Mechatronics and Intelligent Systems for Off-road Vehicles

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Springer

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ISBN 978-1-84996-467-8 e-ISBN 978-1-84996-468-5
DOI 10.1007/978-1-84996-468-5
Springer London Dordrecht Heidelberg New York

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2010932811

Cover design: eStudioCalmar, Girona/Berlin

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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Chapter 1
Introduction

1.1 Evolution of Off-road Vehicles Towards Automation: the Advent of Field Robotics and Intelligent Vehicles

Following their invention, engine-powered machines were not immediately embraced by the agricultural community; some time was required for further technical developments to be made and for users to accept this new technology. One hundred years on from that breakthrough, field robotics and vehicle automation represent a second leap in agricultural technology. However, despite the fact that this technology is still in its infancy, it has already borne significant fruit, such as substantial applications relating to the novel concept of precision agriculture. Several developments have contributed to the birth and subsequent growth over time of the field of intelligent vehicles: the rapid increase in computing power (in terms of speed and storage capacity) in recent years; the availability of a rich assortment of sensors and electronic devices, most of which are relatively inexpensive; and the popularization of global localization systems such as GPS. A close look at the cabin of a modern tractor or harvester will reveal a large number of electronic controls, signaling lights, and even flat touch screens. Intelligent vehicles can already be seen as agricultural and forestry robots, and they constitute the new generation of off-road equipment aimed at *delivering power with intelligence*.

The birth and development of agricultural robotics was long preceded by the nascency of general robotics, and the principles of agricultural robotics obviously need to be considered along with the development of the broader discipline, and particularly mobile robots. Robotics and automation are intimately related to artificial intelligence. The foundations for artificial intelligence, usually referred as "AI," were laid in the 1950s, and this field has been expanding ever since then. In those early days, the hardware available was no match for the level of performance already shown by the first programs written in Lisp. In fact, the bulkiness, small memory capacities, and slow processing speeds of hardware prototypes often discouraged researchers in their quest to create mobile robots. This early software–hardware developmental disparity certainly delayed the completion of robots with the degree of

F. Rovira Más, Q. Zhang, A.C. Hansen, *Mechatronics and Intelligent Systems for Off-road Vehicles*. © Springer 2010

autonomy predicted by the science fiction literature of that era. Nevertheless, computers and sensors have since reached the degree of maturity necessary to provide mobile platforms with a certain degree of autonomy, and a vehicle's ability to carry out computer reasoning efficiently, that is, its *artificial intelligence*, defines its value as an intelligent off-road vehicle.

In general terms, AI has divided roboticists into those who believe that a robot should *behave like humans*; and those who affirm that a robot should *be rational* (that is to say, it should do the right things) [1]. The first approach, historically tied to the Turing test (1950), requires the study of and (to some extent at least) an understanding of the human mind: the enunciation of a model explaining how we think. Cognitive sciences such as psychology and neuroscience develop the tools to address these questions systematically. The alternative tactic is to base reasoning algorithms on *logic rules* that are independent of emotions and human behavior. The latter approach, rather than implying that humans may behave irrationally, tries to eliminate systematic errors in human reasoning. In addition to this philosophical distinction between the two ways of approaching AI, intelligence can be directed towards *acting* or *thinking*; the former belongs to the *behavior domain*, and the latter falls into the *reasoning domain*. These two classifications are not mutually exclusive; as a matter of fact, they tend to intersect such that there are four potential areas of *intelligent behavior design: thinking like humans*, *acting like humans*, *thinking rationally*, and *acting rationally*. At present, design based on rational agents seems to be more successful and widespread [1].

Defining intelligence is a hard endeavor by nature, and so there is no unique answer that ensures universal acceptance. However, the community of researchers and practitioners in the field of robotics all agree that *autonomy* requires some degree of intelligent behavior or ability to handle knowledge. Generally speaking, the grade of autonomy is determined by the *intelligence* of the device, machine, or living creature in question [2]. In more specific terms, three fundamental areas need to be adequately covered: *intelligence*, *cognition*, and *perception*. Humans use these three processes to navigate safely and efficiently. Similarly, an autonomous vehicle would execute reasoning *algorithms* that are programmed into its intelligence unit, would make use of knowledge stored in *databases* and lookup tables, and would constantly perceive its surroundings with *sensors*. If we compare artificial intelligence with human intelligence, we can establish parallels between them by considering their principal systems: the *nervous system* would be represented by architectures, processors and sensors; *experience and learning* would be related to algorithms, functions, and modes of operation. Interestingly enough, it is possible to find a reasonable connection between the nervous system and the artificial system's *hardware*, in the same way that experience and learning is naturally similar to the system's *software*. This dichotomy between software and hardware is actually an extremely important factor in the constitution and behavior of intelligent vehicles, whose reasoning capacities are essential for dealing with the unpredictability usually encountered in open fields.

Even though an approach based upon rational agents does not necessarily require a deep understanding of intelligence, it is always helpful to get a sense of its inner workings. In this context, we may wonder how we can estimate the *capacity* of an

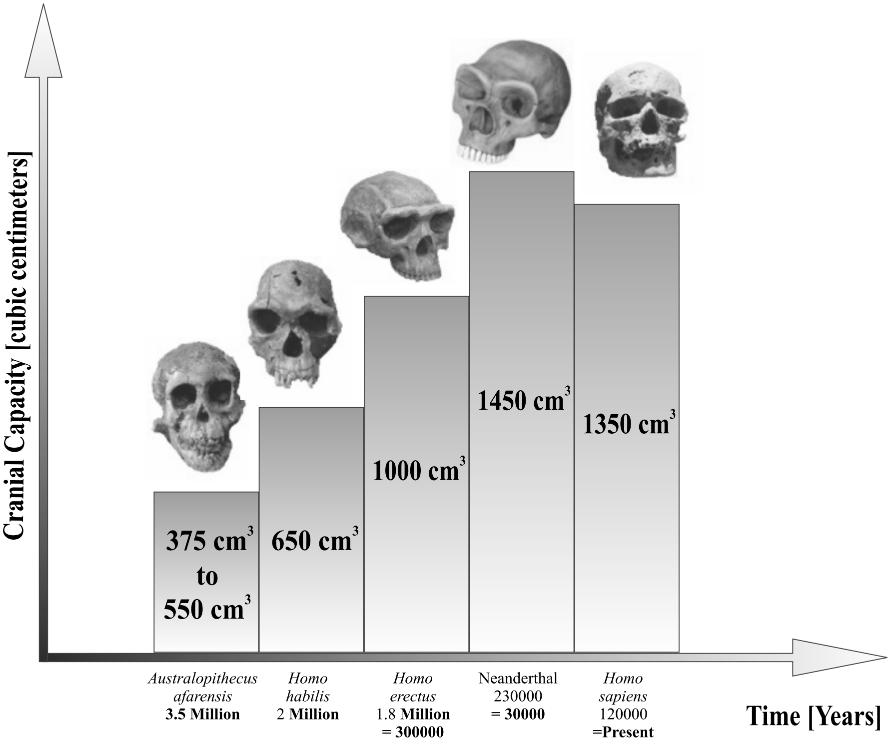

Figure 1.1 Brain capacity and degree of sophistication over the course of evolution

intelligent system, as many things seem easier to understand when we can measure and classify them. A curious fact, however, is shown in Figure 1.1, which depicts how the degree of sophistication of humans over the course of evolution has been directly related to their brain size. According to this “evolutionary stairway,” we generally accept that a bigger brain will lead to a higher level of society. However, some mysteries remain unsolved; for example, Neanderthals had a larger cranial capacity than we do, but they became extinct despite their high potential for natural intelligence.

It is thus appealing to attempt to quantify intelligence and the workings of the human mind; however, the purpose of learning from natural intelligence is to extract knowledge and experience that we can then use to furnish computer algorithms, and eventually off-road vehicles, with reliable and robust artificial thinking. Figure 1.1 provides a means to estimate brain capacity, but is it feasible to compare brain power and computing power? Hans Moravec has compared the evolution of computers with the evolution of life [3]. His conclusions, graphically represented in Figure 1.2, indicate that contemporary computers are reaching the level of intelligence of small mammals. According to his speculations, by 2030 computing power could be comparable to that of humans, and so robots will compete with humans;

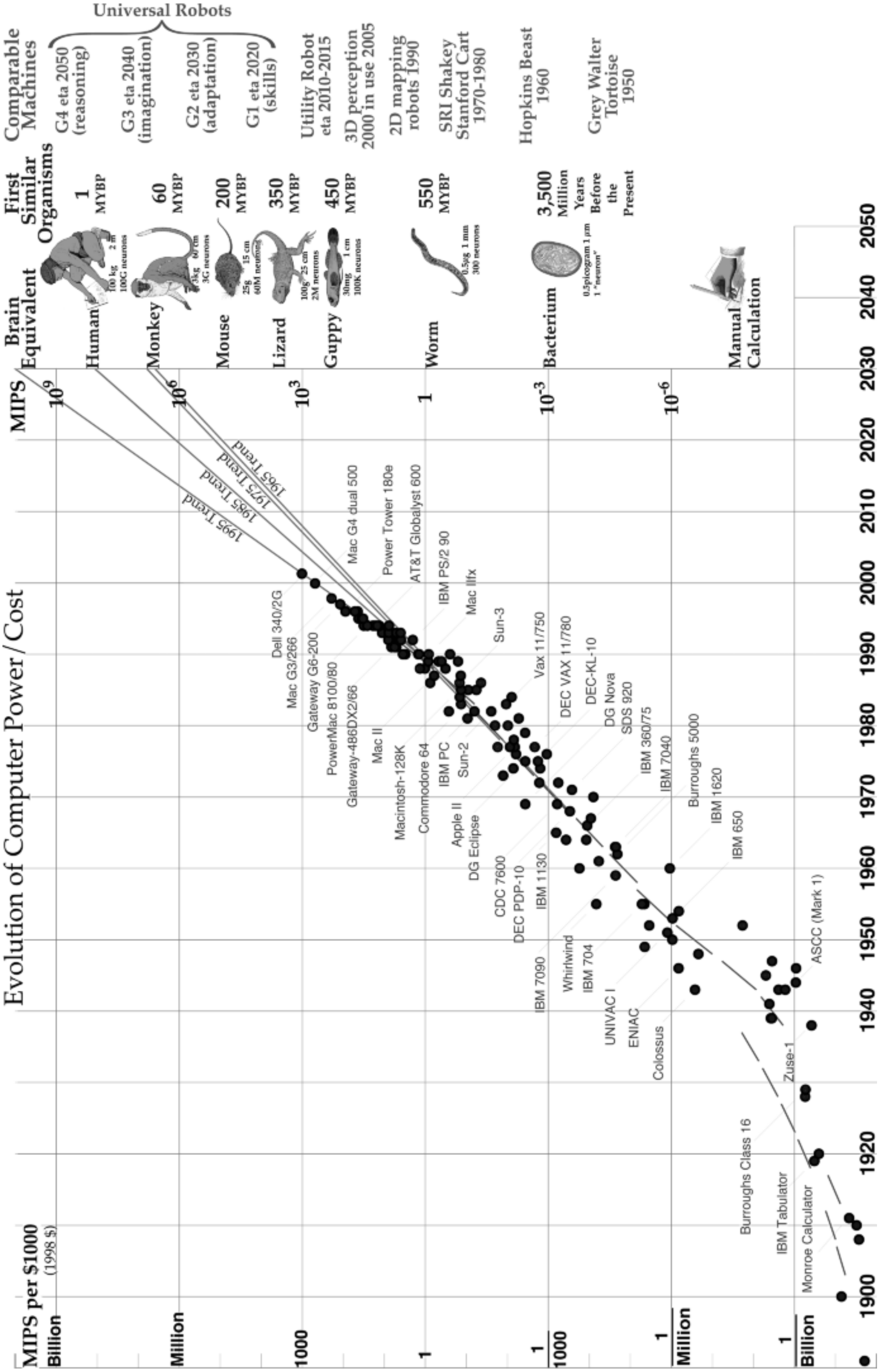

Figure 1.2 Hans Moravec's comparison of the evolution of computers with the evolution of life [3]

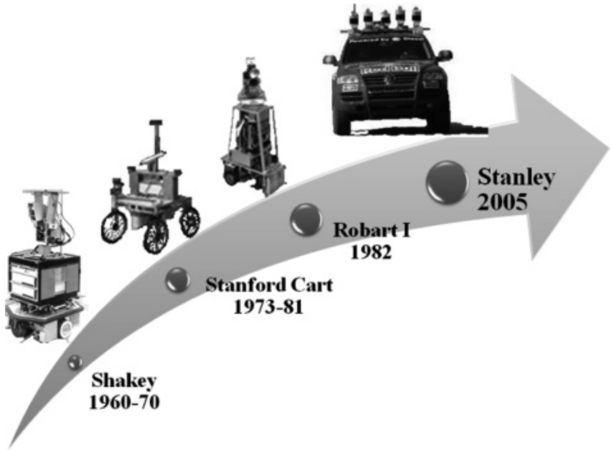

Figure 1.3 Pioneering intelligent vehicles: from laboratory robots to off-road vehicles

in other words, a fourth generation of universal robots may abstract and reason in a humanlike fashion.

Many research teams and visionaries have contributed to the field of mobile robotics in the last five decades, and so it would be impractical to cite all of them in this introductory chapter. Nevertheless, it is interesting to mention some of the breakthroughs that trace the trajectory followed by field robotics from its origins. *Shakey* was a groundbreaking robot, developed at the Stanford Research Institute (1960–1970), which solved simple problems of perception and motion, and demonstrated the benefits of artificial intelligence and machine vision. This pioneering work was continued with the *Stanford Cart* (1973–1981), a four-wheeled robot that proved the feasibility of stereoscopic vision for perception and navigation. In 1982, *ROBART I* was endowed with total autonomy for random patrolling, and two decades later, in 2005, *Stanley* drove for 7 h autonomously across the desert to complete and win Darpa's Grand Challenge. Taking an evolutionary view of the autonomous robots referred to above and depicted in Figure 1.3, successful twenty-first century robots might not be very different from off-road vehicles such as *Stanley*, and so agricultural and forestry machines possess a typology that makes them suited to robotization and automation.

In order to move autonomously, vehicles need to follow a *navigation model.* In general, there are two different architectures for such a model. The *traditional model* requires a cognition unit that receives perceptual information on the surrounding environment from the sensors, processes the acquired information according to its intelligent algorithms, and executes the appropriate actions. This model was implemented, for instance, in the robot *Shakey* shown in Figure 1.3. The alternative model, termed *behavior-based robotics* and developed by Rodney Brooks [4], eliminates the cognition box by merging perception and action. The technique used to apply this approach in practice is to implement sequential layers of control that have different levels of competence. Several robots possessing either legs or wheels have followed this architecture successfully.

In the last decade, the world of robotics has started to make its presence felt in the domestic environment: there has been a real move from laboratory prototypes to retail products. Several robots are currently commercially available, although they look quite differently from research prototypes. Overall, commercial solutions tend to be well finished, very task-specific, and have an appealing look. Popular examples of off-the-shelf robots are vacuum cleaners, lawn mowers, pool-cleaning robots, and entertainment mascots. What these robots have in common are a small size, low power demands, no potential risks from their use, and a competitive price. These properties are just the opposite of those found for off-road vehicles, which are typically enormous, actuated by powerful diesel engines, very expensive and – above all – accident-prone. For these reasons, even though they share a common ground with general field robotics, off-road equipment has very special needs, and so it is reasonable to claim a distinct technological niche for it within robotics: agricultural robotics.

1.2 Applications and Benefits of Automated Machinery

Unlike planetary rovers (the other large group of vehicles that perform autonomous navigation), which wander around unstructured terrain, agricultural vehicles are typically driven in fields arranged into crop rows, orchard lanes or greenhouse corridors; see for example the regular arrangement of the vineyard and the ordered rows of orange trees in Figure 1.4 (a and b, respectively). These man-made structures provide features that can assist in the navigation of autonomous vehicles, thus facilitating the task of auto-steering. However, as well as the layout of the field, the nature of agricultural tasks makes them amenable to automation too. Farm duties such as planting, tilling, cultivating, spraying, and harvesting involve the execution of repetitive patterns where operators need to spend many hours driving along farming rows. These long periods of time repeating the same task often result in tiredness and fatigue that can lead to physical injuries in the long run. In addition, a sudden lapse in driver concentration could result in fatalities.

Figure 1.4 Vineyard in Northern California (**a**) and an orange grove in Valencia, Spain (**b**)

One direct benefit of automating farming tasks is a gain in ergonomics: when the farmer does not need to hold the steering wheel for 8 h per day, but can instead check the vehicle's controls, consult a computer, and even answer the phone, individual workloads clearly diminish. The vehicle's cabin can then be considered a working office where several tasks can be monitored and carried out simultaneously. The machine may be driven in an autopilot mode — similar to that used in commercial aircraft – where the driver has to perform some turns at the ends of the rows, engage some implements, and execute some maneuvers, but the autopilot would be in charge of steering inside the field (corresponding to more than 80% of the time).

Vehicle automation complements the concept of *precision agriculture* (PA). The availability of large amounts of data and multiple sensors increases the accuracy and efficiency of traditional farming tasks. Automated guidance often reaches sub-inch accuracies that only farmers with many years of experience and high skill levels can match, and not even expert operators can reach such a degree of precision when handling oversized equipment. Knowledge of the exact position of the vehicle in real time reduces the amount of overlapping between passes, which not only reduces the working time required but decreases the amount of chemicals sprayed, with obvious economic and environmental benefits. Operating with information obtained from updated maps of the field also contributes to a more rational use of resources and agricultural inputs. For instance, an autonomous sprayer will shut off the nozzles when traversing an irrigation ditch since the contamination of the ditch could have devastating effects on cattle or even people. A scouting camera may stop fertilization if barren patches are detected within the field.

As demonstrated in the previous paragraphs, the benefits and advantages of off-road vehicle automation for agriculture and forestry are numerous. However, safety, reliability and robustness are always concerns that need to be properly addressed before releasing a new system or feature. Automatic vehicles have to outperform humans because mistakes that people would be willing to accept from humans will never be accepted from robotic vehicles. Safety is probably the key factor that has delayed the desired move from research prototypes to commercial vehicles in the field of agricultural intelligent vehicles.

1.3 Automated Modes: Teleoperation, Semiautonomy, and Full Autonomy

So far, we have been discussing vehicle automation without specifying what that term actually means. There are many tasks susceptible to automation, and multiple ways of automating functions in a vehicle, and each one demands a different level of intelligence. As technology evolves and novel applications are devised, new functions will be added to the complex design of an intelligent vehicle, but some of the functions that are (or could be) incorporated into new-generation vehicles include:

- automated navigation, comprising guidance visual assistance, autosteering, and/or obstacle avoidance;
- automatic implement control, including implement alignment with crops, smart spraying, precise planting/fertilizing, raising/lowering the three-point hitch without human intervention, *etc.*;
- mapping and monitoring, gathering valuable data in a real-time fashion and properly storing it for further use by other intelligent functions or just as a historical data recording;
- automatic safety alerts, such as detecting when the operator is not properly seated, has fallen asleep, or is driving too fast in the vicinity of other vehicles or buildings;
- routine messaging to send updated information to the farm station, dealership, loading truck, or selling agent about crop yields and quality, harvesting conditions, picking rates, vehicle maintenance status, *etc.*

Among these automated functions, navigation is the task that relieves drivers the most, allowing them to concentrate on other managerial activities while the vehicle is accurately guided without driver effort. There are different levels of navigation, ranging from providing warnings to full vehicle control, which evidently require different complexity levels. The most basic navigation kit appeared right after the popularization of the global positioning system (GPS), and is probably the most extended system at present. It is known as a *lightbar* guidance assistance device, and consists of an array of red and green LEDs that indicate the magnitude of the offset and the orientation of the correction, but the steering is entirely executed by the driver who follows the lightbar indications. This basic system, regardless of its utility and its importance as the precursor for other guidance systems, cannot be considered an automated mode *per se* because the driver possesses full control over the vehicle and only receives advice from the navigator. The next grade up in complexity is represented by *teleoperated* or *remote-controlled* vehicles. Here, the vehicle is still controlled by the operator, but in this case from outside the cabin, and sometimes from a remote position. This is a hybrid situation because the machine is moving driverless even though all of its guidance is performed by a human operator, and so little or no intelligence is required. This approach, while utilized for planetary rovers (despite frustrating signal delays), is not attractive for off-road equipment since farm and forestry machines are heavy and powerful and so the presence of an operator is normally required to ensure safety. Wireless communications for the remote control of large machines have still not yet reached the desired level of reliability. The next step is, at present, the most interesting for intelligent off-road vehicles, and can be termed *semiautonomy*. It constitutes the main focus of current research into autonomous navigation and corresponds to the autopilots employed in airplanes: the operator is in place and in control, but the majority of time – along the rows within the field – steering is performed automatically. Manual driving is typically performed from the machinery storage building to the field, to engage implements, and in the headlands to shift to the next row. The majority of the material presented in this book and devoted to autonomous driving and autoguidance will refer to semiautonomous applications. The final step in the evolutionary path for autonomous navigation is represented by *full autonomy*. This is the stage that has long been dreamed of by visionaries. In full autonomy, a herd of completely autonomous machines farm the field by themselves and return to the farm after the task is done without human intervention. The current state of technology and even human mentality are not ready for such an idyllic view, and it will certainly take some years, probably decades, to fulfill that dream. System reliability and safety is surely the greatest obstacle to achieving full autonomy (although accomplishing semiautonomy is also a remarkable advance that is well worth pursuing). The future – probably the next two decades – will reveal when this move should be made, if it ever happens.

1.4 Typology of Field Vehicles Considered for Automation

When confronted with the word *robot*, our minds typically drift to the robots familiar to us, often from films or television watched during childhood. Hence, well-known robots like *R2-D2*, *HAL-9000*, or *Mazinger Z* can bias our opinions of what a robot actually is. As a matter of fact, a robotic platform can adopt any configuration that serves a given purpose, and agricultural and forestry production can benefit for many types of vehicles, from tiny scouting robots to colossal harvesters. The rapid development of computers and electronics and the subsequent birth of agricultural robotics have led to the emergence of new vehicles that will coexist with conventional equipment. In general, we can group off-road field vehicles into two categories: conventional vehicles and innovative platforms.

Conventional vehicles are those traditionally involved in farming tasks, such as all types of tractors, grain harvesters, cotton and fruit pickers, sprayers, self-propelled forage harvesters, *etc.* Robotized machines differ from conventional vehicles in that they incorporate a raft of sensors, screens, and processors, but the actual chassis of the vehicle is the same, and so they are also massive, powerful and usually expensive. These vehicles, which we will term robots from now on, are radically different from the small rovers and humanoids that take part in planetary explorations or dwell in research laboratories. Farm equipment moving in (semi)autonomous mode around fields typically frequented by laborers, machines, people or livestock poses acute challenges in terms of liability; mortal accidents are unlikely to occur in extraterrestrial environments, research workshops, or amusement parks, but they do happen in rural areas where off-road equipment is extensively used. Since the drivers of these vehicles need special training and to conduct themselves responsibly, automated versions of these vehicles will have to excel in their precaution and safeguarding protocols. A great advantage of robotized conventional off-road vehicles over typical small mobile robots is the durability of the energy source. One of the known problems with domestic and small-scale robots is their autonomy, due to the limited number of operating hours afforded by their power sources. Most of them are powered by solar cells (planetary rovers) or lithium batteries (humanoids, vacuum cleaners, entertainment toys, *etc.*). This serious inconvenience is nonexistent in farming vehicles, since they are usually powered by potent diesel engines, meaning that the energy requirements of onboard computers, flat screens, and sensors are insignificant.

The quest for updated field data, precision in the application of farming inputs, and the rational adoption of information technology methods has led to a number of novel and unusual vehicles that can be grouped under the common term of *innovative vehicles*. These platforms follow an unconventional design which is especially tailored to the specific task that it is assigned to carry out. Most of them are still under development, or only exist as research prototypes, but the numbers and varieties of innovative vehicles will probably increase in the future as more robotic solutions are incorporated into the traditional farm equipment market. Among these innovative vehicles, it is worth mentioning legged robots capable of climbing steep mountains for forestry exploitation, midsized robotic utility vehicles (Figure 1.5a), localized remote-controlled spraying helicopters (Figure 1.5b), and small scouting robots (Figure 1.5c) that can operate individually or implement swarm intelligence strategies.

Figure 1.5 Innovative field vehicles: (**a**) utility platform; (**b**) spraying helicopter; (**c**) scouting robot (courtesy of Yoshisada Nagasaka)

1.5 Components and Systems in Intelligent Vehicles

Despite of the lure of innovative unconventional vehicles, most of today's intelligent off-road vehicles are conventional agricultural vehicles, and probably most of tomorrow's will be too. These machines possess special characteristics that place them among the largest and most powerful mobile robots. For instance, a common tractor for farming corn and soybeans in the American Midwest can weigh 8400 kg, incorporates an engine of 200 HP, and has an approximate price of $100,000. A wheat harvester that is frequently used in Northern Europe might weigh 16,000 kg, be powered by a 500 HP engine, and have a retail value of $300,000. A self-propelled sprayer for extensive crops can feature a 290 HP engine, weigh 11,000 kg, and cost $280,000. All of these figures indicate that the off-road vehicles that will be robotized for deployment in agricultural fields will not have any trouble powering their sensors, the cost of the sensors and ancillary electronics will represent a modest percentage of the machine's value, and the weight of the "brain" (the hardware and architecture that supports the intelligent systems onboard) will be insignificant compared to the mass of the vehicle. On the other hand, reliability and robustness will be major concerns when automating these giants, so the software used in them will need to be as heavyweight as the vehicle itself – meaning that such machines can be thought of as "smart dinosaurs."

1.5.1 Overview of the Systems that Comprise Automated Vehicles

Given the morphology of the vehicles under consideration, the design of the system architecture must take the following aspects into account (in order of priority): robustness and performance; cost; size; power requirements; weight. An individual description of each sensing system is provided subsequently, but regardless of the specific properties of each system, it is important to consider the intelligent vehicle as a whole rather than as an amalgamation of sensors (typical of laboratory prototyping). In this regard, a great deal of thought must be devoted early in the design process to how all of the sensors and actuators form a unique body, just like the human body. Although field vehicles can be very large, cabins tend to be full of devices, levers and controls without much room to spare, so it is essential to plan efficiently and, for example, merge the information from several sources into a single screen

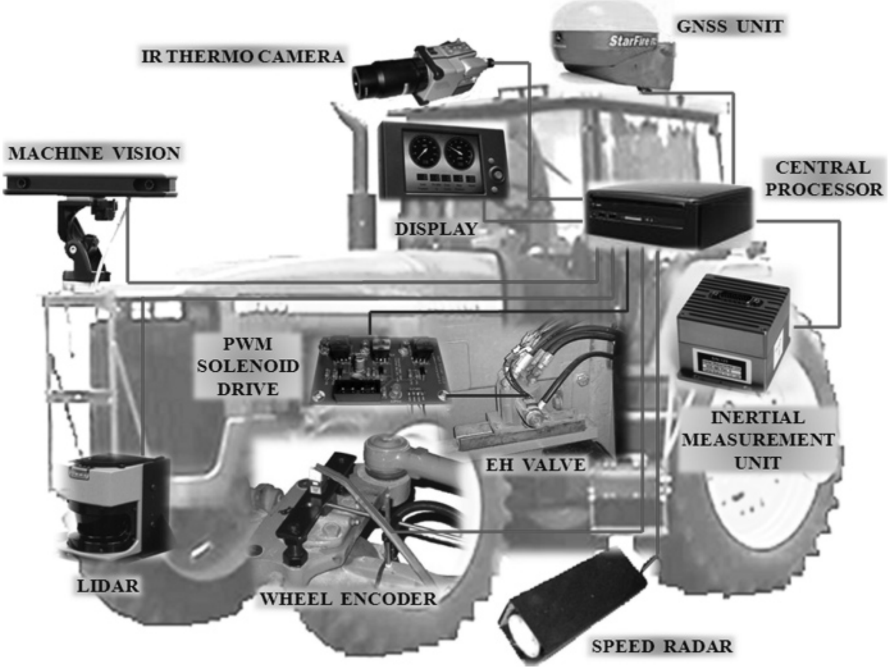

Figure 1.6 General architecture for an intelligent vehicle

with a clear display and friendly interfaces. The complexity of the intelligent system does not necessarily have to be translated into the cabin controls, and it should never be forgotten that the final user of the vehicle is going to be a professional farmer, not an airliner pilot. The physical positions of the sensors and actuators are also critical to ensuring an efficient design. One of the main mistakes made when configuring a robotized vehicle that is intended to roam in the open field is a lack of consideration of the harsh environment to which the vehicle can be exposed: freezing temperatures in the winter, engine and road vibrations, abrasive radiation and temperatures in the summer, strong winds, high humidity, dew and unpredicted rains, dust, friction from branches, exposure to sprayed chemicals, *etc.* These conditions make off-road vehicle design special, as it diverges from classic robotic applications where mobile robots are designed to work indoors (either in offices or in manufacturing buildings). If reliability is the main concern, as previously discussed, hardware endurance is then a crucial issue. Not only must the devices used be of high quality, but they must also have the right protection and be positioned optimally. In many cases, placing a delicate piece in an appropriate position can protect it from rough weather and therefore extend its working life. Figure 1.6 shows a robotized tractor with some of the usual systems that comprise intelligent vehicles.

1.5.2 Flow Meters, Encoders, and Potentiometers for Front Wheel Steering Position

The vast majority of navigation systems, if not all of them, implement *closed loop control* systems to automatically guide the vehicle. Such a system can be either a simple loop or sophisticated nested loops. In any case, it is essential to incorporate a feedback sensor that sends updated information about the actuator generating the steering actions. Generally speaking, two philosophies can be followed to achieve autoguidance in terms of actuation: controlling the steering wheel with a step motor; actuating the steering linkage of the vehicle. Both solutions are being used in many ongoing research projects. While the former allows outdated machinery to be modernized by mounting a compact autosteering kit directly on the steering column, the latter keeps the cabin clearer and permits more flexibility in the design of the navigation system.

When the automatic steering system is designed to actuate on the steering linkage (the second approach), the feedback sensor of the control loop must provide an estimate of the position of the turning wheel. This wheel will generally be one of the two front wheels on tractors, sprayers and utility vehicles (Ackerman steering) or one of the rear wheels on harvesters (inverse Ackerman). Regardless of the wheel used for turning angle estimation, there are three ways to get feedback commands:

1. directly measuring the turned angle with an encoder;
2. indirectly measuring the angle by estimating the displacement of the hydraulic cylinder actuating the steering linkage;

3. indirectly measuring the wheel angle by monitoring the flow traversing the steering cylinder.

Estimating the turning angle through the linear displacement of the cylinder rod of the steering linkage requires sensor calibration to relate linear displacements to angles. As described in Chapter 2, when steering is achieved by turning the front or rear wheels (that is, for non-articulated geometries), the left and right wheels of the same axle do not turn the same amount for a given extension of the cylinder rod. Thus, the nonlinear relationship between both wheels must be established, as the sensor will usually estimate the angle turned by one of them. The sensor typically employed to measure rod displacements is a *linear potentiometer*, where changes in electrical resistivity are converted into displacements. This sort of sensor yields a linear response inside the operating range, and has been successfully used with off-road vehicles, although the potentiometer assemblage is sometimes difficult to mount on the steering mechanism. The position of the rod can also be calculated from the flow rate actuating the cylinder. In this case, the accuracy of the flow meter is vital for accomplishing precise guidance.

An alternative to a linear potentiometer is to use *optical encoders* to estimate the angle turned by one or both of the turning wheels. These electromechanical devices usually consist of a disc with transparent and opaque areas that allow a light beam to track the angular position at any time. Such rotary encoders are preferably mounted on the king pin of the wheel whose angle is being recorded. Assembly is difficult in this case, since it is necessary to fix either the encoder's body or the encoder's shaft to the vehicle's chassis so that relative movements can be tracked and wheel angles measured. King pins are not easy to access, and encoders require a customized housing to keep them or their shafts affixed to the vehicle while protecting them from the harsh surroundings of the tire. The calibration of optical encoders is straightforward (see Section 7.1), and establishes a relationship between output voltage and angle turned. Encoders, as well as potentiometers, require an input voltage, which has to be conducted to the wheels through the appropriate wires. Figure 1.7 shows the assembly of encoders for tractors with two different wheel-types.

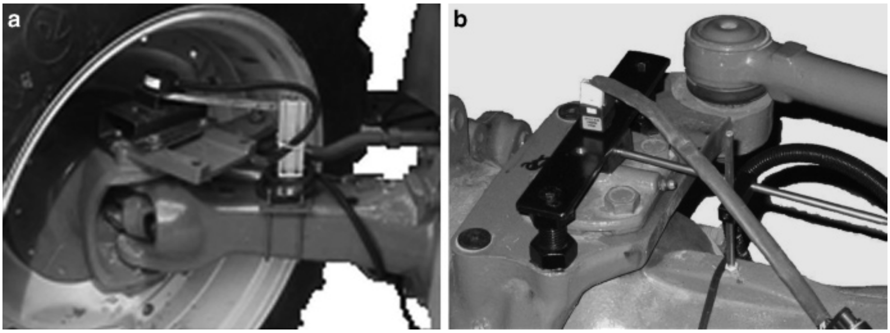

Figure 1.7 Assembly of optical encoders on two robotized tractors with different wheel-types

1.5.3 *Magnetic Pulse Counters and Radars for Theoretical and Ground Speed*

Automatic navigation can be achieved by implementing a great variety of algorithms, from simplistic reactive feelers to sophisticated trajectory planners. Most of the strategies that have actually been used require the estimation of the vehicle forward velocity, as it is incorporated into models that predict and trace trajectories. Knowledge of the speed is indispensable for adjusting the steering angle appropriately as the vehicle increases speed or, for instance, for calculating states in the Kalman filter-based sensor fusion employed by a navigation planner. Dead reckoning is a navigation technique that is used to estimate the current position of a vehicle based on its speed of travel and the time elapsed from a previous position. While it is used in many robotic applications, it is never recommended for off-road vehicles because *wheel slip* is a common phenomenon when traversing off-road terrains, and when such slippage occurs, errors in the positions estimated through dead reckoning grow considerably. The slippage can however be calculated when the theoretical speed of the vehicle and the actual speed can be measured.

The *theoretical forward speed* of a vehicle can be calculated if the number of revolutions made by the wheel in a certain time and the diameter of the wheel are known. The angular speed of the wheel can easily be measured by a magnetic pulse counter installed directly in the wheel or axle shaft. The counter needs a set of stripes or some other means of marking angular positions and a timer.

Although the theoretical speed is necessary to estimate wheel slip, the *real speed* is more important for navigational purposes, as it is the parameter used in most models. Other automated functions aside from navigation also make use of it; for instance, it is used to estimate the changes in nozzle actuation required during intelligent spraying according to the speed. The forward speed can be measured with devices based on the principle of time-of-flight calculations, such as radar. Vehicles equipped with global navigation satellite systems such as GPS can also estimate the forward speed from messages sent to the receiver from satellites, since position and time are acquired in real time.

1.5.4 *Sonar and Laser (Lidar) for Obstacle Detection and Navigation*

Ultrasonic distance sensing became popular for mobile robotics due to a sonar sensor developed by Polaroid for camera range-finding. These sensors were inexpensive and so an affordable solution was to arrange a matrix of them around the body of the robot, thus avoiding the problem of the narrow field of each sensor. This idea worked well for small robots that needed to detect the walls of offices and research labs, but they have not found widespread use in large vehicles. Other perception sensors, such as vision and laser devices, have been found to be more efficient for outdoor applications.

Lidar (light detection and ranging) is an optical device that is used to find ranges or distances to objects and surfaces. Different light sources can be used to find ranges, but the prevalent trend is to use laser pulses, and therefore a lidar and a laser rangefinder will be assumed to be equivalent devices hereafter, unless otherwise specified. Lasers are ideal for vehicle navigation because the beam density and coherency are excellent. However, lasers possess a very narrow beam, which forces the emitter to rotate to cover the field of view in front of the vehicle. The high resolutions of lidars have made them popular for obstacle detection and avoidance in field robots, such as the participants in the Grand Challenge competition for unmanned vehicles, where most of the off-road vehicles featured one – and often several – lidar heads [5]. Figure 1.3 shows *Stanley the Robot*, an intelligent vehicle off-road with five lidars on its roof.

1.5.5 GNSS for Global Localization

The tremendous boost given by GPS to the automation of agricultural vehicles, especially with regards to automatic guidance, has had a very positive effect on the development of agricultural robotics. The cancellation of selective availability by the United States Department of Defense in 2000 marked the beginning of an wave of commercial products and research projects that took advantage of the availability of real-time vehicle localization. While farm equipment firms have directed significant effort toward global navigation systems, other electronics and communications manufacturers have also expanded their market share to include agricultural applications. At the present time, most of the leading manufacturers of agricultural machinery include navigation assistance systems among their advanced products.

Even though GPS triggered the growth of satellite-based navigation, it is more appropriate to consider a general term under which other similar systems can be grouped: *global navigation satellite systems*, often referred to as *GNSS*. Under the umbrella of GNSS, we will consider GPS (USA), Galileo (Europe), GLONASS (Russia), Beidou (China), and other satellite localization systems that may appear in the future. Currently only GPS is fully operational, and so all commercial navigation assistance applications currently rely on it.

In spite of the extensive use and clear benefits of global positioning, it has some important drawbacks that need to be addressed by autonomous navigation applications. The main disadvantage of global sensing is a lack of local awareness. Any unpredicted event that occurs in the vicinity of the vehicle will always remain unnoticed in a global frame. Such events include small trajectory corrections and real-time changes that affect the robot's predetermined course. Another difficulty that is of great importance for orchards and greenhouses is related to double-path errors and signal drops. Tall trees create tunnel-like inter-row lanes where GNSS signals from satellites tend to be inconsistent. The hazards caused by unreliable navigation commands directing a massive off-road vehicle demand sensor redundancy, including local perception, which is usually achieved with lidars or imaging sensors. The tractor depicted in Figure 1.6 features a GPS receiver that is customized for agricultural production needs. The different GNSS solutions that are available for agriculture are discussed in Chapter 3.

It is important to establish a distinction between a GNSS receiver and a complete GNSS-based navigation system. The receiver provides real-time geodesic coordinates and the velocity of the vehicle, and it is the navigation algorithm's task to process these data, often by fusing them with data from other redundant sensors to generate guidance commands. When we refer to a GNSS-based navigation system, we mean a complete system that utilizes global positioning data to feed a controller whose output instructions steer the vehicle. This approach is followed by some manufacturers, and in this case the whole system must be considered a black box with limited or no access to the internals of the controller.

1.5.6 Machine Vision for Local Awareness

It has been noticed by some advanced farmers (early adopters of GNSS and related technologies) that, unless high-accuracy systems such as RTK-GPS are used in the field, the coordinates of crop rows recorded during planting are not the same as the positions of the same rows detected during harvesting. Unless proper corrections are made before harvesting, automated machines could cause irreversible damage to the valuable crops if only global localization is used. A solution to this serious problem can be found in local perception sensors; among them, machine vision probably has the greatest potential due to its ability to "see" ahead of the vehicle. The slight correction that needs to be done to adjust the harvester head to the crop rows can be performed with an onboard camera. These corrections often change over time, and so a fixed offset is not a robust solution to the problem. A camera with a fast frame rate of up to 30 images/s and an adjustable field of view and resolution can calculate the small tolerances that a robotic vehicle needs to navigate without damaging the crops.

Instantaneous rectifications are not the only benefit of image sensors. Moreover, they do not represent their most important advantage over global sensing. The main reason for incorporating video cameras into the perception systems of autonomous robots is usually the advantages of computer vision for safeguarding and obstacle detection. Agricultural vehicles operate in fields where other workers, vehicles, and even livestock move around without following predetermined paths. An obstacle can interfere with the vehicle's trajectory at any time, and there is a need to detect it in real time so that the vehicle can be halted or detoured to avoid collision.

The rich visual information made available by this technique can also be employed for other uses besides vehicle navigation. As features from the field environment are grabbed in a continuous sequence of images, mapping and monitoring algorithms can recreate the field scene and estimate growth status or maturity.

The range of imaging sensors available is diverse, and each concrete application demands a different solution. The detection of plant health for automated fertilizing has been successfully realized with *hyperspectral* and *multispectral cameras*. Smart spraying has been achieved with *monocular cameras*. Autonomous guidance can make use of both monocular cameras and binocular stereovision rigs. Three-dimensional maps can be assembled from images obtained with a *stereoscopic camera*. All of the sensors require appropriate calibration. The vehicle shown in Figure 1.6 features a stereo camera located on the front of the tractor for 3D imaging. Chapters 4 and 5 provide a more detailed description of vision sensors.

There is no perfect sensor that can fulfill all of the requirements of a robotic vehicle, and from that point of view sensor fusion and redundancy is more than necessary. Just like other sensors, vision systems also have weaknesses, such as the computational load associated with many vision algorithms, the amount of data that some processes need to handle (especially for stereo images), and the dependency of such systems on lighting conditions, with notable consequences for reliability and robustness.

1.5.7 Thermocameras and Infrared for Detecting Living Beings

Vision sensors, lidars (lasers), and ultrasonic devices cannot penetrate through a thick layer of densely planted crops at the time of harvesting. Corn, for example, can easily reach over six feet at the end of its vegetative cycle. In this situation, the safeguarding engine of an automated machine cannot detect the presence of living beings standing within the crop if it is exclusively based on local perception sensors such as cameras and optical rangefinders. There have been reports of cattle being run over, and even negligent laborers being injured by (manually operated) farm machines. Accidents caused by agricultural vehicles are not uncommon, and when they do happen they are shocking and are quickly reported by the media. In order to avoid this situation, some sophisticated vehicles incorporate *infrared thermocameras* that are capable of generating a thermographic map of a given scene.

Thermocameras, also called FLIR (forward-looking infrared), are cameras that form images based on the infrared radiation emitted by objects. During low-intensity illumination at, say, dawn or dusk, or even for nighttime tasks, when an operator would found it more difficult to distinguish a person or animal concealed by plants, the temperatures of living beings are significantly superior to those of the surrounding plants and soil. Such temperature differences can be identified on the thermographic profile of the scene, and the safeguarding algorithm can, after conducting a *thermographic analysis* of the infrared image, output warning messages that the vehicle should be detoured or stopped. These sensors have not been widely exploited so far for civil applications, although they have been used for defense purposes for a long time. As the cost of FLIR sensors decreases, more intelligent vehicles will incorporate them into their perception units. Figure 1.8 shows a thermographic map (a) of an agricultural scene (b) that can be used to analyze the water content of the soil.

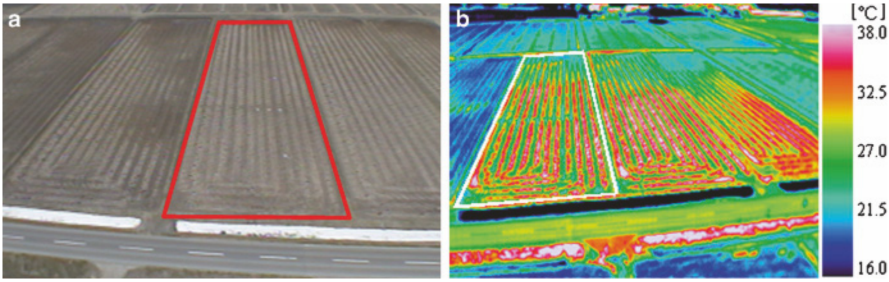

Figure 1.8 Thermographic map (**b**) of a Japanese rural area (**a**) (courtesy of Noboru Noguchi)

1.5.8 Inertial and Magnetic Sensors for Vehicle Dynamics: Accelerometers, Gyroscopes, and Compasses

Feedback control systems are a set of techniques that are universally utilized to achieve automation in field robotics. The basic idea is to estimate the difference (*i.e.*, the error) between the desired state and the actual state and use it to control the vehicle in subsequent motion orders. The specific way to do this is defined by the design of the controller algorithm and control loop. This procedure requires the instantaneous estimation of the states of the vehicle, in other words its position, linear velocity, angular rate (angular velocity), acceleration, pitch, roll, and heading angle. These states are measured by inertial sensors and are essential for assessing the vehicle's dynamic behavior. The dynamics of the motion are related to the response of the vehicle to the navigational commands sent by the intelligence unit, and are usually included in the motion equations of the dynamic model, such as state space control models and Kalman filters.

Inertial measurement units (IMU) are motion sensors created from a combination of accelerometers and gyroscopes. The accelerometers of the IMU detect the acceleration (the change in velocity over time) of the vehicle. Once the acceleration is known, integrating it gives an estimate of the velocity, and integrating it again allows the position to be evaluated. Similarly, the gyroscopes can detect the angular rates turned by the vehicle; integrating these leads to roll, pitch and yaw values. Typical inertial measurement units comprise three accelerometers and three gyroscopes assembled along three perpendicular axes that reproduce a Cartesian coordinate system. With this configuration, it is possible to calculate the three components of acceleration and speed in Cartesian coordinates as well as Euler angles. New IMU designs are smaller and less expensive, which is favorable for multiple and more accurate estimates of vehicle states. The rate of reduction is such that the sizes of some IMUs are similar to those of small devices such as microelectromechanical systems (MEMS).

The principal disadvantage of inertial measurement units is drift – the accumulation of error with time. This problem is caused by the way that measurements are carried out, with previous values being used to calculate current ones, following the same philosophy applied in dead reckoning. The effects of drift on navigation are significant, and other sensing devices need to be taken into account to complement IMU readings. Traditionally, position or motion data from different sources are combined through sensor fusion techniques such as Kalman filtering or fuzzy logic. A common approach to making IMU navigation (also known as inertial navigation systems, or INS) more robust is integrate it with GNSS, which can provide regular corrections of position and speed. GPS, in particular, provides the speed and heading when the roving vehicle is in motion.

Most of the navigation models that are currently implemented require knowledge of the *vehicle's heading*, which gives the orientation of the vehicle with respect to the direction reference, usually north in a local tangent plane system of coordinates. Correction errors for automatic guidance are based on two key parameters: offset and heading, meaning that knowledge of the heading tends to be indispensable. The problem of drift in IMU-based navigation systems practically rules out gyroscopes for heading estimations. Two alternatives are eligible: GPS to determine the vehicle's heading course, although several points are needed for reliability, and the vehicle needs to be in motion; and a magnetic compass, to find the orientation with respect to the magnetic North Pole. Intelligent vehicles utilize a modern version of the conventional magnetic compass: the electronic or fluxgate compass. This device can output electronic measurements that are easier for the vehicle's circuitry to handle.

1.5.9 Other Sensors for Monitoring Engine Functions

Complete automation of an agricultural vehicle may involve many different functions, such as raising the implement in the headlands, slowing down at the ends of rows, accelerating and up-shifting at the beginning of a row, engaging the power take-off, locking the differential or one of the traction wheels for turning, and so on. The implementation of these functions requires the proper actuators and a number of feedback sensors, either to directly assist in the operation of the vehicle or to send the information to a data-acquisition station through a wireless network. Typical sensors may include engine tachometers, speedometers, gear lever position, three-point-hitch position, fuel consumption and tank usage, brake position, differential lock–unlock position, *etc.* A successful way to coordinate these sensors is via an onboard computer area network (CAN), an information bus that links all of the sensors in the vehicle and facilitates its overall control.

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Chapter 2
Off-road Vehicle Dynamics

2.1 Off-road Vehicle Dynamics

A thorough understanding of vehicle dynamics is essential when designing high performance navigation systems for off-road vehicles. This section intends to provide readers with a comprehensive framework of the dynamics involved with wheel-type off-road vehicles. For a theoretical analysis of vehicle dynamics, it is a common practice to define the motion equations in reference to the body of the vehicle, and so vehicle-fixed coordinate systems are often used to describe the fundamental dynamics of vehicles [1]. As depicted in Figure 2.1, a conventional vehicle coordinate system consists of *body-fixed coordinates* (hereafter the *body* coordinates) and *steering wheel-fixed coordinates* (hereafter the *wheel* coordinates). The origin of *body coordinates* is often defined as the center of gravity (CG) of the vehicle, with

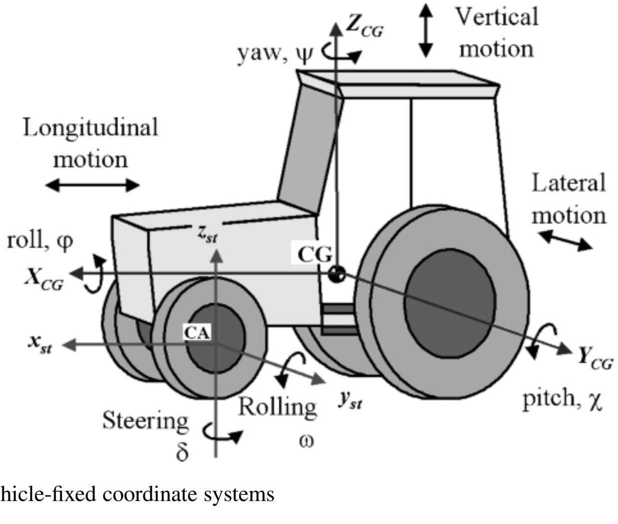

Figure 2.1 Vehicle-fixed coordinate systems

F. Rovira Más, Q. Zhang, A.C. Hansen, *Mechatronics and Intelligent Systems for Off-road Vehicles*. © Springer 2010