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A Safety Architecture for Autonomous Agricultural Vehicles

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Abstract. *Sixty years after debuting in industrial environments, robots are making their way into our everyday life. Farmers have benefited for some time from self-guided machinery including combines and harvesters. More recently, multi-purpose autonomous vehicles have started to be deployed in orchards, groves, nurseries, and other agricultural environments to automate or augment operations such as pruning, thinning, harvesting, mowing, and spraying. Successful commercialization of such vehicles will depend heavily on them being able to operate safely and avoid accidents involving humans, animals, trees, and farm infrastructure.*

We propose a safety architecture to guide the design and deployment of autonomous agricultural vehicles and their introduction into production environments. The architecture spans the three elements that, combined, should ensure safe operation over a wide spectrum of applications: (1) a distributed, sensor-based, intelligent decision-making system that coordinates and guides fleets of vehicles in and around orchards and other agricultural environments; (2) multimodal interfaces for workers to interact with the vehicles using natural language, gestures, and portable devices; (3) a comprehensive regulatory framework of standards for vehicle safety that covers everything from basic robotic technology to advanced behaviors.

In this paper we present the fundamental aspects of this agricultural robotic safety architecture. We illustrate its application with examples of autonomous agricultural vehicles we developed in the past that lay down the path toward full introduction of safe, intelligent machines in agricultural production environments.

Keywords. Agricultural robotics, Autonomous orchard vehicle, Vehicle safety, Human-machine interface, Standards

Introduction

In the not-too-distant future, farms will be equipped with robots that mow and spray; scout trees for stress, disease, insects, and crop yield estimation; and harvest. They may take on familiar forms such as intelligent tractors, or new formats such as walking machines with sensors and arms. This revolution has already started in field crops, with GPS-guided combines and harvesters available commercially [Fendt GuideConnect 2012, Claas Steering Systems 2012, GreenStar Ag Management Solutions 2012]. Recently, multi-purpose autonomous vehicles have started to be deployed in orchards, groves, nurseries, and other specialty crop environments [Hamner 2012, Moorehead 2010]. A rate limiting factor in the progress toward full deployment of robots in agriculture is safety. Robots must be designed to operate in a safe manner, the safety record must be validated and robots need to be perceived by the end user as safe. The obvious question is, then, how do we incorporate safety into agricultural robots? One natural way is to study another category of robots, one that has been around for decades and has proven itself both safe and economically viable.

It's been sixty years since robots were first introduced in industry. Today these machines cut, bend, weld, paint, feed, and assemble, among other tasks, all with an accuracy and speed impossible for humans to match. They are part and parcel of human society, who depends on them for essentially every mass-produced product and device in use today. What makes industrial robots particularly safe? We assert that this is a combination of three factors. First and foremost, they execute their task precisely and correctly, cycle after cycle, year-round. The systems engineering effort that goes into designing and building these machines all but guarantees they meet the specifications of the task to be performed, including safety-related requirements. Second, industrial robots are equipped with the proper human-machine interfaces, allowing trained workers to operate them safely even if they don't understand the intrinsic sensing, computing, and actuation capacity of the robots. Last but not least, standards and regulations clearly dictate how industrial robots are to be installed and used, and how and when humans can interact with them. We recognize that these standards mostly separate man from machine, which is one of the reasons why industrial robots are safe. Agricultural robots, on the other hand, will operate in environments where humans are a constant presence. The point, however, is that there is a body of knowledge we can learn from when establishing a safety paradigm for this new class of machines.

In this paper we propose a safety architecture to guide the development of agricultural robots, with initial focus on autonomous agricultural vehicles. Following the industrial robotics example, we believe their successful commercialization will heavily depend on the robotics community creating machines that meet specific agricultural operations-related requirements; may be operated safely by a farm worker with appropriate training; and be regulated by standards that dictate human-machine coexistence and cooperation. Graphically, we represent the architecture in Figure 1. In this representation, the robot is at the center, and the various applications it enables are on the outside. They are bridged by a layered progression of robotic capabilities, interfaces, and standards that together should guarantee the machine's safe operation and task completion. Agriculture is both a very conservative and very progressive field, one where farm owners must walk the fine line between time-proven methods and the latest technologies. We make safety the centerpiece of our architecture because it is at the heart of growers' acceptance of robots in their domain, on par with acquisition and maintenance costs.

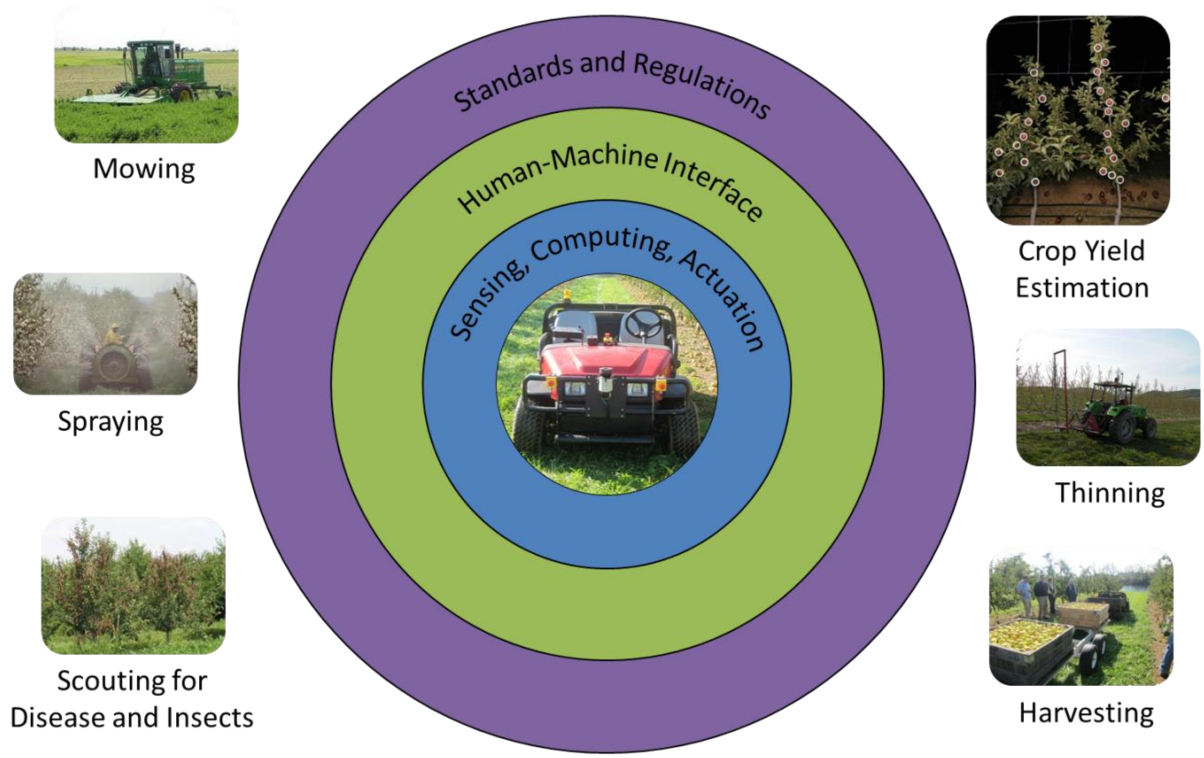

Figure 1. We propose a three-layer architecture to bridge robots and agricultural operations. The architecture combines the traditional robotics disciplines of sensing, computing, and actuation, with human-machine interfaces, and standards and regulations, with a specific focus on safety.

This paper is organized as follows. In the Related Work section we discuss related technological fields to discern what knowledge we can learn from them and transfer to the agricultural robotics domain. In the Safety Architecture section we detail how we envision the three layers of our architecture combining to foster acceptance of autonomous vehicles in agriculture; and present two examples of systems we have recently developed within the architecture's framework. We conclude the paper with a discussion on limitations of our work and next steps.

Related Work

Related work in robotic safety systems can be applied to agricultural vehicle design to guide safe operation. Autonomous farm equipment is often mobile and travels across a large area, while most current guidelines are for fixed industrial robots in controlled environments where light curtains and "keep out" zones can provide safe operation [CDC 2012, Dagalakis 2012]. The goal with this new class of autonomous vehicles is to behave in a safe, reliable and effective manner while operating unmanned. The primary safety guidelines that apply to mobile and fixed robotic systems are safety assessments, safety circuits and training. A safety assessment of the machine is critical to draw attention to operational risks and legal liability [H.W. Griepentrog 2009]. Emergency stop switches have become standard on many autonomous systems. Careful thought is needed in placing the switches where they are accessible and fault tolerant. It is also important to make the switch stop the robot in a safe manner, which might require dynamic breaking and not simply removing power. Guidelines regarding training and enforcement become even more important as robotic systems become more advanced and people get more comfortable working near them. Audible and visible warnings are not safeguarding systems; however they can be used to enhance safety [OSHA 2012].

Nevada recently became the first state to legalize autonomous vehicles on public streets through laws governing their operation. The Nevada law separates operating conditions into various categories that stress different parts of the system, ranging from “easy,” non-cluttered environments, to dense, heavily populated areas. The laws cover a range of aspects from how to build the vehicle and how to handle collisions. By design, the vehicle’s autonomy portions cannot interfere with other required safety systems, there must be a way for the operator to take control of the vehicle, and there must be a system for detecting and reporting component and subsystem failure. This law requires all autonomous vehicles to maintain the last 30 seconds of data in a read-only format to reconstruct any accident or collision. For liability purposes the vehicle needs to be operated for 10,000 miles in autonomous mode in a variety of conditions to prove its reliability; and vehicle owners must have in place a one to three million dollar insurance bond or deposit to be used in the event of any accident [Nevada Department of Motor Vehicles]. These steps have truly paved the way for other autonomous systems to be deployed and have a legal basis to operate from. The states of California, Florida, Hawaii and Georgia are working on similar laws.

Safety Architecture

The agricultural robotics safety architecture we propose is composed of three critical elements. The first two are related to the actual robotic vehicle and its interaction with human workers, while the third focuses on a legal framework that establishes how the vehicle is to be fielded.

The first and innermost element comprises the sensing, computing, and actuation technologies that enable robot autonomy. Here the focus is on ensuring that all hardware and software components, and the resulting robotic system, operate according to functional and non-functional design requirements that include safety aspects. At this level we are concerned with developing systems that execute their task correctly and efficiently, while avoiding accidents with humans, farm infrastructure, and the crop (e.g., trees). Important development concepts at this level include robotic perception, trajectory and motion planning, fault tolerance, and formal verification of hardware and software.

The second element, the user interface, is the link between the robotic vehicle and the workers who will operate it. Initially, the operator will be in or on the vehicle to ensure safe operation. This is the level that the Nevada self-driving cars operate. As autonomy capabilities get tested, validated, and become more reliable we can take the operator out of the cab and put him in the loop from an external location. This will allow for the creation of a new class of agricultural vehicles, one that is not designed to be human-operated and does not need an operator cab. Once an operator is controlling a single vehicle from outside the cab it will not be long until entire fleets are operated by a single operator. At this point multiple vehicles will coordinate work amongst themselves, either dividing tasks on a geographic or temporal basis, or cooperating to complete a task neither can complete alone. The relevant development concepts here include multi-modal human-machine interfaces using portable devices, voice, and gestures; teleoperation and telesupervision of fleets of autonomous robotic systems; and multi-vehicle coordination and cooperation.

These two elements of the safety architecture, robotic autonomy and user interfaces, compose a framework upon which safety standards—the third element of the architecture—can be developed, as depicted in Figure 2. The idea is to establish standards that lay out how agricultural robotic vehicles are expected to “behave” as more autonomy is introduced in the system, and as the operator distances herself from it. Analogously to the industrial robotics industry, the standards would also deal, at least initially, with environment instrumentation to assist the robotic vehicle in navigating safely through fields and orchards; examples potentially include the installation of RFID tags and fiducials along the routes the vehicle is expected to travel. An additional aspect in the standards layer of the safety architecture is the set of operational procedures and processes that define how the autonomous machine functions and the human's function in the system. Proper functional processes can increase safety by preventing unsafe situations from occurring. This is analogous to the processes put in place during chemical spraying in agricultural environments that remove people from the scene and protect the perimeter with signage warning of hazardous chemicals.

The standards element demands that vehicle designers, manufacturers, and users share in the risks associated with agricultural robotics. Each sector understands their respective roles and responsibilities in this new ecosystem and design and operate their system to the best practices available [Reid 2011, Ting et al. 2011].

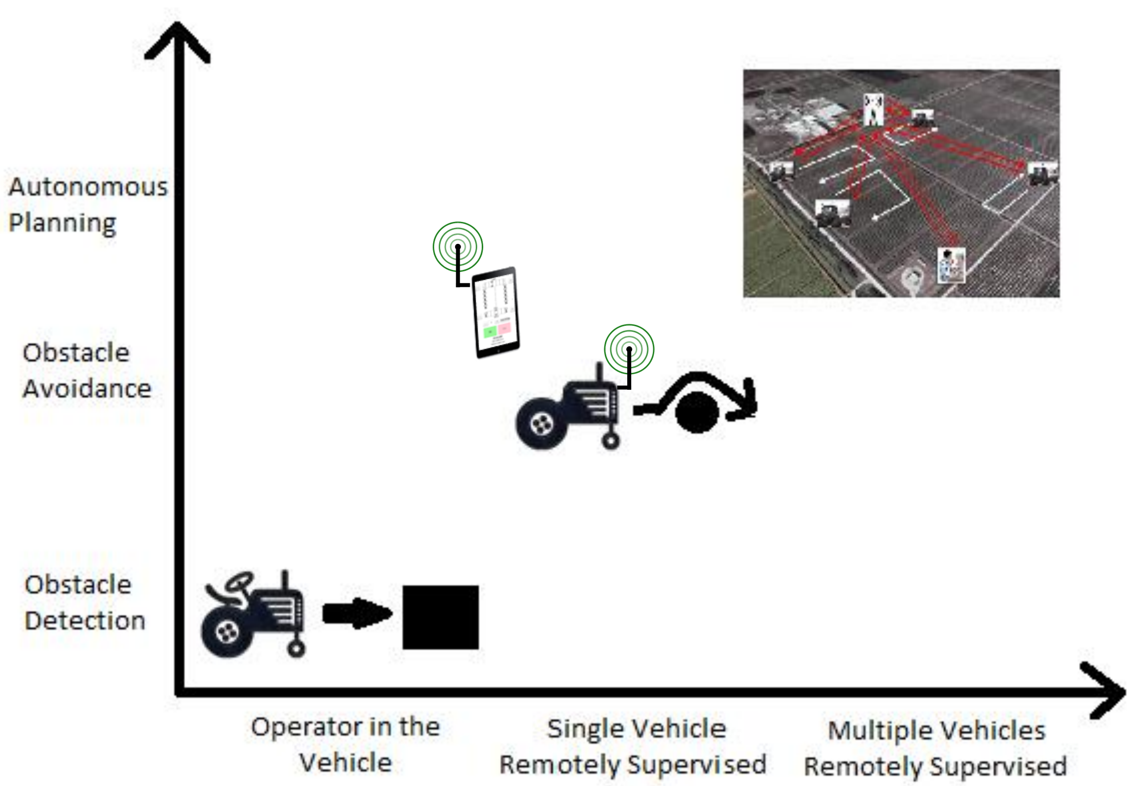

Figure 2. Framework for the establishment of standards for safe deployment of autonomous agricultural vehicles. For each of the various possible scenarios in this matrix, the standards should lay out how the vehicle is to "behave" as it incorporates more and more autonomy capabilities (vertical axis) and as the operator moves away from direct vehicle control to a supervisory role (horizontal axis).

Many standards already exist for the design of advanced systems on tractors and other vehicles that can provide a starting point for the development of standards of autonomous agricultural vehicles. ISO 26262 and IEC 61508 are component-level standards for safety in electronics. ISO 25119, "Tractors and machinery for agriculture and forestry – Safety related parts of control systems," is an important standard that specifies requirements for system/software architectures, design, test and diagnostics in safety critical systems on agricultural and forestry equipment. ISO 11783 (ISOBUS) defines the communication architecture between "smart" implements and tractors and is useful in ensuring compatibility between them. Because some applications, for example bailing hay, require the implement to control the speed of the tractor, ISOBUS provides a useful route towards fully autonomous vehicles.

At this time there are no comprehensive standards for autonomous agricultural vehicles, and in particular standards for obstacle detection sensors and systems. However, standards such as SAE J1741, “Discriminating Back-Up Alarm System,” and even ASTM F2411-07, “Specification for Design and Performance of an Airborne Sense-and-Avoid System,” show that the automotive and unmanned aircraft fields have knowledge that might be applicable to agricultural vehicles.

In the remainder of this section we present recent results and lessons learned with the deployment of robotic vehicles in orchards and groves, and discuss the steps needed to fully develop the three-layer agricultural robotic safety architecture proposed.

The first example is a family of robotic vehicles designed and built under the Comprehensive Automation for Specialty Crops project (CASC). From a technology perspective, our objective was to provide tree fruit growers with vehicles that can drive between rows of trees, and travel up one row, turn at the end of the row, and enter and travel down the adjacent row. This seemingly basic capability allows such vehicles, when equipped with the appropriate attachments and sensors, to mow and spray entire blocks, scout the trees for disease and insects, estimate crop yield, and carry workers conducting pruning, thinning, tree maintenance, and harvesting (Figure 3). To date the five vehicles in the family have driven a combined 350 km in apple and peach orchards, grape vineyards, and tree nurseries. Time trials conducted by the Pennsylvania State and Washington State Universities Extension teams showed that workers on platforms mounted on these robotic vehicles can perform tree fruit production tasks in half the time it takes workers on ladders or on foot when working in the tops of trees.

Figure 3. (Left) Workers thinning green apples from onboard an autonomous orchard platform. (Center) Workers placing pheromone dispensers on apple trees. (Right) Autonomous orchard vehicle in “bin dog” mode carries the bins wherein workers deposit the fruit harvested. In all cases, the only sensors used for row following and turning are a fixed laser scanner and wheel and steering encoders. Compared to the same task performed with ladders, working from onboard an autonomous orchard platform can cut the time in half, decreasing labor costs and increasing efficiency. Videos of these operations can be found at http://www.youtube.com/user/TheCASCrop.

Notwithstanding the efficiency increases demonstrated in our time trials, from the perspective of our safety architecture, these vehicles are relatively simple. With respect to the autonomy, or vertical axis of the framework in Figure 2, they are able to detect and stop for obstacles, but not drive around them (that is, in case there is space around the obstacle); with respect to the user interface, or horizontal axis, they afford “operator in the vehicle” and “single vehicle remotely supervised” modes. The former is enabled by a physical control box designed based on interviews with agricultural producers/end users and extensively tested in research and commercial operations (Figure 4, left; see also the center image in Figure 3, where the interface is seen at the top of the vehicle, between the workers). The latter is enabled by touch screen-type interfaces, a prototype of which is shown in Figure 4, right.

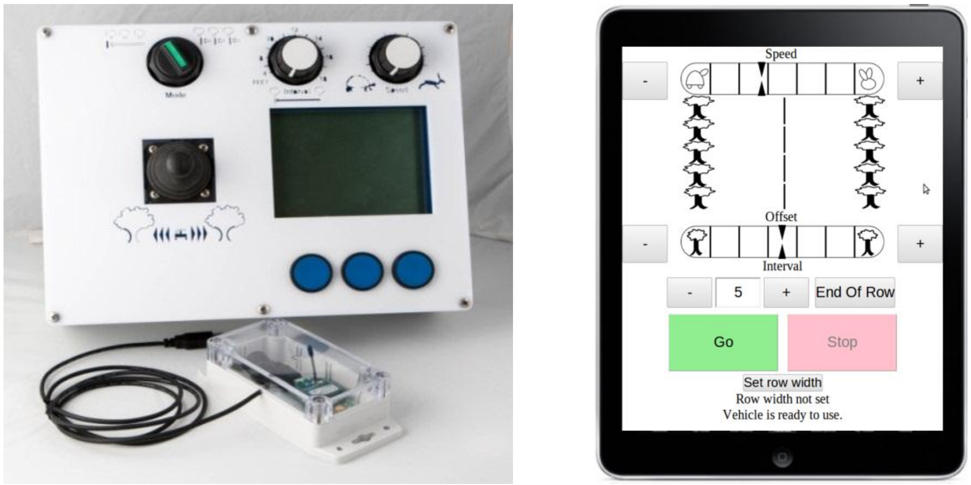

Figure 4. (Left) Physical control interface for our autonomous orchard vehicles. The switches let the user select between continuous and "stop-and-go" driving and vehicle speed. The joystick is used to "nudge" the vehicle left or right during row following. A display gives feedback on the vehicle status. (Right) Prototype of a touch screen-type interface to enable remote supervision of the orchard vehicles.

The second example of an autonomous agricultural system is the set of Autonomous Orchard Tractors built as advanced prototypes by John Deere [Moorehead 2010]. These are factory built 6430 John Deere tractors that have been converted to autonomous control to allow for mowing and spraying operations in orange groves. As in the CASC project, the Autonomous Orchard Tractors are able to navigate through the orchard environment and control the PTO and SCVs to ensure the implement is performing correctly, in the target locations. For example, the mower deck is raised and turned off when crossing a road and the sprayers are turned off during an end row turn.

Figure 5: Autonomous Orchard Tractor turning at the end of the row.

To implement the innermost layer of the safety architecture in Figure 1, the tractors have cameras and a laser scanner that create models of the surrounding world and detect obstacles. This system, developed by Carnegie Mellon University's National Robotics Engineering Center, must be able to distinguish between trees (that the tractor may brush up against at times) and tall grass (which the tractor needs to drive through to mow) from true obstacles such as people, vehicles and other equipment. The tractors also have sensors to determine internal operations and make use of heartbeat timers between critical systems.

With respect to the middle layer if the tractor encounters a situation it does not understand, it will come to a stop. The tractor system makes use of a remote supervisory model, where a human located remotely from the tractors, sends high level tasks, such as “Mow block 202”, from his workstation, to multiple vehicles under supervision. The tractors execute the task, returning status updates and sending images to the remote supervisor to determine if it is safe to continue. This setup physically removes the person from the robotic vehicle and involves the person only at challenging times. Finally, the vehicle and remote supervisor station have emergency stop buttons, the vehicle has visual and audible warnings in case anyone is nearby and the vehicles and supervisor have heartbeat messages to ensure communications are available at all times.

With regards to the outermost layer of the architecture, there are not a lot of external standards or regulations that apply to these systems. The Autonomous Orchard Tractors are still experimental prototypes and not commercial products, which limits the number and type of applicable regulations. John Deere makes use of internal standards and processes to ensure safety in all of its vehicles and these processes also cover field testing of prototypes. Through these processes John Deere has refined their operating procedures to enhance safety. These standard operating procedures include cordoning off the area of operations with physical barriers – just as is currently done in citrus production during manual spraying operations – and ensuring that no people are present in the areas where the robots are operating. This is aided by the layout of an orange grove which, due to canker disease concerns, has a single entrance where everyone entering the grove is sprayed with a chemical sanitizer. This single point of entry makes it easier to regulate who is allowed in the grove and who is inside the grove at any given time.

Conclusion

With the world population poised to reach nine billion in 2050, agricultural production must double, and its productivity increased by 25% if we are to meet our needs for food, feed, fiber, and fuel [Foley 2011, Reid 2011]. Robotics is one of the disciplines that hold the power to meet these challenges. In particular, autonomous agricultural vehicles can significantly increase efficiency and reduce labor demand and costs. We propose in this paper a three-layer safety architecture to guide the design, development, and deployment of such vehicles, with the ultimate goal of promoting their acceptance and adoption by agricultural producers. At this point, we have demonstrated a few elements of the architecture in hundreds of kilometers of autonomous driving in apple and peach orchards and orange groves. We are now in the process of identifying the standards and regulations needed for safe autonomous agricultural vehicle operation, and will pursue their development within the appropriate technical societies, including the IEEE and ASABE.

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