Remote supervision of autonomous agricultural machines: Concepts and feasibility

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ABSTRACT

The scientific literature provides a description of various models depicting autonomous agricultural machines working to complete typical field operations. Many of the models involve some form of automation interface that is used by the machine owner to supervise the operation of the machine from a remote location. The objective of this study was to interview experts in the design of autonomous agricultural machines (university researchers, entrepreneurs, and leaders in the agricultural machinery sector) to ascertain their opinions about future autonomous agricultural machines, particularly related to how such machines will be supervised by the machine's owner. Of the four remote supervision concepts described by participants (within the field, close to the field, from the farm office, and outside the farm site), the close-to-the-field remote supervision concept was determined to be the most viable concept. Designers were divided on the idea of providing real-time live video on the automation interface, however, most of them believed that having live video would reassure the farmer that everything was going well. Desktop computer, tablet and phone were the main devices recommended as tools for remote supervision (i.e., the hardware on which to display the automation interface), with tablet perhaps being the preferred alternative.

RÉSUMÉ

La littérature scientifique fournit une description de divers modèles décrivant des machines agricoles autonomes qui réalisent des travaux au champ typique. Beaucoup de ces modèles impliquent une certaine forme d'interface d'automatisation utilisée par le propriétaire de la machine pour superviser son fonctionnement à distance. L'objectif de cette étude était d'interroger des experts en conception de machines agricoles autonomes (chercheurs universitaires, entrepreneurs et dirigeants du secteur de la machinerie agricole) afin de connaître leur opinion sur les futures machines agricoles autonomes, en particulier sur la manière dont ces machines seront supervisées par leur propriétaire. Parmi les quatre concepts de supervision à distance décrits par les participants (à l'intérieur du champ, à proximité du champ, depuis le bureau de la ferme et à l'extérieur du site de la ferme), le concept de supervision à distance à proximité du champ a été estimé comme étant le concept le plus viable. Les concepteurs étaient divisés sur l'idée de fournir une vidéo en direct et temps réel sur l'interface d'automatisation; cependant, la plupart d'entre eux pensaient qu'avoir une vidéo en direct rassurerait l'agriculteur sur le bon déroulement des travaux. L'ordinateur de bureau, la tablette et le cellulaire ont été les principaux supports recommandés comme outils de supervision à distance (c.-à-d. le dispositif sur lequel s'affiche l'interface d'automatisation), la tablette étant possiblement l'outil préféré.

KEYWORDS

agricultural machines, remote supervision, machine design, autonomous.

MOTS CLÉS

Machines agricoles, supervision à distance, conception de la machine, autonome.

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INTRODUCTION

The concept of autonomous agricultural machines has appeared in the scientific literature over the past couple of decades. A quick search on the internet will produce videos showing different autonomous tractors moving through the fields. Some of these include the Case IH autonomous tractor, Fendt Xaver robot, AGROINTELLI's Robotti (Vougioukas 2019), and Raven's OMNiPOWER (previously called DoT) autonomous power platform. Conceptually, at least four distinct designs are being promoted (Table 1). They range from modifying existing tractors while retaining its operator's station to having fleets of extremely small machines conduct farm operations autonomously (Table 1).

Considering the current trend of research and innovations in agricultural field machinery, autonomous tractors, sprayers, and combines will soon become commercially available, meaning that these agricultural machines will no longer require a human operator to be physically present in their cabin during operation. However, the human is still envisioned to remain in the loop to help minimize any catastrophe that may arise in unexpected situations like system failure or malfunction (Bechar and Vigneault 2016). The human is expected to perform this role from a remote location.

Remote supervision of autonomous systems is not novel but has been practiced for several decades in non-agricultural industries like aviation, marine, military, space exploration, and process control (Dorais et al. 2003; Cummings 2004; Carvalho et al. 2008; Edet et al. 2018; Sivcev et al. 2018; Simetti 2020). For example, in deep-sea operations, robots are used to inspect pipelines for cracks (Wong et al. 2017) or to monitor and control the underwater manipulation of robots (Sivcev et al. 2018; Simetti 2020) have been supervised remotely. Details of the robot's activities are obtained through an automation interface - that is either fixed in a control room or is a portable device (Madni et al. 1983). During search and rescue operations, remote supervision has also been used to monitor the operation of robots (Cubber et al. 2017). In some cases, the field workers and other personnel are equipped with a device to either get a better view of the area or coordinate the operation of the robots. Such a monitoring system was developed by Govindaraj et al. (2017). It had three separate devices (for different personnel) connected via Wi-Fi and/or satellite communication. The system comprised of i) a central planning and coordination mission system (that was embedded in a desktop computer), ii) a field-portable command and control system (i.e., laptop), and iii) a portable interface (tablet). Each of these devices was meant to assist workers at different locations to get a better understanding of the robot's operation and communicate with each other and with the robot. This remote supervision concept can be adapted to agriculture, especially on farms where the supervisor is a hired worker, enabling the farmer to monitor what is happening in the field. Knowledge gained from these sectors can be adapted for agricultural purposes as experienced with past technology (Shearer et al. 2010).

Remote supervision in agriculture

In agriculture, both in-field (e.g., crop scouting, irrigation, etc.) and outside-the-field (grain storage, livestock husbandry, and farm security) operations have been remotely supervised (Edet et al. 2018). For example, Kang et al. (2012) remotely monitored multiple environmental parameters (temperature, humidity, luminous intensity, and soil water content in a greenhouse while Duan et al. (2014) developed a remote system that was used to monitor the physiology of pigs and environmental conditions in the hog barn to help inform the decisions of farmers. Environmental and physiological conditions included air temperature, humidity, the body temperature of the pigs, and concentration of harmful gases (carbon dioxide, hydrogen sulphide, and ammonia).

Unmanned aerial vehicles (commonly known as drones) have been used for crop and soil monitoring (to detect weeds, crop growth, soil type, and deficiencies), chemical application, livestock management, and irrigation mapping (Puri et al. 2017; Vasconez et al. 2019). They are usually equipped with sensors, cameras, and controllers to

Table 1. Autonomous tractor concepts being developed by various companies world-wide.

Concept	Examples	Main Features
Retain operator station	Monarch Tractor	➢ Tractor unit attaches to implements in the traditional manner. ➢ Small-sized tractor targeted towards orchard/vegetable production or livestock operations.
Eliminate operator station	CNH, John Deere, Kubota, Autonomous Tractor Corporation	➢ Tractor unit attaches to implements in the traditional manner. ➢ Large-sized tractors to replace the large-sized tractors currently being used for cereal/oilseed production on the prairies.
Integrated tractor	DOT	➢ Tractor unit is integrated with the implements that it powers.
Swarm/Fleet	Fendt Xaver	➢ Tasks completed by a swarm or fleet of extremely small machines working in an organized manner.

help navigate the field or area to perform the specified tasks. Early drones were mainly teleoperated by a remote user who sent commands to the drone via a portable interface. Advances in computing technology have aided these drones to operate autonomously. However, the human is still included in the control loop to perform high-level cognitive tasks like mission and system monitoring to ensure safety and overall efficiency of the operation (Ruff et al. 2002; Cummings 2015). Currently, one flight operator can supervise multiple drones due to their autonomous capability (Porat et al. 2016). When this occurs, a generic ground control station (comparable to a control station in a process plant) is used to monitor the operation of the drone fleet (Burkle et al. 2011; Gonzalez-de-Santos et al 2017; Ju and Son 2018). This concept can be readily adapted for field machinery (ground vehicles), considering that farmers are already familiar with how drones are supervised.

Remote supervision of unmanned ground vehicles (UGVs) In agricultural field machinery, remote supervision has been employed to monitor both subsystems of the ground vehicle as well as the entire field operation of the machine. Some examples of subsystem monitoring include the precision agriculture tracker (PAT), Case IH Advanced Farming Systems (AFS) Connect, CLAAS Telematics, and JDLink equipment management solution that enable farmers to access and monitor certain machine activities and information in real-time without being present in the field. Li et al. (2013) developed a GPRS-based system used to monitor real-time crop yield remotely. Also, the machine-machine interaction (machine synchronize) feature in tractors and combines is another example of remote subsystem supervision. It enables an operator (who is physically present in one of the machines) to remotely access information from another machine while both are in operation (Deeken et al. 2018; Edet et al. 2018).

Several remote supervision concepts for autonomous field machinery have been proposed by researchers and manufacturers alike. They vary in human involvement, autonomy level, the remote supervisor's proximity, and the number of machines in operation. In terms of human involvement, one concept requires the human to only supervise the operation of the autonomous machine(s) (Gonzalez-de-Santos et al. 2017), while for others, the human was expected to operate a conventional machine while monitoring the operation of the autonomous machine (Zhang et al. 2014). A third category involved controlling the actual operation of the field machine remotely – a process referred to as teleoperation (Murakami et al. 2008). Regarding the number of machines, some researchers envisioned the human to monitor just one machine (Stenz et al. 2002; Berenstein et al. 2012), while others believed that the supervisor would be expected to monitor several machines simultaneously (Emmi et al. 2014).

Regarding the level of autonomy, Shearer et al. (2010) projected that autonomous field machines would initially require constant human supervision. If there is an emergency, the machine can be stopped. The supervisor is notified to help mitigate the emergency. In time, the autonomy of the machines would be increased (i.e., to full automation), thus requiring minimal input from the human supervisor. At this point, Shearer et al. (2010) envisioned one of the autonomous machines also to coordinate the operation of the other autonomous machines in a lead-follower format. Human supervision of the entire fleet (lead and follower) could be carried out from a Central Monitoring Station (CMS). A similar lead-follower system was also proposed by Zhang et al. (2016).

On the contrary, Emmi et al. (2014) and Gonzalez-de-Santos et al. (2017) believed that the autonomous fleet, regardless of the task, would possess the same level of autonomy (as opposed to having a “master” machine coordinating several “slave” machines). Thus, various ideas are described in the literature regarding the supervision of autonomous agricultural machines. Hence, it will be beneficial to examine how well each concept satisfies the needs of the farming community.

The objective of this article was to determine the most viable remote supervision concept for farmers (producers) in the Canadian Prairies. It is imperative to note that this study was developed with ground-based agricultural machines in mind instead of aerial vehicles (i.e., drones). The study also focuses on the in-field operation of the machines.

MATERIALS AND METHODS

The first author (and primary investigator) conducted interviews with designers and experts of automated systems and machines to achieve this objective. The interview comprised pre-defined questions to ensure that key topics were covered, but the principal investigator had the flexibility to ask follow-up questions based on responses from the participants. The first section of pre-defined questions was related to demographic information of the participants (i.e., educational background and experience with autonomous machines), while the second section enquired about how the designer expected the autonomous machine to be supervised and the role of the supervisor (it is hereafter assumed that the farmer fills the role of supervisor) in regard to monitoring the operation of the autonomous machine. Questions on the general design of an automation interface were also asked during this final section of the interview. The questions are provided in the Appendix.

Potential participants were identified from the contacts of the primary investigator and the members of his doctoral advisory committee. In addition, an internet search was also conducted by the primary investigator. The recruitment process involved contacting potential participants via email and/or phone to request an interview. Upon acceptance, a preamble of the interview was sent out to the participant, highlighting the areas to be covered. The preamble intended to make the participant aware of the interview content to enable him/her to either prepare in advance or decline to proceed with the interview. The interview was either conducted in person or over the phone and lasted no longer than two hours based on the participant's preference. In-person interviews took place at a mutually convenient

Table 2. An example of weight assignment of decision factors using the unranked paired comparison method (1= more important, 0.5 = of equal importance, 0 = less important).

Factor	Assignment of weight										Sum	IW_f
F1	0	1	0	1							2.0	$IW_{f1} = 0.20$
F2	1				1	1	1				4.0	$IW_{f2} = 0.40$
F3		0			0			0.5	1		1.5	$IW_{f3} = 0.15$
F4			1			0		0.5		1	2.5	$IW_{f4} = 0.25$
Dummy				0			0		0	0	0	
Total											10.0	1.00

location. Regardless of the interview mode (phone or in-person), participants were required to sign the consent form indicating that they understood the conditions regarding their participation in this study and had voluntarily given their consent. Each participant's interview was recorded using an Olympus digital voice recorder, model WS-853 (Olympus Corporation of the Americas, Center Valley, United States). These recordings were later transcribed and analyzed to identify remote supervision concepts, the supervisor's roles, and automation interface requirements. An unranked paired-comparison analysis (Dean and Nishry 1965) was then performed to examine the benefits and shortcomings of each concept over some selected criteria (decision factors) that were identified from a review of the literature to determine the most viable concepts for farmers (producers) in the Canadian Prairies. The unranked paired-comparison analysis involved comparing each decision factor (concept) relative to other factors (concepts) and tabulating the numerical results of each comparison (Liu and Liptak 1997; Mohorjy 1997). For each paired comparison, a value of 1 is assigned to the factor that was considered more important, while the other factor is assigned a zero value (See the example in Table 2). If two factors were considered to have equal importance, each factor in the pair would be given a value of 0.5. A "dummy" is also included to avoid skewing the process by ensuring that none of the factors end up with a net assigned value of zero (Mohorjy 1997). Hence, anytime the dummy is compared with any of the factors, the latter is given a value of 1 while the dummy is assigned a value of 0 (Table 2). Afterward, the values of each factor are summed up, and its importance coefficient (i.e., the sum of individual factor values divided by the sum of all factors values) is computed.

The comparison is also carried out among alternatives (on a pairwise basis) with respect to each decision factor to determine individual alternative coefficients or rankings. The overall value of each alternative (i.e., composite index) is calculated using equation 1 (Liu and Liptak 1997).

$$Sj_{score} = \sum_i^n (IW)_f * (R)_{sf} \quad (1)$$

where:

- Sj_{score} = the composite index for the *j*th alternative,
- n = number of decision factors,
- IW_f = importance weight of *i*th decision factor,
- R_{sf} = ranking of *j*th alternative for *i*th decision factor.

Examples of how this technique is used can be found in Liu and Liptak (1997), Mohorjy (1997), and Gorai and Pal (2009). In this study, decision factors for comparing the remote supervision concepts were determined based on a review of the scientific literature. Factors considered for remote supervision were response time, labour demand, and cost (Johnson et al. 2009; Emmi et al. 2014; Redhead et al. 2015; Edet et al. 2018).

The research methodology used in this study was approved by the University of Manitoba's Education/Nursing Research Ethics Board. The names of each participant were coded to protect their identity while presenting the findings.

RESULTS

Respondent's demographics

Twelve participants from within and outside Canada were interviewed either in person or over the phone. They comprised five university professors, three entrepreneurs, and four designers working in the agricultural machinery industry. Eight of them had experience with developing a prototype autonomous agricultural machine at the time of the interview. The university professors were experts in machinery and robotics in agriculture (i.e., autonomous control, sensors and instrumentation, mechatronics) and had been researching in the field for at least 13 years. The three entrepreneurs had master's degrees either in agriculture or engineering. Each entrepreneur had founded a company developing autonomous agricultural machines and/or autonomous systems. The industrial designers all had at least a bachelor's degree in engineering (mechanical or agricultural). Furthermore, they all held managerial positions as a result of practicing for more than 20 years in the agricultural machinery industry in the area of design, manufacturing, repair, or testing of agricultural field machines. All participants (hereafter described as "designers" in the remainder of this article) presented unique remote supervision concepts.

Remote supervision of autonomous agricultural machines

All designers acknowledged that future autonomous agricultural machines would require some level of human involvement for the system to be efficient. However, the level of involvement, location of the human with respect to the autonomous machine, and tasks undertaken by the human varied, resulting in different remote supervision concepts.

Remote supervision concept Designers described different concepts regarding how the autonomous agricultural machine should be remotely supervised. For some, the term "remote supervision" meant having the supervisor in the field monitoring the operation of the autonomous machine. An example of this concept is that described by Mr. K, who proposed an autonomous machine and a human-driven machine working simultaneously on the same field. Supervision of the autonomous machine would be done from the interface in the cab of the human-driven machine. Other designers, like Mr. B, felt that

> "… *it (remote supervision) is a solution to the lack of labour but it's not a solution to making your farm autonomous. ...I don't see that as the long-term future sustainable direction that autonomous is going, but it is a nice stepping stone - it helps the labour problem, and it helps people make autonomous better and better because there is someone in the field with an autonomous machine that can observe it and you constantly can be able to compare operator to the autonomous machine and refine and improve the autonomous machine*."

On the other hand, Mr. H thinks that the farmer

> "… *will be at the edge of the field, (i.e, outside of the field). I don't expect him in the field while they operate, No. I think to be successful, I think he would be managing a number of these machines and the better manager he became, the more self-contained he would be operating more machines*."

Dr A also added that for multiple fields,

> "… *the base station will be within the farm or next to the farm, ideally, let us say, the farmer has a field, that is maybe, 10 or 100 acres or 50-acre land and we divide it into several different fields that might produce different crops. Ideally, I would say this station is located centrally, so that it has a distance to the edges of all the field and that is the minimum distance, so it is centrally located."*

This concept enables the remote supervisor to perform other tasks that will aid the field operation (like bringing chemicals to the field to refill the spray tank or performing minor repairs) while monitoring the operation of the autonomous machine. The supervisor utilizes an automation interface to monitor the operation remotely and has a farm vehicle that enables him/her to move back and forth from the field to where the chemicals are kept or from one field to another.

A third concept uses the farm office as the remote station from which the supervisor monitors the operation of the autonomous machine. Designers who adopted this concept believed that this approach would allow the supervisor to attend to other physical tasks on the farm rather than focusing solely on monitoring the autonomous machine.

The last group of designers (Mr. S and Dr. S) presented a concept that involves monitoring the autonomous machine and its operation from a remote station located away from the farm. One of the designers (Dr. S) believed that, in the future, the business model for farming agricultural land would change substantially. He believed that farmers would no longer own agricultural machines, and farming would primarily be done by companies that would deliver autonomous machines to the farm to perform the needed operation when called upon. Monitoring of the machine will be done by the "*machine monitoring support*" of the contracting company, with less involvement on the part of the farmer. Mr. S even explained further that the farmer may not even have to be physically present on the farm, as evidenced by this quote: "*Ultimately the farmer could be sitting on a beach on vacation*."

Overall, these concepts can be grouped under four categories based on the location of the remote supervisor and automation interface in relation to the autonomous agricultural machine: 1) in-field, 2) close to the field, 3) in the farm office, and 4) outside the farm site.

The role of the supervisor (farmer) According to Mr. H, the role of the human was influenced by

> "… *the level of automation and the sensors. For every function that is not properly sensed and monitored, you got to have operator's intervention*."

He also added that the human will also be expected to perform upper-level functions like

> "*co-ordinate on his cell phone, bring or have material delivered to the yard*."

Dr. T proposed that the autonomous machine will be

> "… *taken to the field by a human being. Once it is in the field, then we would use satellite data for it to run itself autonomously through the field*."

He also added that the human would be tasked with 1onitoring the machine(s). Dr. A agreed with having the .uman supervise the machine when he said that the

> "… *farmer will monitor the activities of the machine, and, just make sure that you know that nothing is going out of hand or the machine is not doing something it is not supposed to do*." He went further and stated that "… *they will not need multiple people going to the machine and doing the work and there will be just one person who will be in charge to monitor the whole operation and less labour for the farm, fewer people, and more productivity.*"

Overall, since the tasks undertaken by the individual remotely supervising the autonomous machine would depend on the level of autonomy of the machine and the remote supervision concept employed (since each concept requires the human to adopt a different type of interaction), the farmer may either play an active role to support the overall success of the operation (driving alongside the machine, working elsewhere) or a passive role (on holiday while farm tasks continue).

Monitoring frequency Responses regarding the frequency with which the autonomous machine would be monitored varied among designers. The possible options included the farmer checking i) all the time, ii) every few hours, iii) only when (s)he wanted to, or iv) when (s)he was notified by the autonomous system. This depended on the level of autonomy of the autonomous machine, the trust the farmer had with the machine, and the role of the farmer (active or passive).

Number of machines to monitor Responses regarding the number of machines to be monitored by each supervisor also varied from one designer to another - from as few as one to as many as thirty. During operation, some designers envision having only one autonomous machine in the field. In contrast, others believed that there would be fleets of these machines working "*independently*" and interacting with one another as well as with the supervisor. However, a unique form of monitoring was that described by Dr. F; he envisioned a concept that required the supervisor to monitor only one machine, despite having multiple machines on the field and related the concept to that of mother duck and her ducklings:

> "*…one of them is master, and the other three are slaves let's say slave number 1 slave number 2 slave number 3… and all of them are autonomous, but one of them is controlled carefully. In other words, the speed and direction and so on and the other looks to the master and instead of controlling each individually we control one and the others look to the master and see what direction it is going on.*"

According to Dr F, it would be easier to supervise one machine than a fleet of several machines. An example of where this approach was applicable is where the supervisor wants to perform two or more operations simultaneously, for example, tillage and spraying or harvesting grain and baling the straw.

Managing the machines during field operations For "in-field" remote supervision, depending on the condition or situation, the operator can either i) resolve problems through the onboard interface or ii) stop the machine (s)he is operating and physically attend to the problem. Designers who envisioned either the "close-to-the-field" or "from the farm office" methods of remote supervision expressed a similar approach to tackling machine malfunction. If there was a problem that was beyond the capability of the autonomous sprayer or machine, the supervisor would be required to handle the situation. Depending on how severe the problem is, (s)he will either go into the field to rectify it or call a service technician.

In the case of "outside-the-farmland" remote supervision, the designer envisioned a situation where a couple of service technicians would be driving around the region where the fields are located. The technician's truck will warehouse most of the parts necessary to service these autonomous machines. Hence, once the "*machine monitoring support*" in the remote location notifies them about a malfunction or problem, the service technician would drive to that location and rectify the problem.

Interface requirements

This section presents designers' opinions regarding the physical characteristics of the automation interface, how they intend to communicate wirelessly with the autonomous agricultural machine, and the need for live video of the autonomous machine and its environment.

Display physical characteristics (device) In the case of in-field remote supervision, the remote supervisor will be expected to access status update information or get notifications from the autonomous machine through an onboard interface. Similar information would be obtained from an automation interface on a tablet if the "close-to-the-field" remote supervision scenario was adopted. In the "from-the-farm-office" scenario, the remote supervisor could monitor the operation of the autonomous machine through the automation interface on a desktop computer or laptop. However, it would be beneficial to provide access through a secondary device (i.e., a tablet or phone) to enable him/her to access information while moving around the farmyard. Depending upon where the remote supervisor would be when "outside the farm" (s), he may prefer to access the interface in a variety of ways (i.e., from a desktop computer in an office off the farm, laptop or tablet/phone while on vacation).

Mode of wireless communication Designers indicated that they would envision using radio, cellular, or satellite to receive information from the machine. However, connectivity and rural cellular infrastructure were often discussed as problems. One way the designers intended to address these challenges was to have a mobile wireless station placed near the field. Other solutions included generating one's signal, having offline modalities, and updating cellular infrastructure.

Visual requirements Designers were asked if the remote supervisor would need a live video of the operation. Fifty-eight percent (58%) of them indicated that live video would be useful to the remote supervisor. These designers felt that having a live video would be important in understanding machine errors and the condition of the machine (for example, spray pattern or the type of obstacle encountered by the autonomous machine). They believed that sensors alone would not provide all the information required by the supervisor to make sound judgments. Furthermore, having a live video would reassure the supervisor that everything was functioning correctly. When prompted to consider an autonomous agricultural sprayer as a specific example, these designers suggested some regions of a sprayer that should be presented visually. This included the front view (view ahead), rear view, entire nozzle view (boom view), crop view, side view, and an aerial view of the sprayer. Among these views, the front view was the most recommended view, followed by the boom view (entire nozzle view). Furthermore, a majority of the designers suggested the views to be on request, while the remainder suggested a continuous live video feed. Some designers even stated that recording the videos should be completed for safety and/or legal purposes or documentation of agronomic practices (i.e., record-keeping).

Designers who did not respond affirmatively regarding the need for live video felt that live video was not a suitable medium for communicating machine errors or malfunctions. Furthermore, this approach would require the supervisor to monitor the machine continuously. They also stated that dust, inclement weather, time of day, and poor

Table 3. Ranking of alternative remote supervision concepts based on response time, f_1 (1= more desirable, 0.5 = of equal desirability, 0 = less desirable).

Remote supervision concept (s)	Assignment of desirability										Sum	R_{SF1}
In-field (s_1)	1	1	1	1							4.0	R_{s1f1} = 0.40
Close-to-the-field (s_2)	0				1	1	1				3.0	R_{s2f1} = 0.30
Farm office (s_3)		0			0			1	1		2.0	R_{s3f1} = 0.20
Outside-the-farmland (s_4)			0			0		0		1	1.0	R_{s4f1} = 0.10
Dummy				0			0		0	0	0	0
Total:											10.0	1.00

communication signal were some of the factors that could impede the quality of the video, thereby defeating its purpose. Another concern that was raised was the cost associated with transmitting video wirelessly. However, some of the designers who voiced concerns with the provision of the real-time video did admit that having live video as a secondary source of information for understanding the condition of the autonomous machine in the field context would be beneficial.

DISCUSSION

This section examines the information gathered from the designers/researcher regarding the different remote supervision concepts and compares them against selected criteria (decision factors) identified from a review of the literature to determine the most viable concept for farmers (producers) in the Canadian Prairies.

Analysis of remote supervision concepts

Details of the unranked paired analysis for the remote supervision concepts are presented below. Decision factors include response time, labour demand, and cost. At the same time, the assignment of desirability was derived from the benefits and drawbacks of each remote supervision concept in relation to each decision factor.

Response time (f1) Table 3 presents the results of the unranked pair-wise comparison of the four remote supervision concepts in relation to the factor of response time. Given that autonomous agricultural machines are still at the developmental stage, one of the major concerns for the foreseeable future is the reliability of these machines. If there were to be a problem with the autonomous machine that is beyond the capability of the machine to rectify on its own, the time taken to resolve such an issue would be determined mainly by the distance of the remote supervisor from the autonomous machine. The in-field concept enables the user to react to emergencies promptly compared to other remote supervision concepts. Quick diagnosis or minor repairs can be quickly completed since the operator is envisioned to be near the autonomous machine while both machines are operating in the field. It is envisioned that the lag time will progressively increase as the supervisor is adjacent to the field, back in the farm office, or completely away from the farm. The time lag associated with the "outside the farm" scenario may be the most difficult to predict as service work would likely be performed by a service technician responsible for a large number of machines and who will respond to service calls in order of notification.

Labour demand (f2) One of the major reasons behind the development of autonomous machines in agriculture is to address the shortage of labour experienced by farm owners, especially during peak periods, and the ageing population of farmers. Hence, there is a need to minimize the labour associated with remote supervision of an autonomous agricultural machine. The operator can supervise multiple autonomous machines for the in-field remote supervision concept. However, if one machine breaks down or requires assistance, the entire field operation may come to a standstill since the operator is expected to handle the problem. Alternatively, the operator might request assistance from another farmworker, increasing the number of people required to manage the overall system and defeating one of the purposes for adopting an autonomous machine in the field (i.e., labour shortage). In the close-to-the-field and farm-office remote supervision concepts, the farmer is not controlling any autonomous machines in operation. Hence, (s)he can handle or manage malfunctions beyond the machine's capability and other logistics associated with the operation without assistance from other farmworkers.

The outside-the-farmland concept has an advantage in rectifying machine malfunction better than other remote supervision concepts discussed previously since repairs are performed by skilled service technicians who always have replacement parts and tools kept in their service truck. Their involvement in the field operation is dependent on the customer care unit (as described earlier), thus increasing the number of personnel needed to make the concept successful. The result of the pair-wise comparison is presented in Table 4.

Cost (f3) The cost associated with either acquiring or hiring an autonomous agricultural machine will influence the decision of the farm owner (Shockley and Dillon 2018; Zhang et al. 2019). In the in-field concept, the automation interface is envisioned as an onboard display mounted in the supervisor's machine. Hence, it would likely take advantage of existing facilities, resulting in little or no additional cost to the farmer. Furthermore, since both machines operate in proximity, relatively short-range, inexpensive technologies for communication and data transfer (such as Bluetooth and radio) can be adopted. Also, there may be minimal need for

Table 4. Ranking of alternative remote supervision concepts based on labor demand, f2 (1= more desirable, 0.5 = of equal desirability, 0 = less desirable).

Remote supervision concept (s)	Assignment of desirability										Sum	R_{SF2}
In-field (s_1)	0	0	0.5	1							1.5	R_{s1f2} = 0.15
Close-to-the-field (s_2)	1				0.5	1	1				3.5	R_{s2f2} = 0.35
Farm office (s_3)		1			0.5			1	1		3.5	R_{s3f2} = 0.35
Outside-the-farmland (s_4)			0.5			0		0		1	1.5	R_{s4f2} = 0.15
Dummy				0			0		0	0	0	0
Total:											10.0	1.00

live video since the operator can visually see the slave machine operation from their operator seat in the master machine. The effect would be a reduction in data usage (in the case of cellular communication) and total operating cost compared to other concepts.

Similarly, the close-to-the-field concept may also take advantage of short-range wireless connections and minimal video streaming (since the supervisor can visually see the field). However, this would be dependent on the size and topography of the field. Furthermore, since the remote supervisor can multi-task and no operator is needed to control the machines, the cost of using an operator and additional support would be significantly reduced.

On the other hand, the farm-office concept will depend on streamed video feeds presented on the automation interface to make intelligent decisions (since the supervisor cannot visually assess the situation from his or her location). This means large amounts of data would have to be transmitted wirelessly. Since short-range wireless connections cannot be adopted due to the large distances involved, the operating cost may increase since cellular data usage (or other long-range wireless connections) would be adopted. There is also the additional cost associated with setting up the farm office and the cost resulting from driving back and forth to the field to resolve any problem that is beyond the capability of the machine. Overall, outside-the-farmland would be considered the most expensive since skilled technicians are expected to be on call to handle any problem that may arise while the autonomous machines are in operation (Table 5).

Decision factor ranking (remote supervision concept) A primary reason for developing autonomous agricultural machines is to tackle the labour shortage. Hence, if the time taken to respond to emergencies and the operating cost are both low, but there are no labourers to execute the task, this concept will not be successful. Similarly, if the remote supervision concept is cheap to operate but will likely result in more liability due to increased response time, the benefit of having an inexpensive remote supervision concept will no longer be attractive. Therefore, response time would be considered to have a higher value in comparison to cost. A tabular representation of the paired comparison is shown in Table 6.

The ranking score for each remote supervision concept was computed as follows (refer to Tables 3 to 6 to identify each variable):

For "in-field" remote supervision concept:

$$S1_{score} = (IW_{f1} * R_{s1f1}) + (IW_{f2} * R_{s1f2}) + (IW_{f3} * R_{s1f3}) \quad (2)$$

$$= (0.33 * 0.40) + (0.50 * 0.15) + (0.13 * 0.40)$$
$$= 0.259$$

For close-to-the-field remote supervision concept:

$$S2_{score} = (IW_{f1} * R_{s2f1}) + (IW_{f2} * R_{s2f2}) + (IW_{f3} * R_{s2f3}) \quad (3)$$

$$= (0.33 * 0.30) + (0.50 * 0.35) + (0.13 * 0.30)$$
$$= 0.313$$

For farm-office remote supervision concept:

$$S3_{score} = (IW_{f1} * R_{s3f1}) + (IW_{f2} * R_{s3f2}) + (IW_{f3} * R_{s3f3}) \quad (4)$$

$$= (0.33 * 0.20) + (0.50 * 0.35) + (0.13 * 0.20)$$
$$= 0.267$$

Table 5. Ranking of alternative remote supervision concepts based on cost, f3 (1= more desirable, 0.5 = of equal desirability, 0 = less desirable).

Remote supervision concept (s)	Assignment of desirability										Sum	R_{sf3}
In-field (s_1)	1	1	1	1							4.0	R_{s1f3} = 0.40
Close-to-the-field (s_2)	0				1	1	1				3.0	R_{s2f3} = 0.30
Farm office (s_3)		0			0			1	1		2.0	R_{s3f3} = 0.20
Outside-the-farmland (s_4)			0			0		0		1	1.0	R_{s4f3} = 0.10
Dummy				0			0		0	0	0	0
Total:											10.0	1.00

Table 6. Weight assignment of decision factors associated with remote supervision concept (1= more important, 0.5 = of equal importance, 0 = less important).

Decision factors (f)	Assignment of weight						Sum	Iw$_f$
Response time (f_1)	0	1	1				2.0	IW_{f1} = 0.33
Labour needs (f_2)	1			1	1		3.0	IW_{f2} = 0.50
Cost (f_3)		0		0		1	1.0	IW_{f3} = 0.13
Dummy					0	0	0	0
Total							6.0	1.00

For outside-the-farmland remote supervision concept:

$$S4_{score} = \left(IW_{f1} * R_{s4f1}\right) + \left(IW_{f2} * R_{s4f2}\right) + \left(IW_{f3} * R_{s4f3}\right) \quad (5)$$

$$= (0.33 * 0.10) + (0.50 * 0.15) + (0.13 * 0.10)$$

$$= 0.121$$

Therefore, by the most significant computed score, the close-to-the-field (S3) remote supervision concept seems to be the most viable concept.

Visual requirement analysis

Analysis of the interview data revealed that seven out of the eight designers who had experience developing a prototype autonomous agricultural machine believed that live videos of an autonomous machine and its environment should be provided. The designer with prototype experience who rejected the provision of live video was one of the designers who envisioned the "*in-field*" remote supervision concept. This is understandable considering that the farmer would be close to the machine; therefore, the supervisor (operator) could visually assess the autonomous machine and its operation. In this scenario, having live videos may not add much value.

This finding may be an indication that video footage has a vital role to play towards the success of the overall autonomous machine, considering that designers with existing prototypes also included it in their design. Previous studies on remote supervision (Stenz et al. 2002; Berenstein et al. 2012; Redhead et al. 2015) also supported the inference that video footage was essential to the supervisor when monitoring an autonomous machine or system remotely. Blackmore et al. (2002) noted that the inclusion of video would enable the supervisor to understand the tractor's environment better, while Panfilov and Mann (2018) stated that providing live video will help the supervisor better understand any problems with the machine. Therefore, it would be essential to include real-time video in the automation interface. However, one would expect that the video should be made available on-demand or when there is an issue with the machine since its usefulness is to understand the issue better and not for detecting problems (Panfilov and Mann 2018). The cost associated with wirelessly transmitting live video can be reduced by doing so.

Remote supervision of autonomous agricultural machines in Canadian Prairies

Considering the tasks and needs of the remote supervisor, a viable remote supervision concept for Canadian Prairie farmers should have the remote supervisor situated close to the field but not necessarily operating a master machine in the field (in a master-slave configuration). The supervisor can monitor multiple autonomous machines and/or fields from a location in proximity to the field through a portable, hand-held device such as a tablet. This will allow the supervisor to move freely, perform other farm tasks, and return to the field on time. Should there be any emergency that goes beyond the capability of the autonomous agricultural machine, the machine will notify the supervisor, who then assesses the situation through the automation interface; the supervisor can then take the necessary steps to rectify the problem either personally or with specialized technical assistance if necessary. A schematic of the proposed concept is presented below (Fig. 1).

CONCLUSIONS

A variety of remote supervision concepts were discovered based on interviews with designers of autonomous machines. These concepts can be grouped into four categories based on the location of the remote supervisor in relation to the autonomous agricultural machine: 1) within the field, 2) close to the field, 3) at home in the farm office, and 4) outside the farm site. Based on the unranked paired analysis, the close-to-the-field remote supervision concept was determined to be the most viable concept. Designers were divided on the idea of providing real-time live video on the automation interface. However, most believed that having a live video would reassure the farmer that everything was going well. Also, the Canadian Prairies have vast farmlands compared to 10 to 50 acre fields in other continents. Hence, dependency on videos (and data) could be huge, especially when the autonomous machine is out of sight of the farmer. Desktop computer, tablet and phone were the main devices recommended as tools for remote supervision (i.e., the hardware on which to display the automation interface), with tablet perhaps being the preferred alternative due to it being more portable than a desktop computer and providing a larger display than a phone.

Overall, a suitable remote supervision concept for grain producers would: i) require minimal labour to function, ii) enable the farmer or supervisor to monitor and understand the status of the operating machine in the field, iii) not restrict the movement of the remote supervisor, iv) allow the supervisor to perform other farm tasks, iv) enable the supervisor to attend to in-field problems promptly, and vi)

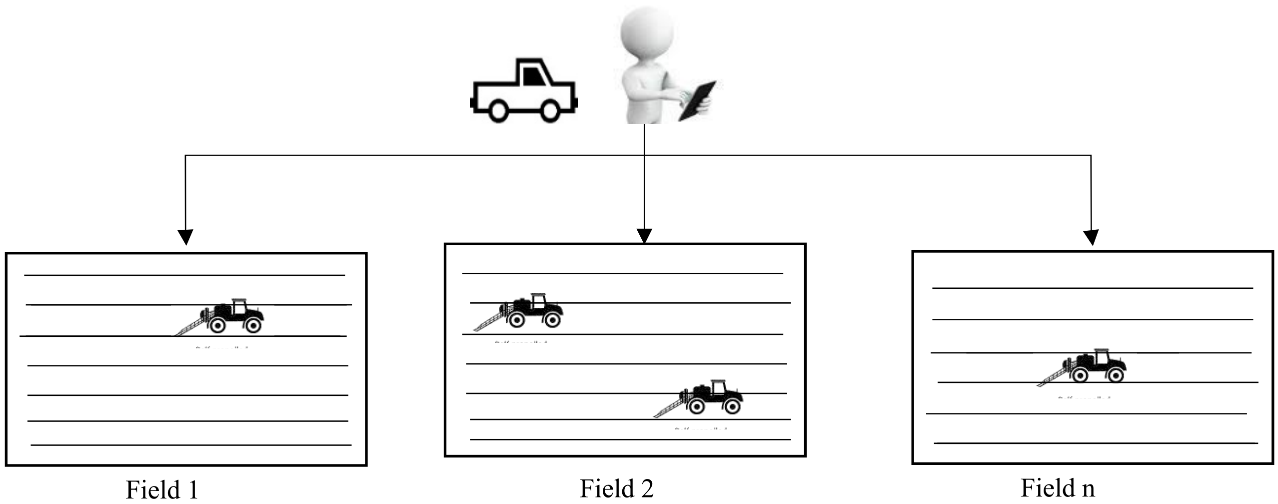

Fig. 1. Close-to-the-field concept for remote supervision of autonomous agricultural machines.

be cost-effective. Other factors that may influence the choice of remote supervision for monitoring the operation of autonomous agricultural machines include the size of the farm, ease of use of the automation interface, type of field operation being conducted, business structure of the farm, the farmer's preference, and future legislation that might relate to the supervision of autonomous agricultural machines.

LIMITATIONS

The study may be limited by the small number of designers who participated in the interview, and some interview responses may have been stated to protect proprietary information. Future research might include a usability study of the proposed remote supervision concept to gather feedback from farmers while remotely monitoring an autonomous agricultural machine.

It is also important to note that the above scenario recommended for Canadian Prairie farmers may depend on the level of confidence built into the machine. If the autonomous machine works very well, the farmer may watch them closely from the border of the field and will gradually move away and get closer to the farmyard. However, if the autonomous machine has constant problems, the farmer will stay in the field more.

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APPENDIX

Pre-defined interview questions

- Can you please tell me about your educational background and experience as a designer of autonomous systems?
- What's your opinion on how to monitor/supervise the operations of the autonomous machine(s).
- What is/are the role(s) of the farmer (if any) when the autonomous machine is in operation?
- How far would the farmer/user be from the machine to monitor it? Why?
- How often is the farmer expected to monitor the machine?
- Will the farmer be required to monitor more than one autonomous machine?
- How would the farmer know what is going on in the field?
- How would the automation interface look like (features and appearance)?
- Would the interface be i) portable, ii) stationary, or iii) both? Why?
- What mode of communication signal would you likely used (e.g. GPS, radio signal, phone, RTK, internet, Bluetooth, etc.) and why?
- What form of communication would likely be adopted when using the automation interface (text, audio, button/tab, etc.)?
- Would there be a live video in the interface to assist the farmer/user monitor the sprayer? Yes or No? Why?
  If "YES",
  - Which side(s) of the sprayer or field will the farmer require live video(s)?
  - Should the live video(s) be provided full time or on-request?
  - Should there also be a pan-tilt-zoom function for the video or just a fixed position?
- What action would the farmer/supervisor take during the following:
  - Malfunction?
  - Lost communication signal?