the drives go idle and the parking brake engages. However, 2.4 GHz band is crowded in urban areas, not necessarily in rural areas like in the fields, but still any unexpected noise is easily created; e.g. by mobile phone (Bluetooth) or computers (WiFi) of the operator; or a WiFi access point nearby. Furthermore, the transmission power is limited, which limits the range to less than 50 m in practice. A closed system operating in 2.4 GHz band, limited range, the nature of wireless communication (scattering, reflection, multipath, diffraction etc.) and the safety feature together caused the tractor to shut down 36 times altogether during two trial days. The restart requires not only restarting the engine, but also resetting the radio communication which typically requires walking closer to the machine; the mean time to recover the system was 52 seconds (range 27-92 seconds).

For instance, Field #3 is surrounded by three houses (see Fig. 6), which is not unusual as the field plots in Finland are rather small. The fields are not in safe from 2.4 GHz noise transmitted by household apparatuses, like WiFi and wireless surveillance cameras.

Fig. 6. Houses surround Field #3. The household equipment using 2.4 GHz wireless band may cause noise to radio communication in the field.

Finally, the autonomous vehicles contain a lot of basic technology, not only the standard equipment like engine control, fuel system, hydraulic system but also more electronics and electrical systems compared with conventional vehicles. There is always a risk that some failure appears in the basic system. This risk realized in the second day, in the last field (Field #4), as only 0.5 ha to go, the hydraulic system breakdown (oil leak) forced the trial to end. Therefore, the covered area during the trials was only 6.1 ha.

3.3 Temporal performance

As explained above, Field #4 was not completed due to the machine breakdown. Otherwise the system was performing in a similar way in all four fields. The Table 1 reveals the statistics when it comes to the interrupts of autonomous operation, the reasons for that. Altogether, the system shut off altogether 36 times during these fields. On average, it takes 52 seconds to recover the system, so about a half an hour was spent on that during the trial days. Manual interventions were done 35 times, usually to clean the coulters or check the level of hoppers (seeds & fertilizer), or to adjust the seed drill settings.

RTK-GPS signal quality dropped under the required level (the number of satellites, HDOP, RTK fix status, STD major axis of pseudorange noise statistics) altogether 30 times, which is worse behaviour than unintended shutdowns as the average recovery time is longer. The total time required to recover from GPS signal quality level drops was 1h27min in four fields together – it would have been even larger if not helping the vehicle couple of times manually away from forest corners where trees shadowed GPS receiver. Generally, the reason inside the GPS receiver was not losing the correction signal for RTK, but the loss of GPS satellites tracking. The median number of satellites was seven and with less than five satellites in view, the positioning accuracy drops below an acceptable level.

Generally, the number of interruptions to the autonomous operation was pretty high, varying from 11-20 times per hectare, as seen in Table 1. However, the variation in the length of continuous autonomous pieces in time is high, the longest period was 1223 seconds (20 minutes) and the shortest was 2.8 seconds. The typical length of a continuous work period is 4-5 minutes.

Table 1. Temporal statistics of autonomous operation in the fields.

	Field #1	Field #2	Field #3	Field #4
Area (ha)	1.07	2.40	1.76	1.36
Operated area (ha)	1.07	2.40	1.76	0.85
# Unintended shutdown	6	10	13	7
# Manual intervention	6	10	11	8
# GPS signal quality lost	3	7	11	9
- of which correction lost	1	1	1	1
- too few satellites / HDOP	2	6	10	8
Total # interrupts in autonomy	15	27	35	24
Area / # Total interrupts	14.0	11.2	19.9	17.6
GPS recov. time, average (s)	72	143	175	155
GPS recov. time, max (s)	108	674	841	346
Uninterrupted work, aver. (s)	233	274	147	111
Uninterrupted work, max (s)	1223	818	880	611

As seen in the results, it is crucial to take the GPS signal quality, properties and breaks into a consideration in the development process of a guidance system and algorithms. Simulation of GPS error is crucial in order to take all the cases into consideration as it is hard to repeat the conditions in the field. [22] presents a simulator model capable creating similar noise and quality signals than happened in real life.

3.4 Spatial accuracy

In coverage operation, a general requirement is to keep the parallel swaths 12.5 cm apart from each other in order to create seamless crop rows. The hard requirement for navigation accuracy is to avoid parallel rows to overlap, which would mean 12.5 cm deviation from the desired path. From this hard requirement it is possible to lead soft requirements, e.g. the navigation accuracy should be better than ±10 cm, ±7.5 cm or ±5 cm. At the beginning of this study the objective ±10 cm was set, in order to avoid overlapping, as the same was used in [23].

The Fig. 7 shows the angular and lateral errors as a histogram, all four fields together. It can be seen that the lateral error is most of the time within the requires ±10 cm tolerance and heading error is relatively small also, under ± one degree. The mean angular error is -0.06° (standard deviation 0.75°) and the mean lateral error is -0.15 cm (standard deviation 5.91 cm). In lateral error, 90% of the samples are in range ±6.2 cm, and 95% of the samples in range ±9.6 cm.

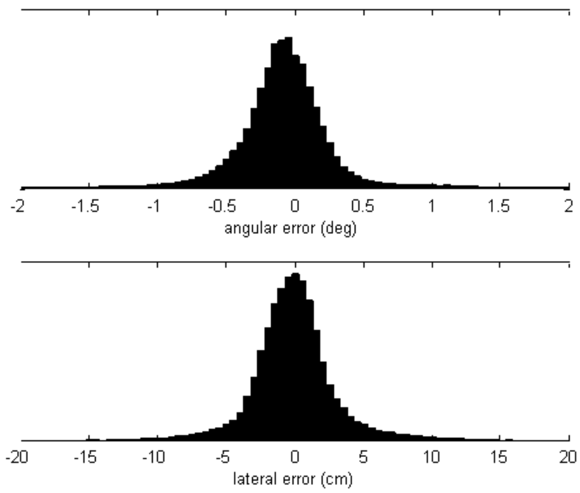

Fig. 7. Histogram of angular and lateral error, respectively.

4 Conclusions

This paper presented the results of the autonomous sowing trial in Finland in the spring of 2013. The guidance system is able to navigate in accuracy that is suitable for cereal sowing; the lateral error is typically less than ±10 cm.

It was discussed also the practical challenges that limit the full autonomy. The positioning system based on RTK-GPS receiver is suffering from shadows and other reasons that cause interrupts for reliable positioning signal. Based on the experiences and presented results, RTK-GPS is not suitable alone for an autonomous tractor that should operate without interrupts. Multi technology GNSS is seen as an option to improve the situation, e.g. by using a receiver that utilizes both GLONASS and GPS satellites. Using multiple technologies increases the number of possible satellites in view, but the RTK system would have to provide correction for all signals as well.

Furthermore, the safety system may also limit operational efficiency, if an operator needs to be all the time within 50 meters; if the operator forgets this, the system will shut down or halt – and valuable time during sowing season is spent on recovering the system back online.

Generally, the after some hectares, monitoring an autonomous field robot becomes very boring, as the only thing to do is to stand and watch with a hand on the emergency button and try to be concentrated all the time to see the risks of hazardous movement. Standing a full day in dust and under the burning hot sun is not necessarily more convenient than sitting in a tractor cabin with air conditioning on. Nevertheless, before the full autonomy is achieved and safety issues solved, it is necessary to supervise the system all the time.

In spite of the problems and harms presented, the autonomous sowing trial was successful and it proved that the developed guidance and control system works in real work.

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