A Survey of Unmanned Ground Vehicles with Applications to Agricultural and Environmental Sensing

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ABSTRACT

Unmanned ground vehicles have been utilized in the last few decades in an effort to increase the efficiency of agriculture, in particular, by reducing labor needs. Unmanned vehicles have been used for a variety of purposes including: soil sampling, irrigation management, precision spraying, mechanical weeding, and crop harvesting. In this paper, unmanned ground vehicles, implemented by researchers or commercial operations, are characterized through a comparison to other vehicles used in agriculture, namely airplanes and UAVs. An overview of different trade-offs of configurations, control schemes, and data collection technologies is provided. Emphasis is given to the use of unmanned ground vehicles in food crops, and includes a discussion of environmental impacts and economics. Factors considered regarding the future trends and potential issues of unmanned ground vehicles include development, management and performance. Also included is a strategy to demonstrate to farmers the safety and profitability of implementing the technology.

Keywords: Unmanned ground vehicles, agriculture, environment, sensing, survey

1. INTRODUCTION

The development of agricultural-based unmanned ground vehicles is an important area of research in both academia and industry. This paper provides a survey of many of the vehicles found in literature, and includes those developed for soil sampling, irrigation management, precision spraying, mechanical weeding, and crop harvesting for food products. Availability of commercial unmanned ground vehicles to perform these tasks in the future has the potential to address rising demands for food in the United States, and other areas of the world [1]. While airplanes and unmanned aerial vehicles (UAVs) exist and are being researched for agricultural use, the uniqueness of ground vehicles makes them particularly useful for a broad range of applications [2]. Various propulsion configurations are used in existing technology, and many different control schemes have been explored to complete specific tasks, demonstrating the extensive options to choose from during development [3, 4]. The availability of sophisticated imaging and detection technologies allows for the development of systems to perform various agricultural tasks efficiently when mounted on unmanned ground vehicles [5]. The arduous task of development, questions about management and performance of unmanned ground vehicles, and resistance from growers and producers are some of the issues faced by scientists and engineers when designing and building vehicles to perform agricultural tasks for food crops. Continued improvements to configurations, control systems, and sensor technology, coupled with further testing of available systems to demonstrate efficacy, will support the adoption of unmanned ground vehicles by farmers.

Labor shortages and food borne illness resulting from contaminated crops are two issues that unmanned ground vehicles in agriculture can be used to address [1, 6]. As the world population continues to increase, expected to reach about 9 billion by 2050, so does the demand for food [7]. Labor shortages have been reported throughout the agricultural industry in the United States, in particular [1, 8, 9]. With fewer workers available, a push towards changing farming practices to reduce the need for workers has developed [1]. Mechanizing and automating agricultural processes such as monitoring, inspecting, seeding, harvesting, and processing produce for the market reduce the need for manual laborers on farms.

Food safety is a concern in the agricultural industry. An estimated 48 million Americans become ill from foodborne diseases each year, and around 3000 of those individuals die as a result of their illness [10]. While progress has been made toward reducing the incidences of food borne illness caused by various bacterial sources, utilizing additional technological resources to inspect various food sources prior to harvest could further reduce these incidences [6]. For example, detection of fecal contamination on leafy greens to supplement current manual inspections is a task that could be automated using an unmanned vehicle. An unmanned ground vehicle configured to autonomously travel through spinach crop rows to search for fecal contamination is currently being developed by the USDA to address this task. The vehicle is equipped with a laser and hyperspectral camera to induce and detect fluorescent responses in the imaging field [11]. Development of unmanned ground vehicles could address the issues of labor shortages and food borne illness.

Over the last century, mechanization of agriculture has reduced manual labor needs on farms [12]. Technological advances now allow mechanized equipment to be automated, leading the way for unmanned vehicles to further reduce labor costs in agriculture. As discussed by Sistler [12] in his 1987 analysis of robotics in agriculture, automation in the agricultural industry began to rise in the 1980s and, by the end of the decade, various automated machines were implemented in the industry. Sistler discussed various machines available at the time, including a citrus grading machine which determined the size and color of fruit as well as detected blemishes and injury due to frost, which had the capacity to inspect 480 fruit per minute. Machine vision applications of the decade included systems to detect broken egg yolks in egg breaking machines, remove defects from potatoes for French fries, and sort and grade cucumbers. Prototypes were developed for automated sheep shearing, seedling transplanting, tree fruit harvesting, and robotic chemical spraying. At the time, while automated machinery had the potential to improve efficiency, Sistler predicted future problems with robotics in agriculture would include uncertain efficiency for use with low value crops, difficulties dealing with the variability of crops, uncertainty in turnaround time for repairs, and questions about developing driving functions.

Around the turn of the twenty-first century, the agricultural industry was faced with maintaining consistency in product quality while facing labor shortages [13]. The focus of agricultural robotics research in 2000, according to Hamrita et al. [13], was shifting to energy and soil management using real-time control applications. The use of sensing and control systems in agricultural production could reduce labor needs, as indicated by Hamrita et al., which would be especially beneficial in difficult environments (e.g. steep slopes [3]). According to Blackmore and Griepentrog [14], technology available to counteract labor shortages and improve efficiency included devices for driver assistance and automatic steering, which were added to existing farm equipment. Driver assistance devices could detect crop edges for use in large combine harvesters, warn operators of deviation in path from desired path during harvesting based on manual inputs from the first field pass, and provide inter-row guidance to the operator for weeding operations. Autonomous steering technology took control of steering operations while operators performed additional tasks like weeding, spraying and plowing. Systems with autonomous steering, in general, depended on preprogrammed routes to navigate the field, and most could not react to the current environment to avoid obstacles. Developing fully autonomous tractors, Blackmore and Griepentrog add, could further address the need for reducing labor requirements by operating without a human operator and remains a major focus in the industry.

In this paper, current applications of unmanned ground vehicles in the agricultural industry, specifically with respect to food crops, will be reviewed. The vehicles included in this review are categorized by their primary function: soil sampling and mapping, irrigation management, precision spraying, mechanical weeding, or harvesting. The unmanned ground vehicles will be characterized by the vehicle configuration, control schemes, and sensing technology that comprise the system. A discussion on the technical and legal problems introduced by the use of autonomous technology in commercial agriculture with respect to development, management, performance, and implementation is also included. Future trends of the autonomous ground vehicle industry for agricultural applications, and environmental and economic benefits of automating farming tasks, are mentioned as well.

2. GROUND VEHICLES

Overview of Agricultural Vehicles

The primary alternative to use of ground vehicles in agriculture is the use of planes. Agricultural planes have been in use since the 1920s as an efficient means to apply pesticides and herbicides for pest and disease control of large areas [15]. While agricultural planes are useful for applications such as quickly applying necessary chemicals to crops without disturbing or compacting the soil around the plants, they are not appropriate for agricultural applications that require higher precision [15]. Various small planes are specifically designed for agricultural use today that can cost upwards of one million dollars, and are relatively expensive to fuel and maintain [16]. These airplanes are typically designed to hold a pilot and are powered by turboprop engines, and may not be an economically viable option for small farm operations [16]. In addition, planes maintain high speeds throughout their flight, and cannot hover or return to a particular point of interest. For applications of mapping and inspection, slower speeds and increased maneuverability may be needed.

In recent years, UAVs, or drones, have been used in agriculture. The additional agility of UAVs and their ability to hover allow them to be used for precision applications of remote sensing, because they permit higher resolution images to be collected at lower costs, when compared to agricultural airplanes [17]. In addition, UAVs have the ability to return to a precise location of interest during flight for further inspection or evaluation. Current and potential uses include crop surveying and mapping, pest control, and disease detection, as discussed by Zhang and Kovacs [17] in their review of UAV systems in agriculture. UAVs, in contrast to airplanes, are commonly powered by batteries and flight time is limited by the battery capacity.

Ground vehicles, in contrast to both planes and UAVs in agriculture, remain in the field during use, and must be designed to interact with the particular environment where they are being applied [18]. Configuration of the vehicle is dependent on the size of crop rows and spaces between the rows, as well as plant height and the characteristics of the environment (e.g. precipitation level and soil composition) [3]. Similar to UAVs, ground vehicles can stop in place as needed, and can be used for mapping and disease detection [19, 20]. In addition, ground vehicles can be used for soil sampling, precision spraying, weeding, and harvesting of crops, as well as broader agricultural applications of grass cutting, land surveying, etc. [2].

Ground Vehicle Configurations

Ground vehicles can take on various configurations for different applications. In agriculture, two propulsion configurations are commonly used in current applications: tracked vehicles and wheeled vehicles [3]. Tracked configurations consist of continuous treads powered by two or more wheels. Tracked configurations increase the contact area of the vehicle with the ground, distributing vehicle load over a larger area. This can be advantageous in difficult terrain to provide improved traction, and some agricultural equipment such as large tractors can be propelled with treads [21]. Wheeled vehicles, summarized by Siegwart et al. [22], can be characterized by the type of wheel used and the number of wheels used. The four basic wheel types used are standard wheels, castor wheels, Swedish wheels, and ball/spherical wheels. Standard wheels have two degrees of freedom, rotating around a wheel axle and the point of contact. Castor wheels also have two degrees of freedom, but rotate around a steering joint that is offset from the wheel center. Swedish wheels have three degrees of freedom, rotating around the wheel axle, rollers, and the contact point, allowing for the vehicle to move in many directions. Finally, spherical wheels are omnidirectional, moving in any direction desired.

There are a number of different wheel configurations described by the number of wheels and the types of wheels used; each with advantages and disadvantages in terms of stability, maneuverability, and controllability, as discussed by Siegwart et al. [22]. The most popular ground vehicle configuration found in agricultural applications, like an automobile, has four wheels. Four wheel configurations include: two motorized wheels in rear with two steered wheels in front (e.g. rear-wheel drive car), two motorized and steered front wheels with two free wheels in rear (e.g. front wheel drive car), four steered and motorized wheels, two differential tractions wheels in front or rear with two omnidirectional wheels at the opposite end, four omnidirectional wheels, and four motorized and steered castor wheels.

The optimal vehicle propulsion configuration depends on the application. For agricultural applications, variable terrain dictates the configurations that can be used. In general, wheeled agricultural ground vehicles reviewed in this paper are designed with four wheels and may use either differential steering or motorized steering configurations. Wheeled vehicles often allow for higher vehicle speeds than tracked vehicles [21]. When difficult terrain is to be navigated for a specific application, tracked vehicles may be preferred [21]. Vidoni, et al. [3] reviewed various popular vehicle configurations, including three wheeled, tracked, and two different four wheeled configurations, to assess their stability on side-slopes, common in terrain faced by some agricultural robots.

Control Schemes

In order to control the motion of an unmanned ground vehicle, manual or autonomous control can be used. A manual control scheme can be utilized to direct a robot in performing desired tasks. For mobile, unmanned ground vehicles, manual control can be executed by synching a wireless handheld controller, mobile device or tablet to the vehicle motion. Control actions may be sent to the vehicle from close proximity or from a remote location, depending on the functionality of the wireless communication. Cameras may be mounted atop the vehicle to stream live feed images to the operator [4]. Instead of using manual control, various automated control schemes can be implemented to enable autonomous navigation in an unmanned ground vehicle. In order to accomplish autonomous motion, the position or location (globally or relative to its surroundings) of the vehicle must be determined and interpreted as an input. Next, the input can be processed to determine a navigational goal (e.g. moving forward, backward, turning, or stopping). Finally, this goal can be outputted as information to the vehicle motors and wheels. Methods of positioning and localization include dead reckoning, range sensing, reflectance sensing, and image processing [23].

Dead reckoning is a positioning method which calculates vehicle position based on the distance, angle, and speed of travel. While the positioning is accurate at first, as the travel time increases, accumulation of error from slipping decreases accuracy [24]. GPS information can be used for autonomous vehicle navigation by determining absolute vehicle location; however the localization information is limited by the GPS receiver. Low-cost GPS sensors can provide accuracy to within meters, while more expensive receivers can provide accuracy to within centimeters [25]. Range sensing can be accomplished by implementing infrared, ultrasonic, or other sensors on a vehicle to detect the distance from an object [24]. In a similar fashion, reflectance information from a photo resistor can provide information about changes in the surrounds. The photo resistor will pick up varied inputs based on the amount of light reflected off of a particular object. Reflectance of plants will be different than that of dirt or other objects in the field [26]. Navigation based on image processing utilizes images as an input signal to detect crop rows or avoid obstacles while travelling through a field. Image processing can be used to navigate an unknown environment and respond to changes in real-time [24].

While the information gathered from these sensors and methods alone may be enough to determine an appropriate output to the vehicle, control algorithms can be implemented to improve the accuracy and efficiency of vehicle movement. For example, to assist in converting input information into viable navigational control, various algorithms can be implemented including: proportional-integral-derivative (PID) control, fuzzy logic control, neural networks/genetic algorithm control, and Kalman filtering. Mousazadeh [24] conducted a review of control algorithms used in various agricultural ground vehicle applications.

Detection and Imaging Systems

Detection and imaging systems can be used on unmanned ground vehicles in agriculture to locate plants, distinguish crops from weeds, detecting edges of crops and rows for navigation control, determining and observing the stress levels and ripeness of crops, and detecting disease or contaminants in the field [5]. Sankaran et al. [5] conducted a review of and described many different techniques used to implement these applications including spectroscopy, imaging, and volatile organic compound assessment. Spectroscopy involves measuring the response of a point of interest to a light source, revealing information such as chemical composition and temperature of the area. Imaging, in contrast collects visual data to produce a copy of an area of interest for processing. Both imaging and spectroscopy rely on a light source to induce reflectance or a fluorescence response. In agricultural fields, sunlight can be used to induce reflectance for data acquisition, while various light sources including ultraviolet light can induce a fluorescent response. Multispectral and hyperspectral imaging techniques extend upon standard imaging and spectroscopy, as they can allow for the collection of response data over a range of relevant spectra for further analysis. Navigation and guidance can be carried out using imaging techniques while detection of plant stress levels, ripeness, and disease can be carried using either spectroscopy or imaging.

Sankaran et al. [5] add that assessing volatile organic compounds released by a plant can reveal information about the plant's environment (e.g. temperature and soil condition) and its growth and development. Techniques for collecting and analyzing volatile organic compounds include electronic nose systems and gas chromatography systems. Electronic nose systems are made up of gas sensors that react to various organic compounds, and are commonly used for food quality assessment and microorganism detection in plants. Gas chromatography systems can detect qualitative and quantitative information about volatile organic compounds and are commonly used to detect bacterial and fungal infections in food products.

Currently, plant disease detection is carried out through a general inspection performed manually by a farmer, however improving disease detection while crops are growing through use of agricultural robots can decrease the spread of disease by alerting growers to apply herbicides or pesticides, or to not harvest the diseased crops at all [20]. In order to perform various tasks during operation, detection systems can be integrated into ground vehicles used in agricultural fields, although commercial products are not yet available for such tasks. Research techniques for disease detection could be integrated with autonomous vehicles in fields for cost effective, real-time, reliable agricultural use. An example of such a system was developed by Moshou et al. [20], by mounting a detection prototype on a tractor to search for yellow rust on winter wheat.

3. APPLICATIONS OF GROUND VEHICLES IN AGRICULTURE

Agriculture is a broad industry consisting of crops not only for food products but for fuel, medicine, and textiles. The cultivation of animals for food, medicine, and textiles are also a part of the agricultural industry. The applications of ground vehicles to agriculture explored in this paper pertain to plant cultivation and agricultural planning. The most common applications found in literature can be categorized as soil sampling/mapping, irrigation management, precision spraying, mechanical weeding, and harvesting. Taking in to the consideration the components of unmanned ground vehicles as discussed in Section 2, the vehicle configuration, control schemes, and sensing technology of each vehicle are discussed, as available.

Soil Sampling and Mapping

Analyzing soil samples can reveal the nutrient composition, and indicate to farmers what fertilizers to provide to reduce associated costs and improve overall crop health. Soil sampling can be carried out by hand or by vehicle. Analysis of the samples involves determining the levels of sulfur, zinc, and other key nutrients as well as the characterization of volatile organic compounds and pH levels in the soil. Products on the market today for the collection of soil samples include the AgRobotics AutoProbe, the Falcon 5000 by Falcon Technologies, and Walter Nietfeld Company sampling equipment. The AutoProbe, when towed by a tractor, collects consistent samples at uniform distances. Its configuration consists of a track with attached probe trailing behind the tractor, rated to sample 120 to 150 acres per hour [27]. Using GPS data to mark the sample location, data can be stored for comparison with future samples in the same location, giving the farmer the ability to assess the effectiveness of fertilizer applications [28]. The Falcon 5000 can be towed by tractors, pick-up trucks, or ATVs for soil sampling and is configured with a rotating drum for sample collection. In addition, an automated tagging system marks the sample with a barcode linked to its recorded GPS location for identification during analysis [29]. The Walter Nietfeld Company, based in Denmark, sells a variety of sampling products that can be mounted to ATVs, trailers, pick-up trucks and other farm equipment for a variety of sampling applications [30]. While the previously mentioned commercial products cannot operate without being towed by an additional vehicle, research vehicles have demonstrated the feasibility of an autonomous sampling system. Cao, et al. developed a GPS guided mobile robot for surface and below ground soil sampling in harsh environments. The vehicle accurately collected samples in target locations based on GPS locations [31].

Clearpath Robotics has developed three unique unmanned ground vehicles for various uses including agriculture that are currently on the market. The Grizzly Robotic Utility Vehicle Explorer Pack is marketed for agricultural applications including field mapping, utilizing an equipped laser range finder, GPS and a dome camera for autonomous operation in outdoor conditions. The vehicle configuration includes four independently controlled wheels, and passive suspension for maintaining wheel contact with the ground in irregular environments [32]. Clearpath's other available ground vehicles for agricultural applications are the Husky and Jackal UGVs which are platforms for various research applications. These vehicles are designed for autonomous navigation and utilized for environment mapping as well, with a four wheel configuration and high payload capacity. The Husky and Jackal UGVs can be configured to perform specific research tasks by operators [33, 34]. For example, the Husky platform was utilized by University of Alberta's Integrated Reliable Oil Sands Systems Lab to perform soil sampling in rugged terrain by mounting application specific sensing and sampling equipment to the vehicle [35].

Irrigation Management

Maximizing harvest yield is dependent on maintaining the health of the crops. Providing crops with adequate irrigation is a necessity to produce healthy crops. Center pivot and lateral move sprinkler irrigation systems have been used for decades to irrigate complex field environments, and can be considered ground vehicles in agricultural fields. Center pivot configurations pivot about a fixed point and thus irrigate along a circular path, while lateral move systems have two free ends. Automation of sprinkler systems in large fields can reduce the labor needs required to monitor and schedule irrigation [2]. Peters et al. [36] developed an automated control system for a center pivot irrigation system in soybean fields to verify the effectiveness of automated versus manual irrigation scheduling. Data was collected using infrared thermocouples to sense the canopy temperature which can indicate stress level of the plants throughout the day. Based on the temperature-time-threshold method, irrigation was scheduled to a particular depth when necessary, based on the canopy temperature data, using a proprietary software algorithm [37]. In comparison to manual irrigation scheduling, which used a neutron probe to measure soil water content levels in this case, the automated system produced statistically similar crop yields and water use. These results validated the automated center pivot system as a tool for reducing labor needs while maintaining the crop yield [36].

Because of the widespread use of center pivot irrigation systems in agriculture across the world, implementing control systems to automate the process to existing systems is desired. Various control systems have been developed for irrigation automation, and have been validated through simulations. Benzzekri et al. [38] designed and implemented a low-cost PC-based controller to schedule field irrigation based on soil water potential measurements and weather conditions. Umair et al. [39] developed an intelligent controller based on an artificial neural network to schedule irrigation based on temperature, soil moisture, and humidity. Implementing low-cost controllers on existing irrigation equipment could reduce labor needs of farmers and maintain crop yield and efficient water usage.

Precision Spraying

Along with effective irrigation, precision spraying of pesticides, herbicides and fertilizers can improve crop yield while only applying these products when needed. Effects of precision spraying include reducing costs, improving safety of food products, and decreasing the quantity of chemicals used to reduce the environmental impact of the farming operation. Autonomous Solutions Inc. produces the Forge Robotic Platform which can be configured for spraying applications using skid steering. The Forge can be operated autonomously or by remote control and is designed for use in open fields or rows of orchards and vineyards, and is available for purchase [40]. An autonomous precision sprayer for nitrogen fertilizer for corn is currently being developed by the small startup, Rowbot. The vehicle consists of a four wheeled configuration which uses GPS and laser scanning data for navigation through corn rows [41]. Field tests have been conducted to validate the robot's ability to navigate through the rows without damaging the crops [42]. Implementation of this unmanned ground vehicle in corn fields could reduce the amount of nitrogen pollution in waterways following rain by applying nitrogen fertilizers directly to the plant base [43].

An agricultural robot was developed by Oberti et al. [44] to detect powdery mildew on grapevines and apply pesticides to reduce disease on these plants. Using the CROPS robotic arm on a wheeled mobile platform, a multispectral camera was used to detect the presence of the fungi. The vehicle moved parallel to the row of the greenhouse in an incremental fashion, in 200 mm increments, without the need for any movement in the direction perpendicular to the row. When mildew was detected at a particular position, the robotic arm was used to spray a pesticide on the infected area from three directions to ensure even coverage. After the spraying was completed, the robot would move forward another 200 mm increment. Results of experimental use of this robot revealed an ability to reduce pesticide use by 65 to 85%.

Gonzalez-de-Soto et al. [45] have developed an autonomous vehicle for precision spraying of herbicides for weed control in cereal crops, such as wheat. The vehicle platform was a modified tractor, retrofitted with GPS antennas for navigation and localization within the field. The spraying system, designed for wide crop rows, applied herbicide to the field when weeds were detected. Image data collected by an IP camera mounted atop the vehicle was utilized to distinguish weeds from the crop. Performance testing of the automated system in a wheat field exhibited herbicide spraying to 95% of the weeds in the field. This platform could also be utilized for pesticide and fertilizer applications.

Mechanical Weeding

Weed control can also be implemented using mechanical weeding technology to avoid the use of added chemicals and eliminate the need for labor for manual weeding. For organic farmers, in particular, mechanical weeding is of great interest because the use of chemical herbicides for weed removal is prohibited. Weeding is needed for inter-row, between two rows of plants, and intra-row, within the plant row, removal. Naio Technologies in France created an inter-row autonomous weeding vehicle, Oz, which can be configured for various crops including cabbage, beans, and beats, as long as the inter-row spacing is greater than the vehicle width of 40 cm. Oz is a four wheel drive skid steered robot that uses laser and imaging data for navigation and is available for sale [46]. Bakker et al. [26] developed an autonomous ground vehicle with four motorized and steered wheels for intra-row weeding. The diesel powered vehicle utilized pattern recognition to distinguish weeds from the plant, while mechanical actuators were used to remove weeds from the crop rows. Based on the vehicle configuration and the open software platform, the robot can be used for research into mechanical intra-row weed detection and removal.

Manuel Pérez-Ruíz et al. [47] developed an autonomous platform to assist manual laborers in the task of weeding crop rows. Using an intra-row hoe weeding device, and with initial knowledge of the crop seeding pattern, the platform was attached to a mobile vehicle and was supervised by a human operator. Because the robot relied on plant spacing to conduct weed removal, the human operator was available to perform a necessary machine learning step at the beginning of the row, and to update the control system if the crop spacing did not align with the mechanical weeding pattern to avoid damage to the crops. The system was tested in transplanted tomato fields, and manual weeding was conducted after the automated weeding. The resulting time savings were nearly 60% when compared to manual weeding alone, and there was no damage to any of the 1119 tomato plants treated.

The intra-row hoe weeding system by Pérez-Ruíz et al. outperformed two previously developed machine-vision based rotary disc hoe weeding systems by Tillett et al. [48] and Fennimore et al. [49] In the Tillett et al. study, an experimental rotary disc hoe was used to remove weeds from cabbage row, resulting in minor crop damage in three runs through the same field at 16, 23, and 33 days after transplant. The damage resulted in the loss of two of the 24 sample plants in the experiment [48]. In the Fennimore et al. study, a commercial version of the rotary disc hoe was used in combination with herbicide applied to the sample plants. The system was used to remove intra-row weeds in various crops including transplanted celery, lettuce, and radicchio, with time saving on follow up manual weeding of 0%, 6.3 to 8.7%, and 29.7%, respectively [49]. Improved performance of the Pérez-Ruíz et al. system could have resulted from delegating the initial visual recognition to the human operator rather than the robot control system, and because the human operator can interfere to prevent plant damage [47].

Harvester Robots

Automated technology for crop harvesting has been a popular research topic over the last 30 years. Labor requirements for harvesting fruits, vegetables, and other high-value crops make up a substantial amount of the production costs for these items. Automating harvesting of these crops has the potential to drastically reduce the costs, in part, by reducing or removing labor needs. Bac et al. [18] conducted a comprehensive review of 50 research robots (both autonomous and non-autonomous) for the harvesting of high-value crops, none of which have been commercialized thus far. Apples, citrus, cucumbers, strawberries, tomatoes and watermelons are among the most common crops that autonomous harvesters are being developed for. Some of the autonomous harvesters from the Bac et al. review are discussed below to demonstrate the variety of technology that has been developed in research for harvesting crops of varying sizes and shapes since the turn of the twenty-first century.

Van Henten et al. [50] developed a cucumber picking vehicle to harvest cucumbers and transport them to a storage area with the intent of replacing human labor with several harvesting robots. The robot was tested in a greenhouse environment in 2001. While the vehicle could operate autonomously, it relied on rails mounted on the greenhouse floor to navigate along the crop rows. Images collected from two CCD cameras were used to detect the cucumbers and determine if they were ripe. A manipulator arm with seven degrees of freedom was used for collection, and a thermal device was used to cut the fruit from the stem once it was secured by the arm. Testing of the system resulted in 80% of the cucumbers being successfully picked at an average of 45 seconds per fruit. Inaccuracy in the determination of the position of the cucumber accounted for many of the failed attempts.

Sakai et al. [21] designed an autonomous watermelon harvesting vehicle to demonstrate the capability of mobile robots in the harvesting of heavy crops. Based on the size of the melons to be harvested, a tracked vehicle was designed, rather than a wheeled vehicle to improve movement along uneven terrain, especially following rain, while carrying heavy payloads. A manipulator arm with four degrees of freedom was selected, and a combination controller to switch between PD control and two linear quadratic controls was used to control the arm. A separate, optical instrument was used to determine the location of the fruits, and position information was programmed into the robot. In 2006, two experiments were conducted, one using PID control, and the other with the combination controller. Both experiments resulted in a harvest success rate of 86.7%, however the PID controller alone required 40 seconds per watermelon harvested, while the combination controller allow for an average of 14 seconds per watermelon.

De-An et al. [51] developed a fully autonomous apple harvesting robot. A tracked configuration, rather than wheeled, was chosen, and GPS data was utilized for navigation through the apple orchards. A harvesting arm with five degrees of freedom was designed to carry out the harvesting task. Image processing using a CCD video camera to distinguish the apple from the rest of the tree. Indoor harvesting experiments resulted in successful harvesting of 86% of the apples in an average of 14.3 seconds per fruit. In 2009, outdoor testing in an orchard resulted in a 77% harvesting success rate with an average of 15.4 seconds per fruit. Limitations of the system included failure of the knife system to remove the apple from the tree and inability to recognize apples hidden behind branches.

A strawberry harvester was developed by Feng et al. [52]. A six degree of freedom manipulator arm with pneumatic gripping fingers and a suction cup was mounted atop a four wheel drive vehicle for harvesting in a greenhouse. Sonar sensors were used for navigation along crop rows while a camera on the front of the vehicle was used to detect the end of a row based on a line on the ground. Image processing was performed to locate the ripe fruit on the plants, and a thermal cutting device was used to remove the fruit. Testing performed in 2011 resulted in a successful harvesting rate of 86% with an average of 31.3 seconds per fruit. The failed harvest attempts were attributed to the inability of the suction cup to secure and transport the fruit to the collection bin, due to small fruit size or large positioning error of the arm.

4. TECHNICAL ISSUES AND PROBLEMS

Development

Because of the high variability within a crop, the field environment, and in the types of food crops in high demand, development of autonomous ground vehicles is challenging. Many of the research vehicles are built from the ground up, rather than utilizing commercially available platforms which can operate autonomously and be configured for specific tasks. Increased collaboration between researchers and commercial developers could reduce the complexity of research efforts to improve development time. Lack of open source software for task specific applications in agricultural also leads to researchers developing algorithms on their own, increasing system development time. Jensen et al. [53] propose an open software platform, FroboMind, for use in autonomous vehicles for precision agriculture applications, to improve development time. In addition, the growing popularity of ROS, or the Robot Operating System, provides an option for developing autonomous navigation controls for unmanned ground vehicle platforms, allowing developers to focus more time on agricultural task controls rather than vehicle movement [54].

Management

The addition of autonomous ground vehicles to agricultural environments requires the farmer to modify current planning methods. Bochtis et al. [55] conducted a review on the advances in management with respect to agricultural machinery to outline the efforts required to integrate unmanned systems into the process. Updated models for capacity planning, task times planning, scheduling, route planning, and performance evaluation will be required to optimize the implementation of autonomous robots in agricultural tasks, according to Bochtis et al. Machine learning can improve the effectiveness of unmanned system integration into farming operations by allowing vehicles to adapt to current field conditions rather than relying on a single, initial input of information. Efficiency may be improved by combining the use of multiple independent vehicles in collaboration with one another to complete a task. This could lead to a decrease in the size of the vehicle and even allow for less expensive sensors and cameras to be used in certain applications, because the speed of the robot can be decreased while still improving the time it takes to complete the task [24].

Performance

Bac et al. [18] discuss challenges faced in improving existing agricultural vehicles based on the complexity of a lack of reported requirements and performance indicators. Without information about design requirements and an ability to express performance makes it difficult to compare the success of various vehicles for respective tasks. Without set requirements during the design process, and reporting the success or failure of the vehicle meeting those requirements, determining what tasks need to be improved upon is difficult.

Although commercially available vehicles can be utilized in a variety of crop fields, fields with narrow paths between rows and crop rows of larger widths may not be accessible by these vehicles. Alternative vehicle configurations to those that are currently used in commercially available autonomous platforms are still actively being developed for research projects, such as platforms that straddle crop rows for weeding as seen in Bakker et al. [26]. Vehicles that straddle crop rows are also of interest in disease detection for spinach and lettuce applications. Configuration selection will depend on stability, maneuverability, and controllability of the vehicle in the specific environment for each application [22].

Power consumption of small autonomous ground vehicles in agricultural fields is also of concern [24]. Improvements in battery technology continue to increase the life of a battery on a single charge, while decreasing the weight. Weight optimization versus operation time is to be considered based on the required sensors and systems for the various applications. While smaller vehicles have improved mobility, increasing the operating life of the vehicle may require increased battery sizes, leading to weight increases which could affect the motors used to propel the movement of the vehicle. Increasing the size of the vehicle to improve operation time could introduce the issue of soil compaction which is a common problem with standard tractors [24].

Resistance from Farmers

Growers and producers of commercial food crops are concerned with the profitability of autonomous vehicle implementation as well as safety. While unmanned ground vehicles have the potential to lessen the labor need, affordability of the systems is of concern [2]. Balancing the effectiveness of the technology with cost is an important factor to be considered by researchers. In addition, safety of both the humans working alongside the vehicles, and the plants around which they will operate is important [24]. Lasers, shears, and moving parts on autonomous vehicles should be equipped with redundant emergency shut-offs to avoid injury to human workers and crops if the vehicle path deviates or if an object interferes with its path. Growers and producers will resist the implementation of these technologies until they are proven to be safe and profitable.

5. FUTURE TRENDS

In the coming years, further development of autonomous robotic platforms will continue and commercial versions will become available for configuration for various agricultural tasks. Different configurations may be necessary to accommodate the various applications. Bawden et al. [56] have designed a lightweight modular robotic vehicle for agricultural use which balances stability, energy efficiency, and traction while ensuring minimal impact to the soil. This work demonstrates a trend towards improving platforms for unmanned ground vehicles in agriculture.

Improvements in camera and sensor capabilities coupled with continued research into plant disease detection could lead to agricultural vehicles for these tasks. Autonomous vehicle-based disease detection could be utilized for locating and treating disease in problem areas and collecting and tracking disease location data for future use in disease prevention. With the widespread availability and affordability of sophisticated sensing technology, the outlook for commercial viability of autonomous ground vehicles in agriculture is promising.

Resistance to the implementation of fully autonomous ground vehicles from growers and producers may increase the development of systems retrofitted onto existing farm equipment, such as tractors. Widespread use of commercially available autonomous weeding systems that attach to a tractor could further encourage the adoption of autonomous ground vehicles to carry out the task. Resistance to implementation of the technology based on lack of profitability can be reduced by further exploring previous research vehicles to improve their accuracy and reduce costs. If harvesting tasks can be automated to collect food crops at an accuracy rate and pace that is more profitable than equivalent manual labor, which has yet to be demonstrated by a majority of the research-based harvesters, the use of such technology could become commercially viable.

6. CONCLUSIONS

While research into unmanned ground systems in agriculture has been conducted over the last three decades, very few commercial products have been adopted by farmers. The combination of improved sensor technology with the increased availability of a variety of vehicle platforms will provide the opportunity to continue research in this area. The development of autonomous ground vehicles for applications of soil sampling, irrigation management, precision spraying, mechanical weeding, and harvesting of crops is continual. While most available unmanned ground vehicles are currently used as research tools, further development can lead to commercially viable products in the coming decades to address foodborne illness concerns and changes in agricultural labor.

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