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CICLO XXVI

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DESIGN AND REALIZATION OF AN INNOVATIVE AUTOMATIC MACHINE ABLE TO PERFORM SITE-SPECIFIC THERMAL WEED CONTROL IN MAIZE

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CONTENTS

Abstract

This PhD thesis contains a detailed introduction on the state of the art of precision agriculture. The introduction is a brief guide to the technologies used in precision agriculture such as global navigation satellite system (GNSS), computer vision, remote and proximal sensors, Geographic Information System (GIS), Variable-Rate Application (VRA) and yield monitoring systems. In the introduction are also described in details the techniques for site-specific weed control and focuses on the most innovative methods for automatic detection and discrimination of crop and weeds, including the existing automatic or autonomous machines for precision chemical or physical weed management. The last chapter of the introduction concerns with a detailed description of the RHEA (Robot Fleets for Highly Effective Agriculture and Forestry Management) Project. The RHEA Project is really innovative as application of precision agriculture because focused on the design, development and testing of a fleet of heterogeneous and autonomous robots working together according to a proper use of innovative technologies.

The first chapter of the experimental part of the thesis concerns with the description of the innovative automatic machine designed and realized within the RHEA Project at the University of Pisa in order to perform site-specific thermal weed control in maize. This implement is able to perform mechanical non-selective treatment in the inter-row space and site-specific flaming in the intra-row space of heat-tolerant crops. According to the Description of Work of the RHEA Project the machine was adjusted in order to properly work in maize planted at 0.75 m of inter-row. Preliminary tests in order to verify the management of actuation devices and sensors by the PLC, the coupling with the ground mobile unit and the integration with the perception system for weed and row detection (that make the machine autonomous) were satisfying, although further research activities are needed in order to optimize all the sub-systems and verify their integrated functioning.

In the second chapter of the experimental part a research carried out at CiRAA “E. Avanzi” of the University of Pisa aiming to evaluate the field performances of the hoeing flaming system is described.

The field trial aimed to test the tolerance of maize (*Zea mays* L.) to cross flaming and the effectiveness in weed control as influenced by LPG dose and maize growth stage at the time of treatment. The obtained results showed that maize flamed with cross burners proves to have a high heat tolerance even if treated with high LPG doses because, despite of the reduced growth observed during the first month after the treatment, plants successively recovered and produced as much as the untreated ones. Differences in maize yield were observed as a consequence of flaming effectiveness in controlling weeds according to their stage of development and the used LPG dose. As a matter of fact, dicot weeds at seedling stage are more sensitive than well developed plants and high LPG doses resulted in a higher weeding effect. Finally, it is possible to state that the future use in the field of the automatic machine realized within the RHEA Project, besides allowing to perform site-specific flaming, will assure to obtain satisfying levels of weed control and good results in terms of maize yield.

CHAPTER 1. GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

Satellite-based positioning is the determination of the position of observing sites on land or sea, in air and space by means of artificial satellites (Hofmann-Wellenhof *et al*., 2008).
A satellite navigation system with global coverage may be defined a Global Navigation Satellite System or GNSS and indicates each existing and planned individual global satellite-based navigation system (Hofmann-Wellenhof *et al*., 2008). A satellite navigation system is a system of satellites that provide autonomous geo-spatial positioning with global coverage (Rao, 2010). GNSS is used in providing the user location in terms of latitude, longitude, altitude, speed, direction and time using a mathematical process called "trilateration". This is a method of determining the position of an object by measuring its distance from other objects with known locations (Rao, 2010). Trilateration locates a point by knowing the position of at least two reference points and three distances. Generally, at least 3 reference points are needed to determine accurately and uniquely the relative location of a point in a 2D plane using trilateration alone. The basic idea of trilateration is to locate the position (x_d, y_d) of a point (d) starting from three reference points, (a), (b) and (c), whose position, (x_a, y_a), (x_b, y_b) and (x_c, y_c), respectively, are known. As illustrated in figure 1.1, the position of (d) should be located at the intersection of the three circles centred at (a), (b), and (c), respectively. Trilateration can also work in three-dimensional networks. The only difference is that to locate a point in 3D networks four instead of three references points are needed (Wang & Li, 2010).

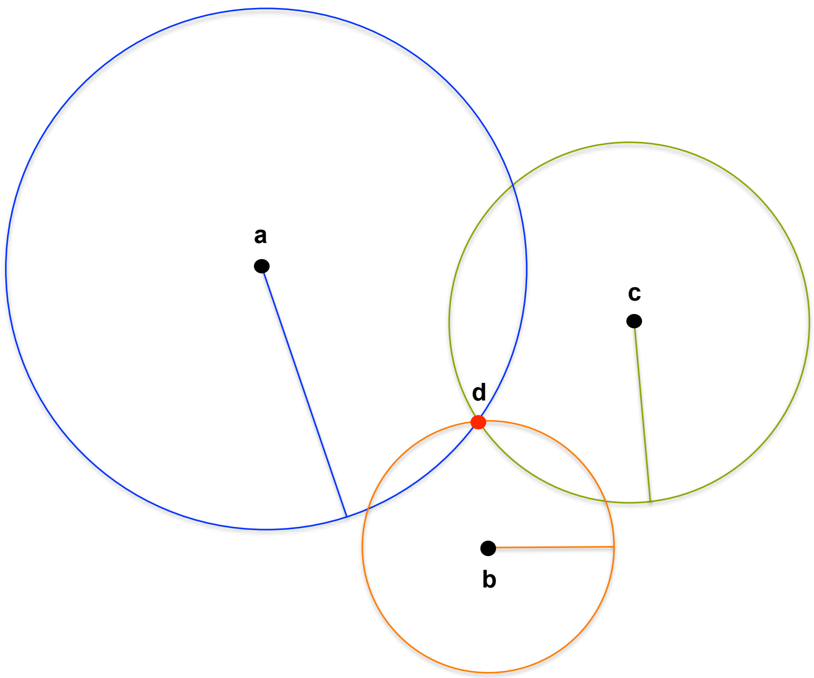

Figure 1.1. Basic idea of trilateration. Reference points: (a), (b), (c). Unknown point: (d) (redrawn from Wang & Li, 2010).

To determine the location of the receiver, this one needs to know two things: the satellites location in the space and the distance between the satellites and itself (Rao, 2010). Operational satellite-based positioning systems assume that the satellites positions are known at every epoch (calculated using the ephemeris) (Hofmann-Wellenhof *et al*., 2008) and the pseudoranges (the pseudo distances between a satellite and a navigation satellite receiver) were measured by multiplying the speed of light by the time the signal has taken to reach the receiver from the satellite. The trilateration determines the position of the receiver and its clock bias (Fig. 1.2) (Harper, 2010). In a time-synchronized system, calculating a three-dimensional position would require the position and distance from three satellites. However, a receiver is not perfectly synchronized to GNSS time, so four satellites are required in order to solve for the receiver's (x, y, z) positions and the clock bias (t) (Harper, 2010). Geometrically, the unknown position is accomplished by a sphere being tangent to the four spheres defined by the pseudoranges. The centre of this sphere corresponds to the unknown position of the receiver and its radius is equal to the range correction caused by the receiver clock error (Hofmann-Wellenhof *et al*., 2008). The accuracy of the position determined using a single receiver is essentially affected by the accuracy of each satellite position, pseudorange measurements and geometry (Hofmann-Wellenhof *et al*., 2008).

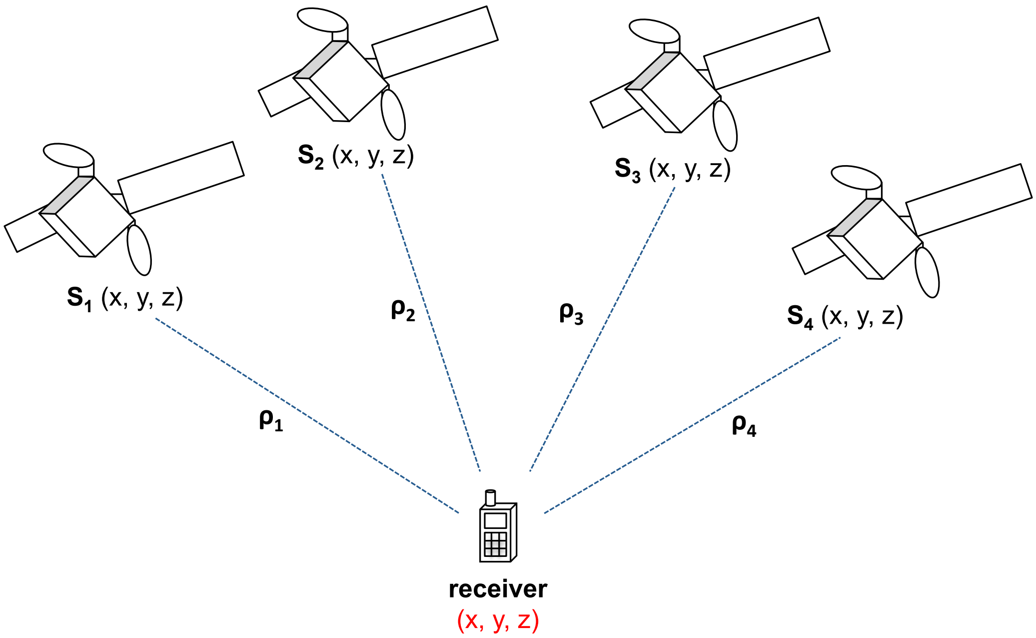

Figure 1.2. High-level model of the trilateration process. The position of the satellites (S_1, S_2, S_3 and S_4) and the relative pseudoranges (ρ_1, ρ_2, ρ_3 and ρ_4) are known and necessary for determining the receiver position (redrawn from Harper, 2010).

GNSS consist of three segments: the space segment, the control segment and the user segment (Fig. 1.3). The space segment consists of the satellite constellation. In order to provide a continuous global positioning capability, a constellation with a sufficient number of satellites must be developed for each GNSS to ensure that (at least) four satellites (three for trilateration and one for synchronize the receiver clock with the satellite clocks) are simultaneously and electronically visible at every site (Hofmann-Wellenhof *et al*., 2008). The satellites are equipped with very accurate atomic clocks to generate timing signals (Grisso *et al*. 2009b).

The control segment is responsible for steering the whole system and generally comprises a master control station coordinating all activities, a monitor station forming the tracking network, and a ground antenna being the communication link to the satellites (Hofmann-Wellenhof *et al*., 2008).

The user segment can be classified into user categories (military and civilian), receiver types, and various information services (Hofmann-Wellenhof *et al*., 2008). The receivers are composed of an antenna, tuned to the frequencies transmitted by the satellites, receiver-processors, and a highly stable clock (often a crystal oscillator) to compare the timing signals received from the satellites to internally generated timing signals. They may also include a display for providing location and speed information to the user (Grisso *et al*. 2009b).

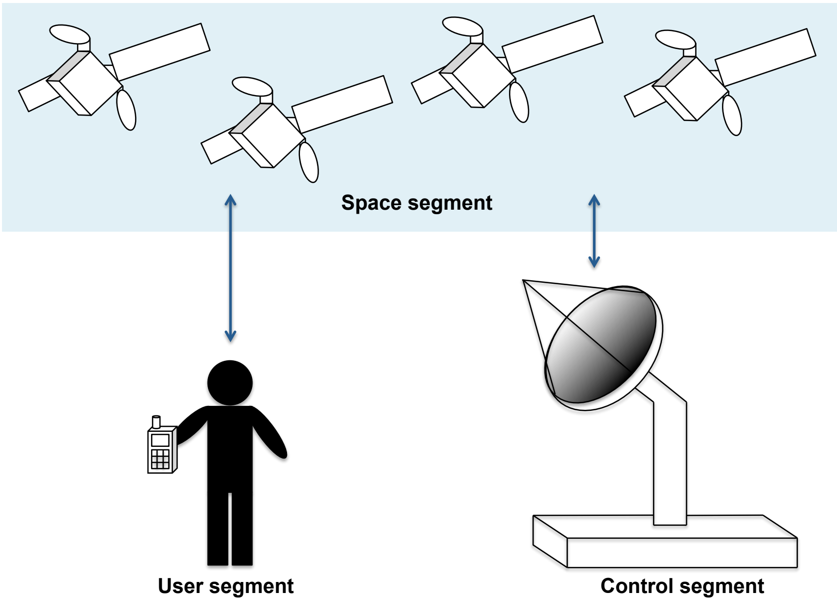

Figure 1.3. Scheme of GNSS segments (redrawn from Rao, 2010).

The existing and the planning GNSS constellations are the United States Global Positioning System (GPS), the Russian Federation's Global Orbiting Navigation Satellite System (GLONASS), the European GALILEO, the Chinese COMPASS/BeiDou, the Indian Regional Navigation System (IRNSS) and the Japanese Quasi Zenith Satellite System (QZSS). Two GNSS constellations are currently in operation: GPS and GLONASS (Rao, 2010). The positioning accuracy of GNSS varies from less than one centimetre to about 10 m depending from many factors, which include satellite availability and visibility, signal blockage from trees and buildings, the effect of multipath errors, the design of the used GNSS receiver, the number and the geometry of the collected observations, the used mode (point *vs* relative positioning) and type of observation (pseudorange or carrier phase), the measurement model used, the level of biases and errors affecting the observables, and the error differential correction service used (Rao, 2010). The differential correction services available are the DGPS radio beacons, the Space-Based Augmentation System (SBAS) and the Real-Time kinematic (RTK). The DGPS radio beacons can provide sub-meter accuracy. The SBAS provides correction signals through the use of additional satellite-broadcast messages. These providers have a high-accuracy service that uses dual-frequency receivers and antennas for performances in the decimetre range (0.1-

0.3 m). RTK systems establish the most accurate solution for GNSS applications, producing typical errors of less than 0.02 m (Perez-Ruiz & Upadhyaya, 2012)
The GPS satellite constellation is not enough for many applications. The signals are often obstructed at many locations, particularly in the urban areas. Hence, the use of all available GNSS signals generally improves positioning performance. As a matter of fact, the GNSS receivers can combine the signals from both GLONASS and GPS satellites to increase the accuracy (Cai & Gao, 2013). GPS + GLONASS provide minimum of 6 to 14 satellites above the horizon anywhere on the earth surface. Similarly, in the future GPS + GLONASS + Galileo are expected to provide improved precision and greater availability (due to the higher number of visible satellites), faster, more reliable ambiguity resolution and better ionospheric bias estimation due to the additional frequencies. GNSS constellations are required to provide relatively similar signals in order to simplify GNSS receivers that used combined GNSS constellations (Rao, 2010). GNSS constellations can be combined with non-GNSS constellations such as conventional surveying, Long Range Aid to Navigation (LORAN-C) and Inertial Navigation Systems (INS) to assist where GNSS contellations fail, as inside forests and tunnels (Awange, 2012).

1.1 Global Positioning System (GPS)

The Global Positioning System (GPS) is a worldwide satellite-based navigation system developed by the U.S. Department of Defence under its NAVSTAR satellite program (Grewal *et al*, 2013). Current PPP techniques are mainly based on GPS (Cai & Gao, 2013). GPS provides highly accurate position of objects, their velocity and time data. It was originally intended for military applications, but in the 1980s, the US government made the system available for civilian use (Rao, 2010).
The space segment consists of 31 or more active satellites approximately dispersed in a uniform way around six circular orbits with four or more satellites each (Fig. 1.4). Each orbits is at an altitude of 20200 km above the earth. The orbits are inclined at an angle of 55° relative to the equator and are separated from each other by multiples of 60° to cover the complete 360°. The orbits are no geostationary and approximately circular, with radii of 26560 km and orbital periods of one-half sidereal day (~11.967 h). Theoretically, three or more GPS satellites would always be visible from most points on earth surface, and four or more GPS satellites can be used to determine the position of an observer anywhere on earth surface 24h day^{-1} (Grewal *et al.*, 2013). These satellites transmit one-way signals that give the current GPS position and time (Rao, 2010). Each satellite transmits signals on two frequencies, L1 (1575.42 MHz) and L2 (1227.60 MHz), which can be detected by receivers on the ground (Rao, 2010). GPS satellite signals are generated using a process known as Direct Sequence Spread Spectrum (DSSS) modulation. GPS satellites are equipped with four extremely stable atomic clocks made of rubidium (Rb) and cesium (Cs) (Rao, 2010). To distinguish the satellites, GPS uses Code Division Multiple Access (CDMA) technique. In CMDA systems, satellites are distinguished by different pseudorandom noise codes broadcast on the same frequencies (Rao, 2010).
The control segment consists of a master control station (MCS), an alternate master control station, four dedicated ground antennas and six dedicated monitor stations that maintain

the satellites in their proper orbits. Control segment tracks the GPS satellites, unloads the updated navigational data, and maintains health and status of the satellite constellation (Rao, 2010).

The user segment consists of the GPS receiver equipment (which the user can hold in the hand or mount in a vehicle), which receives the signal from the GPS satellites and uses the transmitted information to calculate three-dimensional position of the user and time (Rao, 2010). In the user segment there are two classes of receivers, military and civilian. The civilian receiver can read the L1 frequency. Military or authorized users with cryptographic equipment, keys, and specially equipped receivers can read the L2 as well the L1 frequency. The combination of the two frequencies greatly increases the accuracy (Grisso *et al.*, 2009b).

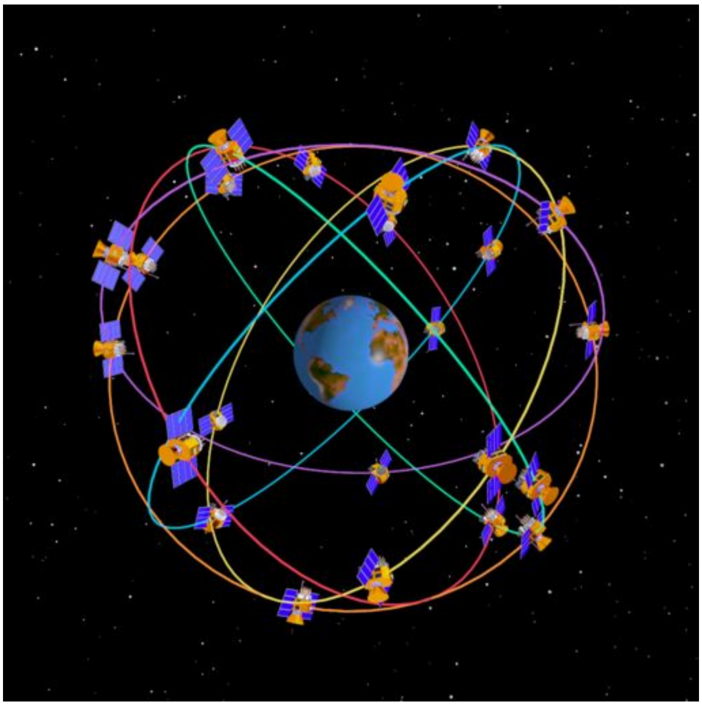

Figure 1.4. Draw of the six GPS orbits contain four or more satellites each (from Dev Track Solution, 2013).

1.2 GLObal orbiting NAvigation Satellite System (GLONASS)

The Global Orbiting Navigation Satellite System (GLONASS) is the Russian counterpart to GPS and differs from GPS in terms of the space segment, the control segment, and the signal structure (Hofmann-Wellenhof *et al.*, 2008). GLONASS is the only alternative to GPS in operations with global coverage and with comparable precision (Cai & Gao, 2013). Development of GLONASS started in the Soviet Union in 1976. Starting from October 12 1982, numerous rocket launches added satellites to the system until the "constellation" was completed in 1995. During the 2000s, to makes the restoration of the system, a top government priority and funding was substantially increased. GLONASS is the most expensive program of the Russian Federal Space Agency, as it consumed a third of its budget in 2010 (Reshetnev Company, 2012).

At the end of 2010, GLONASS had achieved 100% coverage of Russia territory and in October 2011, the full orbital constellation of 24 operational satellites was restored, enabling full global coverage. The GLONASS satellites designs have undergone several upgrades, with the latest version being GLONASS-K (Fig. 1.5) that was inserted into orbit on February 2011 (Reshetnev Company, 2012).

GLONASS satellites provide real time position and velocity determination for military and civilian users. The space segment operates in three orbits, with 8 evenly spaced satellites on each. The orbits are located at 19100 km altitude with a 64.8° inclination and a period of 11.15 h. (Rao, 2010) GLONASS orbit makes it especially suited for usage in high latitudes (north or south), where getting a GPS signal can be problematic (Harvey, 2007).

GLONASS satellites transmit two types of signals: a Standard Precision (SP) signal and an obfuscated High Precision (HP) signal. All satellites transmit the same code as their SP signal. However, each one of them transmits on a different frequency using a 15-channel Frequency Division Multiple Access (FDMA) technique spanning either side from 1602.0 MHz, known as the L1 band. The L2 signals use the same FDMA as the L1 band signals, but transmit straddling 1246 MHz (Rao, 2010).

The control segment is almost entirely located within former Soviet Union territory. The Ground Control Center and Time Standards is located in Moscow and the telemary and tracking stations are in Saint Petersburg, Ternopol, Eniseisk, and Komsomolsk-na-Amure (Rao, 2010).

The main difference between GPS and GLONASS is that in GLONASS each satellite has its own frequencies but the same code, whereas in GPS all satellites use the same frequencies but have different codes: GLONASS uses FDMA method whereas GPS uses CDMA (Rao, 2010). GLONASS orbit are slightly lower than GPS altitudes, so that their orbits repeat every 8 days (Rao, 2010).

GLONASS observations were increasingly integrated into GPS-based PPP since adding GLONASS can help improve the availability of navigation satellites for position determination (Tolman *et al*., 2010). With more and more modernized GLONASS satellites and improved quality of GLONASS precise products, the GLONASS-based PPP is expected to provide comparable performance as GPS based PPP (Cai & Gao, 2013).

Figure 1.5. Draw of the GLONASS-K satellite (from Zoonar GmbH, 2013).

1.3 Galileo

The Galileo system is the third satellite-based navigation system currently under development (Grewal *et al.*, 2013). It provides a highly accurate, guaranteed global positioning service under civilian control (Rao, 2010).

The first Galileo In-Orbit Validation Element (GIOVE) satellites, designed as GIOVE-A, GIOVE-B, were launched in 2005 and 2008, respectively. Two more satellites were launched in October 2011 and started broadcasting in December 2011 (Grewal *et al.*, 2013). Under current planning, the Galileo system is expected to be at least partially operational by 2014 (Rao, 2010).

The main difference between the GPS and Galileo system is that Galileo uses only three orbital planes instead of six, each containing 9 satellites. Each orbit is at an altitude of 23616 km above the earth (Fig. 1.6). The orbits are inclined at an angle of 56° relative to the equator and the orbital period is 14.22 h. The inclination angle of the orbits was chosen to ensure a good coverage of polar latitudes, which are poorly served by the GPS. Galileo transmits signal in 4 frequency bands: E5a, E5b, E6 and L1 and provides 4 types of service compared to GPS (Rao, 2010).

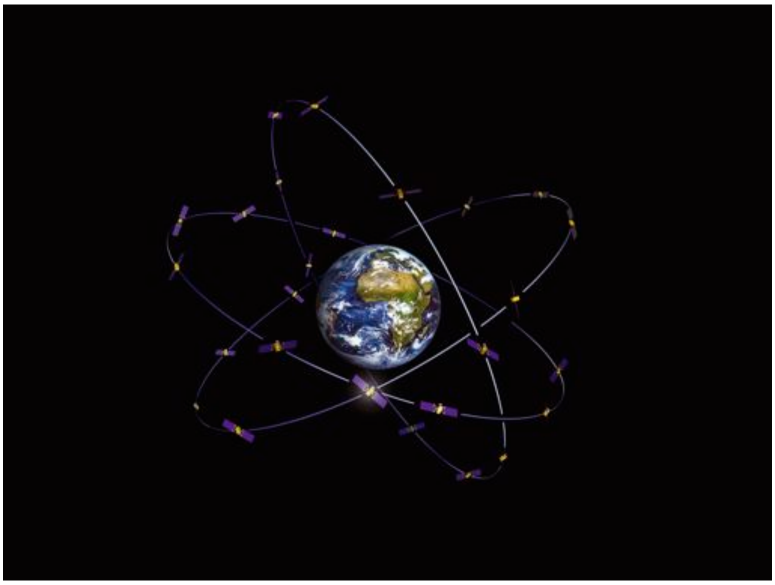

Figure 1.6. Draw of the Galileo constellation contains three orbits with 9 satellites each (ESA image from Gibbons Media & Research LLC, 2013).

1.4 COMPASS (BeiDou-2), Indian Regional Navigation System (IRNSS) and Japanese Quasi Zenith Satellite System (QZSS)

A Chinese system called Compass, which is the evolution of the first-generation regional system BeiDou, is presently under development. The BeiDou Navigation Satellite System is being developed by the People Republic of China (PRC), starting with regional services, and later provisionally expanding to global service (by 2020). There will be two levels of service provided: free service to civilians and licensed service to Chinese government and military users. BeiDou-2 will consist of 35 satellites that will offer complete coverage of the globe. The ranging signals are based on the CDMA principle. Frequencies are allocated in four bands: E1, E2, E5b, and E6 and overlap with Galileo (Grewal *et al.*, 2013).

The Indian Regional Navigational Satellite System (IRNSS) is an autonomous regional satellite navigation system being developed by the Indian Space Research Organisation (ISRO), which would be under complete control of the Indian government. The requirement of such a navigation system is driven by the fact that access to Global Navigation Satellite Systems, GPS, is not guaranteed in hostile situations. The IRNSS would provide two services, with the Standard Positioning Service open for civilian use and the Restricted encrypted Service, available only for authorised users (military). The full system is planned to be realised by 2014 and would consist of a constellation of seven satellites and a support ground segment (Lele, 2013). IRNSS signals will consist of a Special Positioning Service and a Precision Service. Both will be carried on L5 (1176.45 MHz) and S band (2492.08 MHz) (Rizos, 2010).

The Quasi-Zenith Satellite System (QZSS) is a proposed three-satellite regional time transfer system and Satellite Based Augmentation System for the GPS that would be receivable in Japan (Lele, 2013). QZSS can enhance GPS services in two ways: (1) availability enhancement, whereby the availability of GPS signals is improved; (2) performance enhancement whereby the accuracy and reliability of GPS derived navigation solutions is increased (Rizos, 2010).

CHAPTER 2. PRECISION AGRICULTURE TECHNOLOGIES

Precision agriculture, also known as precision farming, site-specific crop management or even site-specific farming (Zhang & Kovacs, 2012) is a farm management strategy, which utilizes precise information and information gathering technology dealing with spatial and temporal variation within a field and then using that information to manage inputs and practices aiming to increase farmers incoming and reduce environmental impact (Grisso *et al*., 2009b,c). Information is a primary requirement and considered as the heart of precision agriculture (Sarkate *et al*., 2013). Precision agriculture is a production system that involves crop management according to field variability and site-specific conditions (Tey & Brindal, 2012). Precision agriculture has the following goals and outcomes: to increase profitability and sustainability, improve product quality, perform effective pest management, energy, water and soil conservation, surface and ground water protection (Grisso *et al*., 2009c). The central concept of precision agriculture is to apply the inputs, what you need, where you need, and when you need, and this can only be done if large amount of geo-refenced data are available to make informed management decision (Perez-Ruiz & Upadhyaya, 2012). Consequently, precision agriculture provides an alternative and realistic means to reduce and optimize the use of potentially harmful compounds and thus can promote a healthier environment for humans beings (Zhang & Kovacs, 2012).

The general stages of precision agriculture practice are data collection, field variability mapping, decision making, and finally management practice (Zhang & Kovacs, 2012). In precision agriculture, the farm field is broken into “management zones” based on soil pH, yield rates, pest infestation, and other factors that affect crop production. Management decisions are based on the requirements of each zone and precision agriculture technologies are used to control zone inputs (Grisso *et al*., 2009c).

Precision agriculture relies on three main elements: information, technology and decision support (management). Timely and accurate information is the most valuable resource of a “modern farmer”. This information should include data on crop characteristics, hybrid responses, soil properties, fertility requirements, weather forecast, weed and pest populations, plant growth responses, harvest yield, post harvest processing, and marketing projections. Precision farmers must find, analyse, and use the available information at each step in the crop system (Grisso *et al*., 2009c).

Precision farmers must assess how new technologies can be adapted to their operations. For example, the personal computer (PC) can be used to effectively organize, analyse, and manage data. Record keeping is easy on a PC and information from past years can be easily accessed. Computer software including spreadsheets, databases, GIS, and other types of application software are available. Another technology that precision farmers use is the global positioning system (GPS). GPS allows producers and agricultural consultants to locate specific field positions. The GIS can be used to create field maps based on GPS position data to record and assess the impact of farm management decisions. Data sensors used to monitor soil properties, crop stress, growth conditions, yields, or post harvest processing are either available or under development. These sensors provide the precision farmer with instant (real-time) information that can be used to adjust or control operational inputs. Precision agriculture uses three general technologies or sets of tools: (1) crop, soil, and positioning sensors (these include both remote and vehicle-mounted "on-the-go" sensors that detect soil texture, soil moisture, crop stress, and disease and weed infestations), (2) machine controls (these are used to guide field equipment and can vary the rate, mix, and location of water, seeds, nutrients, or chemical applications), and (3) computer-based systems (these include GIS maps and databases that use sensors information to "prescribe" specific machine controls) (Grisso *et al*., 2009c). Decision support combines traditional management skills with precision agriculture technologies in order to help precision farmers to make the best management choices or "prescriptions" for their crop production system (Fig. 2.1) (Grisso *et al*., 2009c).

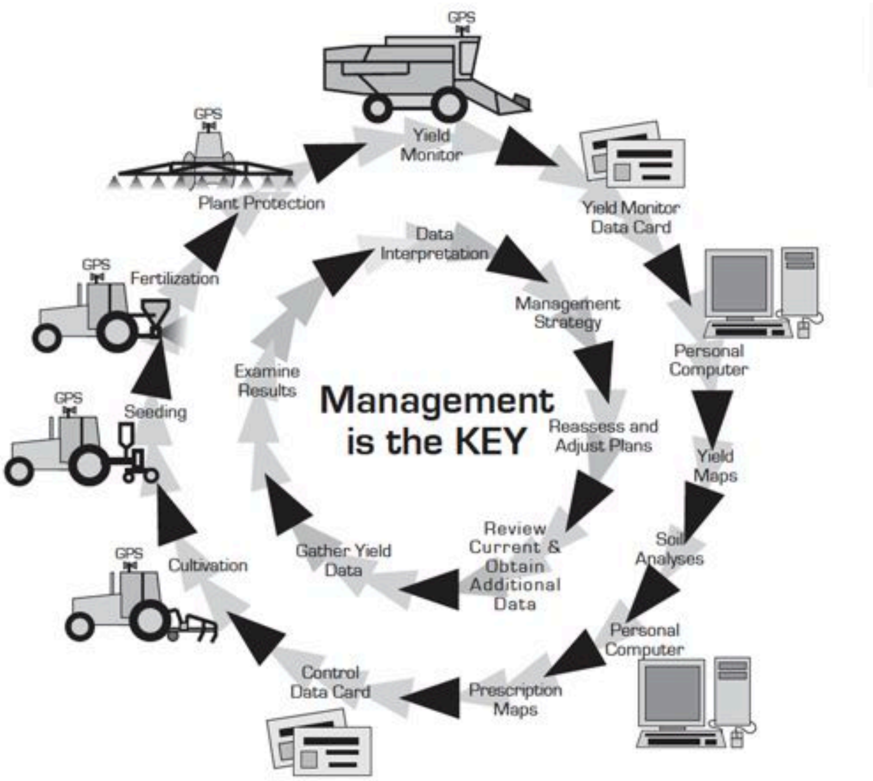

Figure 2.1. The learning cycle with equipment use and technology overlaid. The precision farming technologies provide a means to record and save information for year-to-year comparisons of a location (from Grisso *et al*., 2009c).

Precision agriculture technologies are those technologies which can be used singly or in combination, as the means to realize precision agriculture (Tey & Brindal, 2012). Currently, the available commercial technologies include GPS navigation devices, computer vision, remote sensing and proximal sensors, Geographic Information Systems (GIS), variable-rate applicators and yield monitors (Robertson *et al*., 2012). Since 1980's, to facilitate the adoption of precision agriculture technologies by farmers or appointed third parties, public and private initiatives were fostered within the agricultural industry in Developed Countries. In more recent years, similar efforts started in Developing Countries, including Brazil, China, India, and Uruguay. Such initiatives have largely targeted specific "major" crops (e.g. cotton, maize, sugar cane, wheat, and rice) with the aim to increase their yield in order to obtain relevant economic returns (Tey & Brindal, 2012). A primary goal of farmers using precision agriculture technologies is to increase their income.

Conceptually, this is possible through more cost-effect use of farm inputs (chemicals, fuel, labour and machinery), yield gain and selective harvesting (for quality products) (Chen *et al*., 2009). In the meantime, the results of many studies suggest that precision agriculture technologies have the potential to reduce agriculture caused environmental impact. The improvement of the use of farm inputs according to the needs of the crops, avoids excess applications. For istance, applying only the nitrogen needed by the crops to reach their maximum potential yield could reduce nitrate contamination in groundwater and the pollution of downstream water sources. This is particularly important since agricultural non-point source pollution is a major consideration in the contamination of many of the world waterways. Therefore, while boosting economic efficiency in on-farm activities, precision agriculture technologies offer environmental protection (Tey & Brindal, 2012).
The adoption of precision agriculture technologies by farmers is positively associated with socio-economic factors (farmers who are older and have higher education level), agro-ecological factors (farmers whose farms have better soil quality, are self-owned and large), institutional factors (farmers who face greater pressure for sustainability), informational factors (farmers who hired consultants and agreed on the usefulness of extension services), farmer perception (farmers who perceived that PATs can increase their income), and technological factors (farmers who use computers) (Tey & Brindal, 2012).

2.1 GPS navigation devices

A GPS navigation device is any device that receives GPS signals with the purpose of determining its current location on Earth. GPS devices provide latitude and longitude information. GPS navigation products are distinguished by the compactness of their components and user interfaces, and are used in many types of agricultural operations (Grisso *et al*., 2009a). GPS allows to perform site-specific management of farming practices and resources in an attempt to optimize production efficiency while minimizing environmental costs (Slaughter *et al*., 2008). GPS systems are useful particularly in applying pesticides and fertilizers and tracking wide planters or large grain-harvesting platforms. Navigation systems help operators to reduce skips and overlaps, especially when using methods that rely on visual estimation of swath distance and/or counting rows. This technology reduces the chance of misapplication of agrochemicals and has the potential to safeguard water quality. Again, GPS navigation device can be used to keep implement in the same traffic pattern year-after-year (controlled traffic), thus minimizing soil compaction and trafficability. Crop producers are starting to adopt these systems, because GPS navigation is an excellent way to improve accuracy, speed, and uniformity of application (Grisso *et al*., 2009a).
Proper alignment and installation of the GPS navigation system is required for effective field operation management. Poor quality of the steering-control systems, a sloped terrain, or misaligned implements can cause severe problems in field performance of GPS navigation. A sloped terrain makes control of vehicle dynamics challenging. Roll (tilt from side-to-side), pitch (movement from front-to-rear), and yaw (rotation around the vertical axis) alter the GPS antenna location with the projected centre of the vehicle (Fig. 2.2). For instance, when driving across a slope, the horizontal position of the GPS antenna is

downhill with respect of the centre of the vehicle, and the guidance is in error down the slope (Fig. 2.3). Some systems include gyroscopes, accelerometers, or additional GPS antennas can be used in order to solve this problem. Less advanced terrain-compensation modules deal with only roll and pitch angles of the vehicle, while others can measure total dynamic attitude in six degrees of freedom and enable the system to compensate for variable terrain (Grisso *et al.*, 2009a).

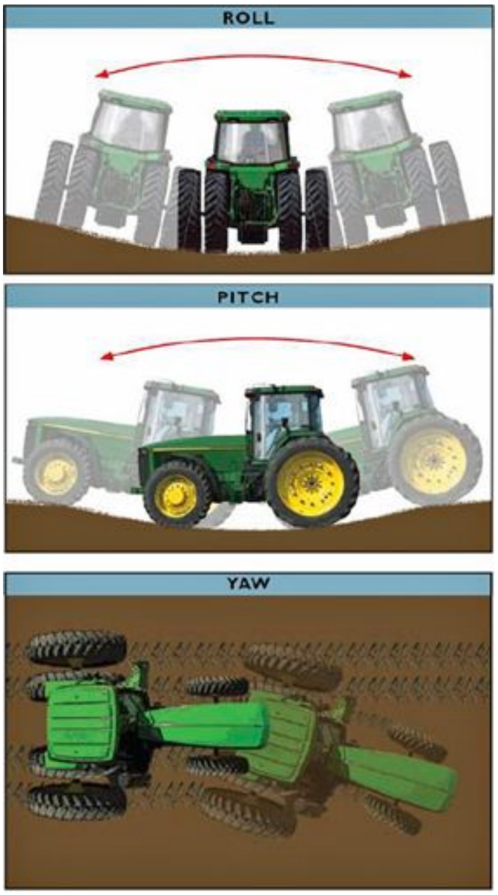

Figure 2.2. Compensation needed based on vehicle orientation and field operation (from Grisso *et al.*, 2009a).

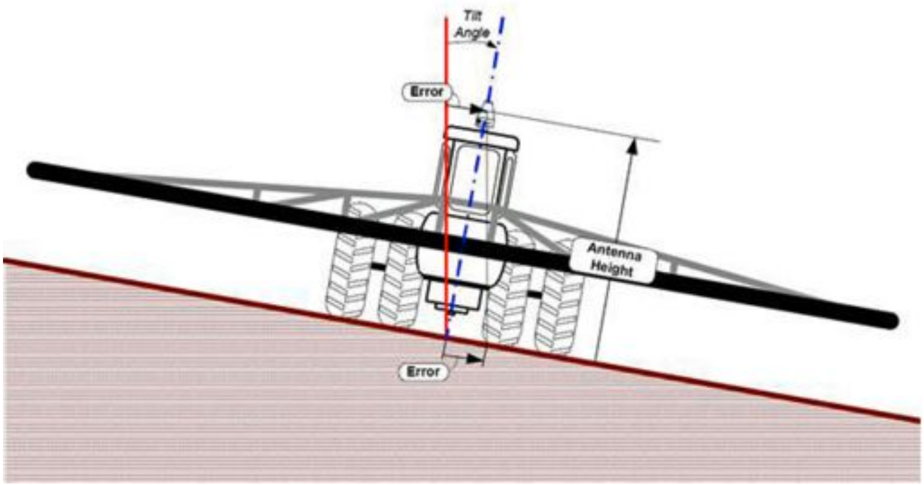

Figure 2.3. Antenna positioning error on sloping terrain (from Grisso *et al.*, 2009a).

2.1.1 Use of GPS navigation device for creating plant maps

RTK-GPS (characterized by errors lower than 0.02 m) can be used to create a plant map by monitoring the seeds or plants while they are being sown or transplanted. Thus, a plant map can be utilized for subsequent agronomical treatments (Perez-Ruiz & Upadhyaya, 2012).

Precise agriculture applications such as yield monitoring, variable rate application, plant mapping, precise weed management, etc. require many sensors to acquire data from the field, but these data can only be linked together through a map by means of the location information provided by the GPS or any other GNSS receiver (Perez-Ruiz & Upadhyaya, 2012).

Ehsani and colleagues developed a planter retrofitted with a RTK-GPS device. The system consists of two microcomputers one of which monitors the seeds using optical sensors (one per row) as they are being planted and records the event along with the time. Moreover, it obtains the RTK-GPS coordinates and records them along with the time tag. The second microcomputer monitors the first microcomputer and displays the planter performance information on a monitor mounted in the cab. The time tag allows to determine the exact location where a given seed was dropped into the ground making easy the creation of a seed planting map. The seed map coordinates obtained mapping corn seeds were within an average distance of 3.4 cm. For weed control applications any plants detected at locations different from those where the crop seed was planted would be classified as weeds (Ehsani *et al.*, 2004).

In a similar study, Griepentrog and colleagues tested a precision seed planting system able to create automatically a seed map of a sugar beet field using RTK-GPS for location sensing and optical seed drop sensors. They observed an average error between the automatically generated GPS seed map and the actual plant location after emergence of about 16-43 mm depending on vehicle speed and seed spacing. Location errors were attributed to lack of accuracy of the RTK-GPS location system, motion of the planter relative to the GPS antenna, motion of seed after passing the optical seed sensors (e.g. seed bounce in the furrow), soil conditions (e.g. clods) that affect a deviation in the emerged plant location relative to the initial seed location (Griepentrog *et al.*, 2005).

Perez-Ruiz & Upadhyaya developed a centimetre-level accuracy plant mapping system for transplanted row crop, which utilized a RTK-GPS mounted on the tractor. When combined with tractor mounted RTK-GPS coordinate data a transplant map can be created by sensing transplant placement during planting with an accuracy of 3.2 cm. Figure 2.4 shows the crop plant locations determined by the automatic GPS mapping transplanter during planting (yellow triangles). The inset photo shows the manual RTK-GPS survey measurements of the plant location obtained during ground truthing. The ground truth points (black circles) were overlaid on the automatically generated map in order to perform a comparison (Perez-Ruiz & Upadhyaya, 2012).

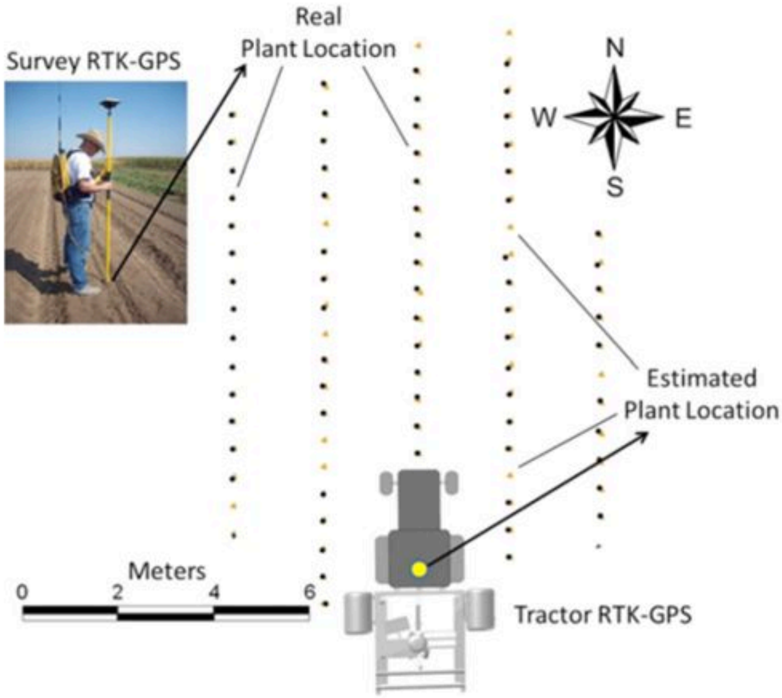

Figure 2.4. Automatically generated crop geoposition map (from Perez-Ruiz & Upadhyaya, 2012).

A major advantage of RTK-GPS mapping technology over machine vision-based methods consists in the independency of the accuracy and precision from the visual appearance of the crop, shadows, missing plants, weed density or other conditions that degrade the performance of machine vision or other plant sensing systems. Moreover, no crop specific knowledge, such as visual texture, biological morphology, or spectral reflectance characteristics, is required for operation. Furthermore, while many weed sensing techniques are severely challenged by visual occlusion or by the change in plant appearance over time, the GPS crop plant map remains valid throughout the crop life cycle and is unaffected by the diversity or quantity of weed species present in the field. (Perez-Ruiz *et al*., 2012).

2.1.2 Use of GPS navigation device in automated guidance of agricultural machines

The definition and realization of automated guidance systems of agricultural machines (tractors, combines, sprayers, spreaders) was carried out for several reasons, the most important of which concerns with the possibility to relieve the operator from continuously making steering adjustments while striving to maintain field equipment or implement performance at an acceptable level (Grisso *et al*., 2009a).
Relatively inexpensive navigation aids known as parallel-tracking devices assist the operators to visualize their position with respect to previous passes and to recognize the need for steering adjustments. These aids are commercially available in several configurations. One system is a lightbar (Fig. 2.5), which consists of a horizontal series of Light Emitting Diodes (LEDs) in a plastic case 30 cm to 46 cm long. This system is linked to a GPS receiver and a microprocessor. The lightbar is usually positioned in front of the operator, so he can see the accuracy indicator display without taking their eyes off the

field. The lightbar can be mounted inside or outside of the cab, and the operator watches the "bar of light." If the light is on the centreline, the machine is on target. If a bar of light extends to the left, the machine is off the path to the left and needs to be corrected. In like manner, if a bar of light extends to the right, the machine is off to the right (Grisso *et al.*, 2009a).

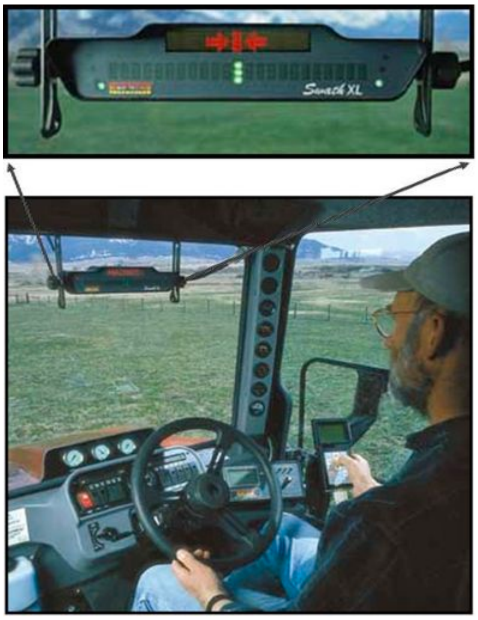

Figure 2.5. Lightbar navigation system mounted in a tractor cab and in view of forward travel (from Grisso *et al.*, 2009a).

More advanced navigation systems (auto-steer systems) have similar capabilities as the parallel-tracking devices and also have the additional option to automatically steer the vehicle. Auto-steering is accomplished with a device mounted to the steering column or through the electro-hydraulic steering system. The accuracy level of these systems is based on the quality of differential correction and internal data processing: as the accuracy improves, the corresponding cost increases (Grisso *et al.*, 2009a).
Auto guidance tractors equipped with RTK-GPS have becoming very popular in recent years. Although these auto guidance systems use cm accuracy RTK-GPS systems, the overall pass-to-pass accuracy of the tractor is expected to be about 2.5 cm (Perez-Ruiz & Upadhyaya, 2012). RTK-GPS auto guidance based system can be used to cultivate or spray very close to the crop row (about 5 cm) at a very high ground speed (up to 11 km h^{-1}) and chisel or subsoiler a field very close to buried drip irrigation tapes without damaging them (Abidine *et al.*, 2004).

2.1.3 Use of GPS navigation device in agrochemicals application

The use of GPS navigation in agrochemicals application with ground equipment has grew rapidly and commercial applicators are quickly adopting the tool (Grisso *et al.*, 2009a). GPS navigation reduces pesticides use by reducing overlaps. For example if a 10% overlap is reduced to 5%, pesticides use also is reduced by 5%. The same is true for fertilizers and

seeds. Thus the use of GPS navigation is really environmental friendly and fully sustainable as it allows to reduce costs (Grisso *et al*., 2009a).
The system can also reduce operator fatigue and anxiety regarding fertilizers and pesticides application. Finally, use of this technology can help to demonstrate to the non-agricultural community that advanced technologies can be used at farm level in order to increase efficiency and safety (Grisso *et al*., 2009a).
Band spraying can reduce inputs with economic and environmental benefits. However, to achieve the full benefit it is necessary to maintain high precision over long periods. RTK-GPS linked with a local base station was used to guide implements and tractors whit the purposes of performing banded treatment and to improving general efficiency (Tillett & Hague, 2006).

2.2 Computer vision

Computational vision is the science responsible for the study and application of methods, which enable computers to understand the content of an image. This interpretation involves the extraction of certain characteristics, which are important for a given aim. A system of visual inspection requires a data input (image) normally obtained by cameras or videos, and the further processing of these data in order to transform them into the desired information (Gomes & Leta, 2012). A theme in the development of computer vision was to duplicate the abilities of human vision by electronically perceiving and understanding an image (Sonka *et al*., 2008).
The use of computer vision is not new to agriculture. Crop disease detection, fruit quality, flower processing, crop area or yield estimation are some areas of agriculture that uses computer vision for processing and analysing related data (Sarkate *et al*., 2013). Actually, agriculture represent one of the main fields of application of computational vision, since in the analysis of a product it is required, a reproduction of human perception with regard to its image, involving the analysis of attributes, such as size, shape, texture, brightness, colour, etc., which directly influence quality assessment (Gomes & Leta, 2012).
Despite systems of visual inspection are organized according to a particular application, typical stages are observed in different computational systems which may be summarized as: image acquisition, pre-processing, segmentation, extraction of characteristics and processing. The stage of image acquisition consists of capturing a real image and transforming it into a digital image using devices such as cameras, scanners, videos, etc. A digital image is a numerical representation of an image that can be computationally processed. Pre-processing is the stage preceding the extraction of characteristics, which aims at improving the acquired image and highlighting the features or regions of interest, thus removing distortions and noise while not adding further information to its content. Pre-processing involves techniques able to highlight regions and details and remove any noise, which may interfere in the analysis of objects and/or regions of interest. In this context, there is a great variety of techniques that allow to highlight the grey scale and colour transformation, as well as thresholding and filtering. This is an important stage in an automatic inspection system. The segmentation process can be based on the similarity of the colour of each pixel and its neigh-boring pixels. Sometimes similar pixels, in terms of

colour, are not part of the same object or feature. The extraction of parameters enables the association between regions of the image and objects in the scene. After these stages, the image should be ready for the extraction of important characteristics. The final stage (processing) aims to recognize and interpret the images, seeking to make sense of the set of objects of the image, with the goal of improving human visualization and automatic perception of data in a computer (Gomes & Leta, 2012).

After the stages of pre-processing and segmentation, the image is ready for the extraction of important characteristics, where it is possible to obtain relevant data on the item to be analysed. The characteristics most commonly extracted are number of objects, dimensions, geometry, luminosity and texture, and they may be grouped into four categories: morphological, chromatic, textural and structural. The morphological characteristics, such as circularity, area, width, etc., consist in measuring the shape of the object that makes up the image, without considering the intensity of the pixels, and it can be calculated on binary images resulting from the processing of colour images.

The chromatic properties describe the colour or the spectral composition of the radiation emitted or reflected from objects, quantified by the intensity of pixels in different spectral bands. The textural characteristics consist in the measure of the local variability of the intensities of pixels. The structural or contextual characteristics describe the relationship between one or more objects that make up the image (Gomes & Leta, 2012).

Machine vision applications in agriculture can be categorized in the three following areas: non-destructive measurement, visual navigation, and behavioural surveillance (Ji *et al*., 2009). According to the increase of knowledge in research and development and the availability of inexpensive and fast hardware, automatic machine vision systems became promising solutions in the quality evaluation and classification of plants (Mebatsion *et al*., 2013).

A variable field-of-view machine vision based guidance system was developed by Xue and colleagues to navigate a robot through maize rows. Three field of view arrangements were tested being near field-of-view, far field-of-view and lateral field-of-view. Morphological operations were used to calculate guidance lines in the field, and a fuzzy logic control scheme was used to guide the robot. RTK-GPS data were used to evaluate the guidance performance. The results showed that the far field-of-view guidance method had the best performance with an average error of 1 mm and a standard deviation of 7.1 mm. The near field-of-view guidance had the poorest performance with an average absolute error of 3.9 mm and a standard deviation of 7.5 mm. Overall, the three methods had acceptable accuracy since the worst-case guidance error was 15.8 mm, and no plants were touched or run over during the tests. The results show that the method developed is capable of guiding a robot through a maize field, with acceptable accuracy and stability and without damaging the crop (Xue *et al*., 2012). In recent years, numerous studies have used machine vision techniques to detect and identify plant species (either crops or weeds) based on their shape, colour and texture (Slaughter *et al*., 2008).

2.3 Remote sensing

Remote sensing is the subject of study associated with the extraction of information about an object without coming in physical contact with it (Schott, 2007). There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive sensors detect natural radiation that is emitted or reflected by the object or surrounding areas. Reflected sunlight is the most common source of radiation measured by passive sensors. Examples of passive remote sensors include film photography, infrared, charge-coupled devices, and radiometers. Active sensors, on the other hand, emit energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target (Kuman, 2005). Remote sensing uses satellites and aerial imagery from low flying aircraft for acquiring data (Inman *et al*., 2008). Nowadays, several unmanned platforms, near-range-airborne and satellite-based remote sensing systems with different temporal, spatial and also spectral resolution are available for data acquisition (Voss *et al*., 2010).

Precision crop protection requires spatially explicit information on the within-field heterogeneity of crop growth conditions at particular times. Remote sensing offers the possibility to identify these heterogeneities with comparatively small expenditure (Voss *et al*., 2010). Remote sensing could be involved in the data collection, field variability mapping and decision making of precision agriculture practice (Zhang & Kovacs, 2013). General agricultural applications using remote sensing include soil properties monitoring and mapping, crop species classification, crop pest management, plant water stress detection, leaf chemical content analysis and weed control monitoring (Zhang & Kovacs, 2013). Environmental remote sensing essentially makes use of radiant energy to extract information on ground features along large swath areas within a short period of time. Remote sensing, along with other geospatial techniques, was applied in agriculture since the 1950s. Remote sensing applications in precision agriculture are based upon the detection of the differences in crop growth and soil conditions by means of the variations within the spectral responses (i.e. changes in remotely sensed reflectance can be detected before symptoms such as fungal and mildew leaf infections become visible to the human eye) (Zhang & Kovacs, 2013).

2.3.1 Unmanned Aerial Systems (UAS)

Recent technological advances in aerospace engineering allow to develop the Low Altitude Remote Sensing (LARS) system, a relatively new concept of acquiring Earth surface images at a low altitude using unmanned aerial systems (UAS) (Swain *et al*., 2007), that was promoted as an alternative platform to common remote sensing ones. The ultra-high spatial resolution (e.g. centimetres), relatively low operational costs, and the near real-time image acquisition (Xiang & Tian, 2011) would indicate that these platforms are ideal technologies for mapping and monitoring in precision agriculture (Zhang & Kovacs, 2012).

Common remote sensing platforms include satellites, airplanes, balloons and helicopters equipped with a variety of sensors such as optical and near infrared sensors and RADAR.

Diagnostic information derived from images collected from these on-board sensors, such as biomass, Leaf Area Index (LAI), disease, water stress and lodging, can thus assist in crop management, yield forecasting, and environmental protection (Zhang & Kovacs, 2012).

In comparison with satellite imagery, UAS acquired images are characterized by higher temporal and spatial resolutions, which makes it necessary to examine the application of high-resolution images in precision agriculture (Zhang & Kovacs, 2012). Moreover, UAS could be an inexpensive and more practical substitute for satellite and general aviation aircraft for high resolution remotely sensed data (Zhang & Kovacs, 2012).

In recent years, small commercial UAS (<50 kg) (Laliberte & Rango, 2011) were available for environmental and agricultural applications (Zhang & Kovacs, 2012). Many applications use small unmanned aircrafts, unmanned helicopters, powered gliders, power parachute and quadrocopters (Fig. 2.6). These platforms include assembled units from off-the-self parts (Xiang & Tian, 2011) or complete commercially available ones (Laliberte & Rango, 2011).

Figure 2.6. Examples of UAS currently used in environmental studies include (A) powered glider, (B) powered parachute, (C) helicopter, (D) fixed wing aircraft, (E) Draganflyer X8 quadrocopter, and (F) Aeryon Scout quadrocopter (from Zhang & Kovacs, 2012).

In addition to the variety of platforms available, there are numerous types of remotely sensed sensors that can be used for the actual data collection. Sensors for image capture include film cameras, off-the-shelf commercial grade (non-metric) digital cameras and even modified digital cameras with a near infrared band (Zhang & Kovacs, 2012).

GPS/INS data on-board the UAS and a ground control station with a flight planning system are needed in order to obtain images for further georeferencing and/or mosaic or images for predefined points. (Laliberte & Rango 2011; Xiang & Tian, 2011). GPS/INS is the use of GPS satellite signals to correct or calibrate a solution from an Inertial Navigation System (INS). Images captured can thus be transmitted to the ground station or stored in the unit sensor memory until the vehicle landed. There are also navigation and flight control components for the newer generation of UAS (Laliberte & Rango, 2011, Xiang & Tian, 2011). The navigation component is used to control the flight path of the UAS and to monitor and/or correct the flight status (position and orientation) of the platform. The flight control component is used to maintain the stability of the platform in order to make sure that the position of the platform is optimal for image acquisition (Xiang & Tian, 2011). The ground station provides a user interface that incorporates flight planning, flight control and/or image acquisition (Xiang & Tian, 2011) (Fig. 2.7).

Figure 2.7. Examples of UAS control stations: (A) the command station for the Aeryon Scout UAS, (B) controller for the Draganflyer X8 UAS (from Zhang & Kovacs, 2012).

UAS acquired images were successfully employed for estimating the degree and extent of shrub utilization, mapping grass species, mapping forest fires, measuring shrub biomass, aiding in vineyard management and mapping rangeland vegetation. Moreover, they were used for detecting small weed patches in rangelands, documenting water stress in crops, monitoring crop biomass, mapping vineyard vigour and examining the results of various nitrogen treatments on crops. UAS were also used to assess irrigation systems at the field scale. The crop types examined using UAS-collected data include rice, wheat, maize, turf grass and even coffee. Furthermore, UAS were used to sample pollen, spore, and agricultural disease agents (Zhang & Kovacs, 2012).

Successful applications of UAS supported image capture could shorten the time frame needed for agricultural practice adjustment. The results of this remote sensing monitoring could exceed those obtained with traditional control treatments (Beeri & Peled, 2009). Although there are already a variety of UAS applications, problems still exist in platform reliability, sensor capability, image processing, and final products dissemination (Zhang & Kovacs, 2012).

As pointed out by Hardin, Jensen, Laliberte and Rango, aviation rules could be one of the most important impediments to the adoption of UAS in environmental and agricultural applications (Hardin & Jensen, 2011; Laliberte & Rango, 2011). In many countries these rules are quite loose such as in Germany where no permission is required for UAS with less than 5 kg overall mass and flight site 1.5 km away from residential areas and airfields (Aber *et al*., 2010). However, in the USA a Certificate of Authorization (COA) is required as well as a large ground team during operation. Similarly, in Canada a Special Flight

Operations Certificate (SFOC) is required on an annual basis and a certain level of UAS training is highly recommended. As part of the certificate, insurance is required in the case of failure of the platform, which may cause damage to humans, livestock or buildings. These types of requirements are seen as the largest obstacle for the application of UAS in environmental studies (Hardin & Jensen, 2011). Moreover, other rules affect the actual operation of the UAS. For example, in Canada and the USA, the UAS must always be in the view of the operator. Again, in the USA, a pilot license is required. Consequently a flying team is needed during operations increasing the cost of UAS operation (Rango & Laliberte, 2010). The flying height regulations also limit the spatial resolution and swath area of these images. The maximum altitude for UAS in Canada is 120 m, even though 640 m is reported to be the minimum height in avoiding major impacts from turbulence. It is believed that such aviation rules need to be relaxed in order to allow that the use of UAS in environmental monitoring is successful (Rango & Laliberte, 2010).

2.4 Proximal sensors

Crop, soil, and positioning sensors, in addiction to remote sensing, include proximal sensors (ground-based sensors and cameras) that detect soil texture, soil moisture, crop stress and disease and weed infestations (Grisso *et al*., 2009c). Proximal sensing, which uses near-range sensors, recently received increased attention. Many different types of proximal sensors are actually available (De Benedetto *et al*., 2013). On-the-go sensors refer to those proximal sensing technologies used to collet data while moving across a landscape. An on-the-go sensor to measure key soil properties based on visible and near infrared spectroscopy is an example. A key benefit of such on-the-go sensors is mapping the spatial variation is soil and crop at field/subfield scale as a valuable input for decision support. A variety of on-the-go instruments are available to measure essential parameters on soil and crop (Peets *et al*., 2012).
Some proximal sensor systems can be operated in a stationary field position and used to: make a single site measurement, produce a set of measurements related to different depths at a given site, or monitor changes in soil properties when installed at a site for a period of time. Although single site measurements can be beneficial for a variety of applications, high-resolution thematic soil maps are typically obtained when measurements are conducted while the sensor systems are moved across the landscape. These on-the-go proximal soil sensing technologies have became a multidisciplinary subject of research and their development provides essential tools for precision agriculture (Viscarra Rossel *et al*., 2011). Proximal crop sensors have been used to determine such physiological parameters as biomass, chlorophyll content, height, etc. that indicate a spatially non-consistent status of agricultural crops, such as nitrogen deficiency or water stress (Samborski *et al*., 2009). Sensors that measure a variety of essential soil properties on-the-go can be used to control variable rate application equipment in real-time or in conjunction with GPS devices to generate field maps of particular soil properties (Adamchuck & Jasa, 2002).

2.4.1 Electromagnetic sensors

Electromagnetic sensors use electric circuits to measure the capability for soil particles to conduct or accumulate electrical charge. When using these sensors, the soil becomes part of an electromagnetic circuit, and changing local conditions immediately affect the signal recorded by data logger. Soil texture, salinity, organic matter, and moisture content influence electromagnetic soil properties. In some cases, other soil properties such residual nitrates or soil pH can be predicted using these sensors (Adamchuck & Jasa, 2002).
A commercially available electromagnetic sensor is the Veris®EC Probe (Fig. 2.8) that measures electrical conductivity using a set of coulter electrodes that send out an electrical signal through the soil. The signal is received by two sets of electrode coulters that measure voltage drop due to the resistivity of the soil, indicating electrical conductivity of two depth ranges (Adamchuck & Jasa, 2002).

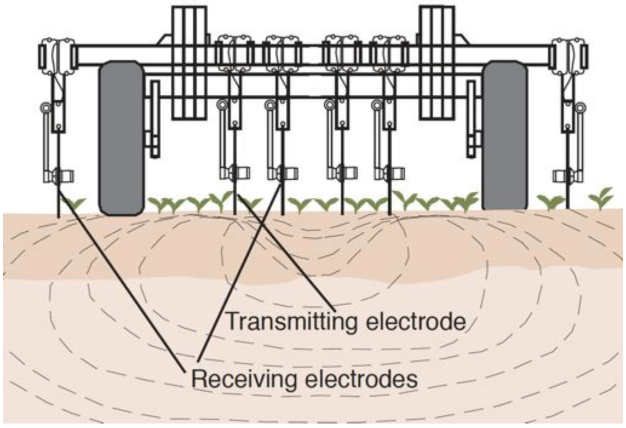

Figure 2.8. Veris®EC Probe electrical conductively mapping system (from Adamchuck & Jasa, 2002).

2.4.2 Optical and optoelectronic sensors

Optical sensors use reflectance spectroscopy to detect the level of energy absorbed/reflected by soil particles and nutrient ions (Kim *et al.*, 2009). These sensors can simulate the human eye when looking at soil as well as measure near-infrared, mid-infrared, or polarized light reflectance. Vehicle-based optical sensors use the same principle technique as remote sensing (Adamchuck & Jasa, 2002).
Optoelectronic sensors combine optical and electronic systems. The basic type of optoelectronic sensor combines light-conducting fibers with spectrophotometry, fluorimetry, or reflecrometry. It is capable of indicating changes of optical parameters, such as light absorption, wavelength, or refraction index, in that part of the measuring medium immediately surrounding the fiber. These devices incorporate either a single or a dual optical fiber bundle the incident light and the light beam to be measured (Scheller & Schubert, 1992).
The inability of non-imaging of optoelectronic sensors to discriminate plant species, including weed/crop discrimination, limits their application for site-specific weed management. Nevertheless, promising results with optoelectronic sensors specially designed for wheat at row spacing 0.25 m (Wang *et al.*, 2007) or monitoring restricted to the inter-rows have been reported (Dammer & Wartenberg, 2007). The non-specific

information generated by this type of sensor may be useful for indicating areas at high risk of weed infestation (Andujar *et al.*, 2011b).
Close-range, subsurface, vehicle-based optical sensors (Fig. 2.9) have the potential to be used on-the-go and can provide more information about single data points since reflectance can be easily measured in more than one portion of the spectrum at a time (Adamchuck & Jasa, 2002).

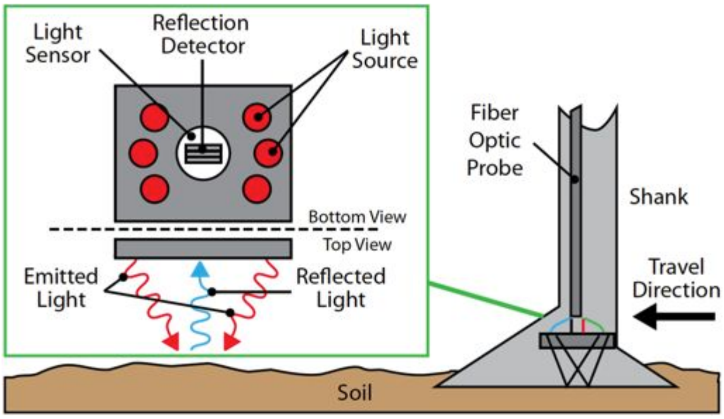

Figure 2.9. Cross-section schematic of a subsurface, soil-reflectance optical sensor to measure soil organic matter (from Adamchuck & Jasa, 2002).

Many authors reported high correlations between reflectance techniques and standard methods when using diffuse reflectance spectroscopy in conjunction with various calibration and signal processing methods to estimate soil physical properties (Kim *et al.*, 2009).
Optical sensors were used in the past to map and/or spray weed patches present in fallow sites and in various wide-row crops (Andujar *et al.*, 2011b). The use of reflectance data of bare ground contrasted with green weeds growing between crop rows, allows some sprayers to switch the application device on and off. One example of a commercial unit is the WeedSeeker® system, which has a reflectance sensor that identifies chlorophyll. The microprocessor interprets that data and when a threshold signal is crossed in presence of weeds, a controller turns on the spray nozzle. The WeedSeeker® system is built around close-proximity optical sensors using near-infrared and light-reflectance measurements to distinguish between green vegetation, bare soil, and crop residue. Each sensor unit consist of a light source and an optical sensor (Fig. 2.10) The sensors are mounted on a bar or spray boom ahead of the spray nozzle and aimed at the ground. When a chlorophyll "green" reflectance signal exceeds a threshold (set during calibration by the operator), a signal is sent from a controller to a solenoid-operated valve to release herbicide. The system is designed to turn on slightly before a weed is reached and stay on until slightly after a weed is passed. In areas where weed infestation levels are variable, the unit can significantly reduce chemical application amounts (compared to uniform, continuous applications). As the WeedSeeker® sensor is not design to distinguish between plant types (weed/crop discrimination), its agricultural use is focused on between-the-row applications in standing crops or on-spot treatment of fallow ground (Grisso *et al.*, 2011).

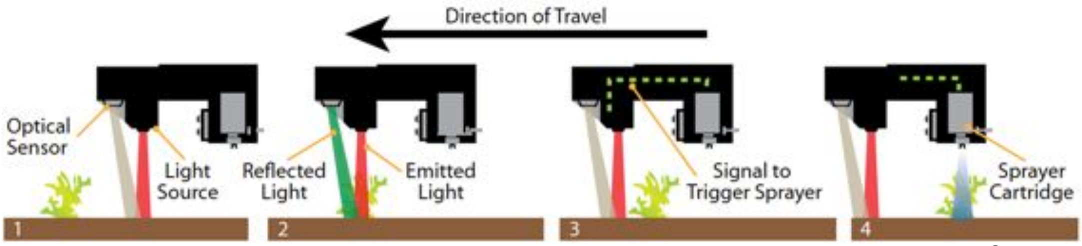

Figure 2.10. The optical sensor control of the spray nozzle (from WeedSeeker®, 2013).

The sensors of the commercial system WEEDit® have an active red light source that continually shines on the ground. When red light pass over live plants their chlorophyll absorbs some of the red light, converts and emits it as Near Infra Red light (NIR) (Fig. 2.11). The WEEDit® sensors are continually on the hunt for presence of NIR, looking at the ground 40,000 times per second. They are very prominent in the case of spraying at night (WeedSeeker® and WEEDit®, 2013).

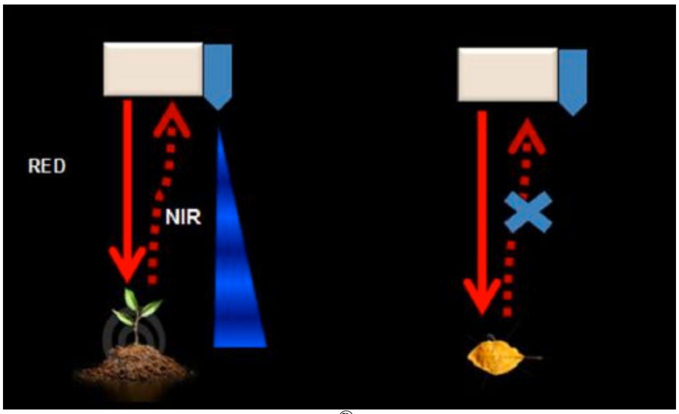

Figure 2.11. Scheme of how WEEDit® sensors work (from WEEDit, 2013).

Although these kind of sensors are not able to differentiate weed species from crops, this does not represent a major problem if the sensor is operated only in the inter-row area and the infested areas are treated with broad-spectrum contact action herbicides. However, the lack of discrimination power and the relatively high cost of these sensors are serious deterrents to wider acceptance (Andujar *et al*., 2011a).
OptRx crop sensors (AgLeader Technology, 2013) measure and record data about crops in real-time using the reflectance of light shined on the growing plants. Sensors can be mounted on any type of vehicle to collect information while driving through the field. The data are logged and mapped, and be used in further analysis or for real-time variable rate applications. The OptRx crop sensor helps growers to apply nitrogen according to crop vigour. The OptRx crop sensors, in combination with the INTEGRA display (AgLeader Technology, 2013) can be used to improve the application of agrochemicals (fertilizers, herbicides, etc.) to any crop that needs a variable rate. Working with an agronomist or crop consultant, farmers can select a Vegetative Index range and assign the recommended rates based on the range chosen. OptRx's patent-pending advanced light-sensing technology is not dependent on ambient light, offering maximum flexibility to be used at day or night time (AgLeader Technology, 2013).

The Yara N-Sensor® determines the crop nitrogen demand by measuring its light reflectance. Yara N-Sensor® is mounted on the tractor roof and is "on the move" measuring light reflectance from the crop, translating this into an optimum application rate. Thus, Yara N-Sensor® can measure the crop, translate the data into an application rate and send a signal to the spreader or sprayer rate controller, which will adjust the levels of application. The average application rate is always determined by the operator (Yara, 2013).

2.4.3 Mechanical sensors

Mechanical sensors can be used to estimate soil mechanical resistance (often related to compaction). These sensors use a mechanism that penetrates or cuts through the soil and records the force measured by strain gauges or load cells (Fig. 2.12) (Adamchuck & Jasa, 2002).

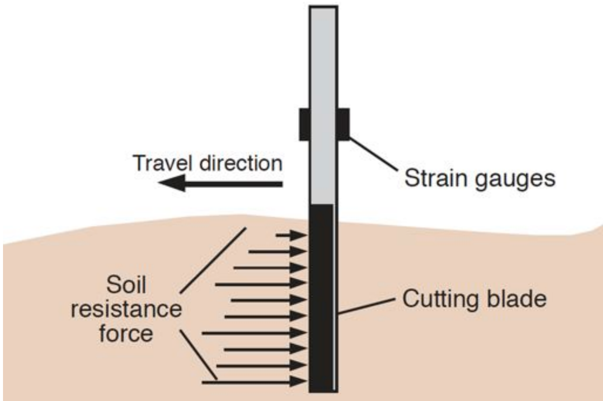

Figure 2.12. An example of a soil mechanical resistance measurement device (from Adamchuck & Jasa, 2002).

Andrade-Sanchez and colleagues developed a compaction profile sensor capable of getting soil cutting resistance data over the depth profile of 7.5 to 45.7 cm below the surface using a set of five force transducers (that converts a load acting on them into an analog electrical signal). This sensor consists of an instrumented shank, a data acquisition system and a GPS receiver. The instrumented blade has a thickness of 29 mm. The sensor is attached to a frame that is mounted on the 3-point hitch of a tractor and pulled through the field engaging the soil in a way similar to a commercial ripper shank. The active cutting elements are directly connected to the transducers and can measure cutting resistance of soil directly ahead of the cutting elements (Andrade-Sanchez *et al.*, 2008).

2.4.4 Electrochemical sensors

Electrochemical sensors can provide information about soil nutrient and pH. Some measurements (i.e. determination of pH) are performed using an ion-selective electrode (with grass or polymer membrane or ion sensitive field effect transistor). These electrodes detect the activity of specific ions (nitrate, potassium, or hydrogen in case of pH) (Adamchuck & Jasa, 2002).

The best results for sensing nitrate in soils were obtained with PVC ion-selective membranes prepared with quaternary ammonium compounds, such as TDDA or MTDA as the sensing element for nitrate. These membranes were able to determine nitrate across the concentration range important for N fertilizer application management, i.e. 10-30 mg kg^{-1} NO_3 (Kim *et al.*, 2009). Ion-selective membranes prepared with valinomycin as an ionophore, has been the most commonly used ionophore for sensing potassium due to its remarkable K sensitivity and selectivity. Furthermore, with the high sensitivity of valinomycin-based membranes to potassium in soil extracts and their lifetimes of more than one month it seems reasonable that a K-ion sensor based on valinomycin would have high potential for commercialization (Kim *et al.*, 2009). Phosphate sensors can be mainly classified into three types: polymer membranes based on organotin, cyclic polyamine, or uranyl salophene derivative; protein-based biosensors; and cobalt-based electrodes. The solid cobalt electrode demonstrated to have sufficient sensitivity, selectivity and durability in order to provide a quantitative measure of phosphates in soil extracts (Kim *et al.*, 2009).

2.4.5 Airflow sensors

Airflow sensors were used to measure soil air permeability on-the-go. The pressure required to squeeze a given volume of air into the soil at fixed depth was compared to several soil properties (Adamchuck & Jasa, 2002).

2.4.6 Acoustic sensors

Acoustic sensors have been investigated to determine soil texture by measuring the change in noise level due to the interaction of a tool with soil particles. A low signal-to-noise ratio did not allow this technology to develop (Adamchuck & Jasa, 2002).

2.4.7 Ultrasonic sensors

Ultrasonic sensors provide an estimation of the distance from the sensor to the first obstacle, generating an echo according to the time-of-flight method (Andujar *et al.*, 2011a). Ultrasonic sensors were used in crop production since late 80s aiming measure tree canopy volume and, subsequently, to control sprayer for saving chemicals (Lee *et al.*, 2010). Sonar technologies could also describe weed geometry and discriminate different weed species (Andujar *et al.*, 2011a).
A boom-height control device by ultrasonic sensors (Fig. 2.13) is able to improve proper coverage from a spray boom, eliminating streaks and improper overlaps. The ultrasonic sensors measure the distance to the ground. This information allows the control system to make responsive height adjustments so that sprayer booms automatically follow the contours of the land (Grisso *et al.*, 2011). Standard ultrasonic sensors are robust and relatively cheap, compared with other sensors. However, their performance is affected by the target to be detected (Escolà *et al.*, 2011).

Figure 2.13. Spray-boom control device used in order to eliminate streaks and improper overlaps (from Norac, 2013).

2.5 GIS (Geographic Information System)

The Association for geographic information defines Geographic Information System (GIS) as a system for capturing, storing, checking, integrating, manipulating, analysing, and displaying data, which are spatially referenced to the Earth. A GIS can also more simply defined as a computer-based approach to interpret maps and images and apply them to problem solving (Kuman, 2005). A GIS basically consist of four main components: geographic data, human knowledge and experience, hardware and map software. The interaction of these components enables to produce, analyse and present the information around the Earth with the aid of digital technology. In other words, a GIS is a collection of map systems, geographic data, routines and human knowledge and experience that makes possible to produce, analyse and present the geography around us with the aid of digital technology (Grinderud *et al*., 2009).

GIS technologies are the most important of the technologies in precision agriculture for the management and handling of spatial data. They are described by Srinivasan as “geospatial information and communication technologies” (Srinivasan, 2006). Remote sensing (satellite, aerial imagery) and proximal sensing data (soil, crop parameter) are collected and must be georeferenced. For this purpose, GNSS receivers are used. Via the communication component, these spatial data flow into the GIS component for further analyses in which additional geodata from official sources (e.g. digital evaluation model, topographic data), can be integrated in the system (Bareth & Doluschitz, 2010). Spatial data are the most valuable component for GIS and they need to be considered also in a cost-benefit context (Torez, 2009). The core data for precision agriculture are management data, yield maps, nutrient maps, rating surveys, soil maps, weather data, sensing data, cadastral maps, digital elevation model and topographic maps (Bareth & Doluschitz, 2010). GIS are used to combine and analyse the information of different sensors and help to develop new approaches as well as they become more and more an integral part of the instruments on the field. The information can be used to reduce the amount of herbicide and to improve the management decisions at a sub-field level (Weis *et al*., 2008).

Management data are usually generated by the farmers and are highly depending on agronomy aspects. Important issues are the type of management (e.g. weeding), time (e.g. sowing date), amount (e.g. fertilizer application rate), crop rotation, etc. Usually the data are stored for control and documentation, supporting management improvement strategies. For the application of fertilizer and chemicals for crop protection, rating data are required. Ratings include weeds, plant diseases, and plant vitality and are carried out by the farmer or extension specialists. The results answer to questions as where the treatments are to carry out and what a.i. dose have to be used. Ratings provide spatial data of within-field variability. Further data collected in the farm domain are yield maps. Nowadays, yield maps are created by combined harvesters in real time during harvest and are available directly after harvest for spatial analysis. Besides amount per unit, water content and ingredients are detected. Yield maps are closely connected to nutrition maps. These latter are required to analyse reasons for spatial yield variability and to spatially adjust respective fertilizer applications. Besides plant nutrition contents, available spatial data of soil nutrients are important. Extension services can provide such data and usually do this for soil nitrogen content. In this context, soil maps are important and are available from soil surveying companies. Large-scale data provide soil horizons, clay content, soil texture, pH, etc. Various spatial data are collected by remote and proximal sensing. Obviously all these data are extremely heterogeneous in terms of format, spatial and time scales, sources and authors, etc. Thus, the only way to use all these types of spatial information in the process of precision agriculture is to apply defined data standards, services, and interfaces (e.g. OGC standards, agro XML) (Bareth & Doluschitz, 2010).

Many of the digital spatial data stored in a GIS are derived from external sources, such as analogue maps, ground surveys, global positioning system (GPS) and, last but not least, remote sensing. Furthermore, remote sensing, in the form of aerial photographs, is also the predominant resource for producing many of the topographic compilations from environmental indicators. As a matter of fact, elevation, hydrology and land cover, are digitized into sharp vector boundaries and entered into GIS (Mesev *et al*., 2007). Remotely sensed image data, especially from satellites, can be used to generate current, accurate and synoptic information about all parts of the Earth as a basis for geoscientific analysis in GIS. Consequently, almost all major GIS software packages now offer at least the possibility to display and query digital images as part of their GIS database. With the advent of the new satellites of 1 m spatial resolution or even better, we will reach a higher level another push for the integration of remote sensing images into GIS. Integration is restricted to mere georeferencing and image overlay. A complete analysis from a remotely sensed image to a geo-object can be performed only by manual interpretation. GIS and remote sensing information is usually processed separately. The ideal goal should be that GIS objects could be extracted from a remote sensing image to update the GIS database. In return, GIS "intelligence" (e.g. object and analysis models) should be used to automate this object extraction process (Fig 2.14). Nevertheless, the current status can still be described primarily as data exchange between a GIS and an image analysis system or an add-on of some image processing functionally to a separate GIS (Ehlers *et al*., 2007).

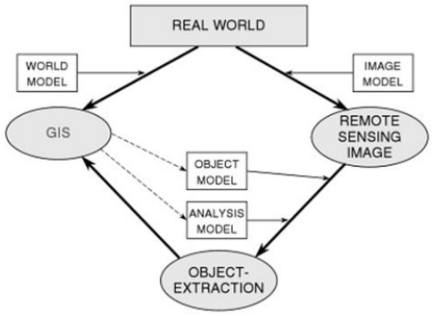

Figure 2.14. Concept for automatic extraction of GIS objects from remote sensing imagery (from Ehlers, 2007).

2.6 Variable-Rate Application (VRA)

Variable rate application (VRA) or variable rate technology (VRT) are synonyms used to define a technique that allows to vary the application rate of agricultural inputs according to heterogeneous features like soil properties or plant density. The range of application covers the whole area of plant production like sowing, fertilization, irrigation and plant protection. Adequate sensors are needed to obtain spatial information about a field, like soil parameters, estimated crop yield, weed density or weed flora composition. Collected data are used to control the application rate of agricultural machinery like planters, spreaders or sprayers (Sökefeld, 2010).

The goals of VRA are to maximize profit to its fullest potential, optimize input application, and ensure sustainability and environmental safety. VRA increases economic return by strategically optimizing inputs in each management zone. VRA allows focusing inputs on management zones that provide the highest return, while reducing inputs in lower productivity zones or where previous management showed a reduced input need. Many farmers practiced a form of VRA with a conventional sprayer. A conventional sprayer applies a chemical that is tank-mixed with a carrier (usually water) using spray nozzles and a pressure-regulating valve to provide a desired volumetric application of spray mix at a certain machine speed (Grisso *et al*., 2011). Any change in the boom pressure or machine speed from that of the calibration results in an application rate different from the planned one. Applicators can use these changes to their advantage at times. For example, when observing an area of heavy weed infestation, the applicator can manually increase the pressure or reduce the speed to apply a higher (but somewhat unknown) rate of herbicide (Grisso *et al*., 2011).

The two basic technologies for VRA are: map-based and sensor-based. Map-based VRA adjusts the application rate based on a prescription map (an electronic data file containing specific information about input rates to be applied in every zone of a field). Using the field position derived from a GPS receiver and a prescription map of desired rates, the concentration of input is changed as the applicator moves in the field. Sensor-based VRA requires no map or positioning system. In this case, sensors on the applicator measure soil properties or crop characteristics "on the go." A control system calculates the input needs of the soil or plants on the base of the information given by sensors and transfers the information to a controller, which delivers the input (Grisso *et al*., 2011).

Because map-based and sensor-based VRA have unique benefits and limitations, some site-specific crop management systems were developed in order to take advantage of the benefits of both methods. The sensor-based VRA method does not need the use of a positioning system and extensive data analysis before performing variable-rate applications. However, if the sensor data are recorded and geo-referenced, the information can be used in future site-specific crop management exercises for creating a prescription map for other operations, as well as to provide an "as applied" application record for the grower (Grisso *et al*., 2011).

2.6.1 Map-based VRA

The map-based method uses maps of previously measured items and can be implemented by means of different strategies. Crop producers and consultants defined strategies for varying inputs based on: soil type, soil texture, topography, crop yield, field scouting data, remotely sensed images, and numerous other information sources that can be crop- and location-specific. Some strategies are based on a single information source while others involve a combination of sources. Regardless of the actual strategy, the user is ultimately able to control the application rate. These systems must have the ability to determine machine location within the field and relate the position to a desired application rate by "reading" the prescription map. For example, to develop a prescription map for nutrient VRA in a particular field, the map-based method could include the following steps: perform systematic soil sampling (and lab analysis) for the field; generate site-specific maps of the soil nutrient properties of interest; use an algorithm to develop a site-specific nutrient prescription map; use the prescription map to control a dispenser of fertilizers VRA (Grisso *et al*., 2011).
A positioning system is used during the sampling and application steps to record location of the sampling points in the field and to apply the prescribed nutrient rates in the appropriate areas of the field (Grisso *et al*., 2011).

2.6.2 Sensor-based VRA

The sensor-based method provides the capability to vary the application rate of inputs with no prior mapping or data collection involved. Real-time sensors measure the desired properties, usually soil properties or crop characteristics, while on-the-go. Measurements made by such a system are then processed and used immediately to control a variable-rate applicator (Grisso *et al*., 2011).
Because on-site, rapid measurements of soil nutrients are an ideal approach to variable-rate application, beginning in the early 1990s, have reported on real-time on-the-go soil nutrient sensing using custom-designed soil samplers and commercially available ion-selective electrodes for sensing nitrate and pH soils (Kim *et al*., 2009).

2.6.3 Planting VRA

Variable rate planting is based on the adaptation of planting rate to the potential yield. Reduced populations should be established in zones with lower potential yield. Higher rates are recommended for sites with potential high-yield with high soil-fertility levels and water-holding capacity. Variability in topsoil, which can be estimated by soil electrical conductivity measurement, is also an actuating variable for the variation in planting rate (Sökefeld, 2010).

Planters and drills can act as VRA seed distributors by adjusting the speed of the seed-metering drive. This will effectively change the plant population. VRA planting is accomplished by separating or disconnecting the seed-meter systems from the ground drive wheel. The seed rate can be varied on the go using an engine or a gear box able to change the speed of the ground wheel. Most of these devices will be matched with a prescription map and can have two or more rates. A two-rate scenario may be a system that reduces the seed rates outside of the reach of a centre- pivot irrigation system, while multiple rates may be needed to adjust for soil types (water-holding capacity) and organic matter content. On-the go sensors for VRA planting could also be used (Fig. 2.15). There are sensors that detect different levels of organic matter and adjust the plant population rate accordingly. Soil moisture meters, which can be used for depth adjustment and for changing seed rates, are also available (Grisso *et al*., 2011).

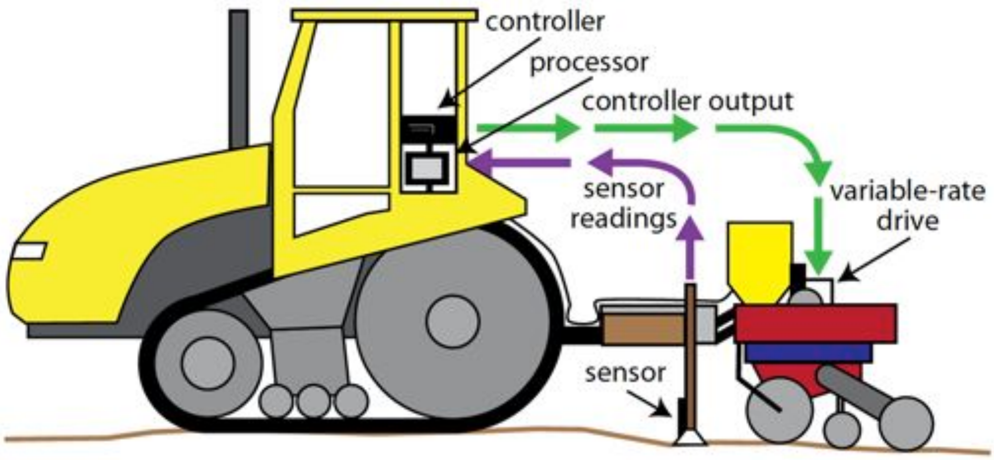

Figure 2.15. "On-the-go" sensor measures soil characteristics (texture, electrical conductively or soil organic matter) before planting and adjusting the seed rate (from Grisso *et al*., 2011).

2.6.4 Plant protection VRA

VRA in plant protection can be divided according to the application of fungicides, growth regulators and herbicides (Sökefeld, 2010). Dammer and Ehlert described a technique for variable fungicide spraying in cereals (Dammer & Ehlert, 2006). The concept was based on the idea to apply the same concentration of a.i. per unit of crop canopy surface area in order to achieve a homogeneous coverage of the foliar surface. A good indicator to calculate the density of the canopy is the leaf area index. The crop meter, a real-time sensor for crop biomass density was used for the measurement (Dammer & Ehlert 2006). An automatic detection of the fungus or the estimation of the quality of the disease is not possible (Sökefeld, 2010).

A similar approach was used for the application of growth regulators. The sensor signal of the Yara N-Sensor® (see Chapter 2.4.2), which analyses the spectra of the reflected light of the crop surface, was utilized for the calculation of the crop biomass in order to obtain an application rate of the growth regulators proportional to the biomass (Sökefeld, 2010).

There are different factors affecting the optimal dose rate of herbicides. For soil-applied herbicides Williams and colleagues mentioned the importance of the amount of active ingredients, which are available for the plant (Williams *et al*., 2002). The potential uptake depends on several soil properties, which influence the adsorption capacity like organic matter content, pH, texture, water content and cation exchange capacity. Other authors used parameters like weed density or weed species composition in order to adjust the optimal herbicide dose rate (Sökefeld, 2010).

At the time of application of pre-emergence herbicides normally no information about the later weed infestation is available. Thus pre-emergence herbicides are typically used at a uniform rate as broadcast or band applications. In order to use pre-emergence herbicides in a variable rate manner, spatial field information about soil properties or weed maps from previous years (historical weed maps) must be available (Sökefeld, 2010). The amount of soil-applied herbicide needed to control weeds depends on the soil texture and soil organic matter content. Field soil variability can be determined by measuring soil electrical conductivity or using soil survey data (Sökefeld, 2010).

Mohammadzamani and colleagues conducted a field trial, testing site-specific herbicides application using soil parameters (Mohammadzamani *et al*., 2009). Considering the differences in organic matter content and texture a field was divided into four management zones. Different rates of a pre-emergence herbicide were applied in the different zones. Herbicide application could be decreased by up to 13% in comparison to a uniform application rate, retaining successful weed suppression in most management zones.

In post-emergence weed control VRA systems, some form of "task computer" is required to provide a signal indicating the target rate for any location. Moreover, a system for physically changing the application rate to match the prescribed rate is required. Actually on the market there is a large number of sprayers control systems adaptable to VRA. Three categories will be discussed: flow-based control of a tank mix, chemical-injection-based control, and modulated spraying-nozzle control system. These systems eliminate much of the error in application that could occur if groundspeeds change from the calibrated setup (Grisso *et al*., 2011). A regulation of the nozzle flow rate compared to the driving speed ensures a constant distribution of the spray mixture on the entire plant canopy and thus an uniform cover of the leaf surface (Sökefeld, 2010).

2.6.4.1 Flow-based control systems

The flow-based control of a tank mix is the easiest system to apply VRA. These systems (also known as pressure based control systems) combine a flow meter, a groundspeed sensor, and an adjustable valve (servo valve) with an electronic controller to apply the desired rate of the tank mix (Fig. 2.16). The flow rate of the premixed solution is controlled by adjusting the system pressure. A microprocessor in the console uses information regarding sprayer width and prescribed dose (L ha^{-1}) to calculate the appropriate flow rate (L min^{-1}) for the current groundspeed. The servo valve is then opened or closed until the flow-meter measurement matches the calculated flow rate. If a communication link can be established between this controller and a "map system," a VRA can be made. These systems have the advantage of being reasonably easy to use. They are also able to make rate changes across the boom as quickly as the control system can respond to a new rate command, which is generally quite fast (three to five seconds) (Grisso *et al*., 2011).

Flow-based controllers have limitations. The flow sensor and servo valve control the flow of tank mix by allowing variable pressure rates to be delivered to the spray nozzles. This can result in large changes in spray droplet size and potential problems with drift (Grisso *et al*., 2011).

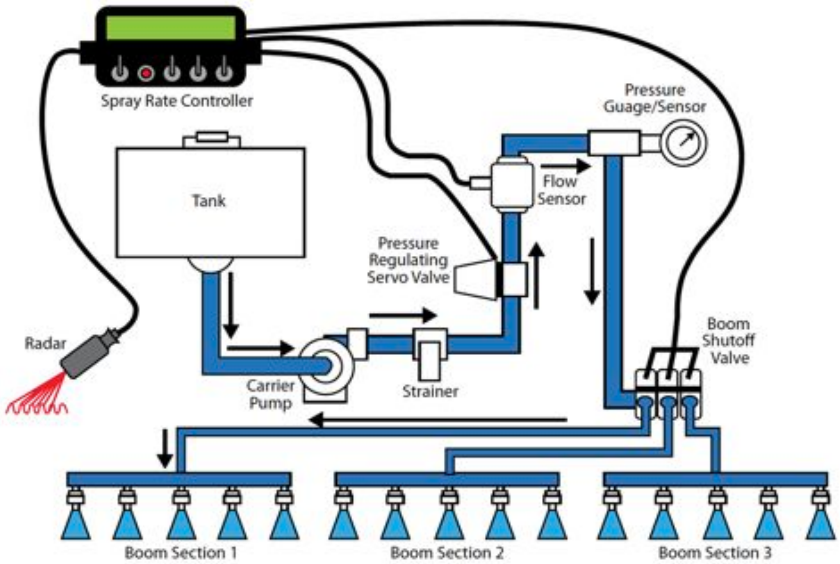

Figure 2.16. VRA spraying system that is a flow-based control system of application rate (from Grisso *et al*., 2011).

A multiple sprayer with three separated hydraulic circuits was developed at the University of Bonn in cooperation with Kverneland Group (Weis *et al*., 2008). It allows varying the herbicide mixture on-the-go. Each of the three sprayer circuits had a boom width of 21 m, divided into seven sections of 3 m. Each sprayer circuit and each section were separately turned on and off by a control unit via solenoid valves. The herbicide dose for the full spray boom was regulated by the same control unit via a spray computer. Three different volume rates could be applied by changing the pressure in the system. The main hydraulic circuit of each of the three sprayer circuits was similar to that used in a conventional sprayer with an output from the main pump fed to a pressure control valve, which regulated the concentration that was set by the spray computer. During the herbicide application, the spray control system was linked to an on-board computer loaded with the weed treatment maps. A DGPS was used for real-time location of the patch sprayer. The on-board computer compared the actual position of the sprayer with the information coming from the weed treatment maps and signals were transmitted to the control unit via a data bus to open each individual solenoid valve when herbicide application was warranted. In the same way, the herbicide dose was adjusted to the recommended rate in the treatment map. Application maps were created according to interpolated maps of weed distribution and economic weed thresholds (Weis *et al*., 2008).

2.6.4.2 Chemical direct-injection systems

An alternative approach to chemical application and control consists in using the direct injection of the formulation into a stream of water. In direct injection systems the active ingredient and the carrier (water) are kept separately. Chemicals are metered into the carrier at the time of application. These systems (Fig. 2.17) utilize the controller and a chemical pump to manage the rate of chemical injection rather than the flow rate of a tank mix. The flow rate of the carrier is usually constant and the injection rate is varied to accommodate changes in groundspeed or changes in prescribed rate. Again, if the controller was designed or modified to accept an external command (from a GPS signal and prescription map), the system can be used to perform VRA (Grisso *et al*., 2011).

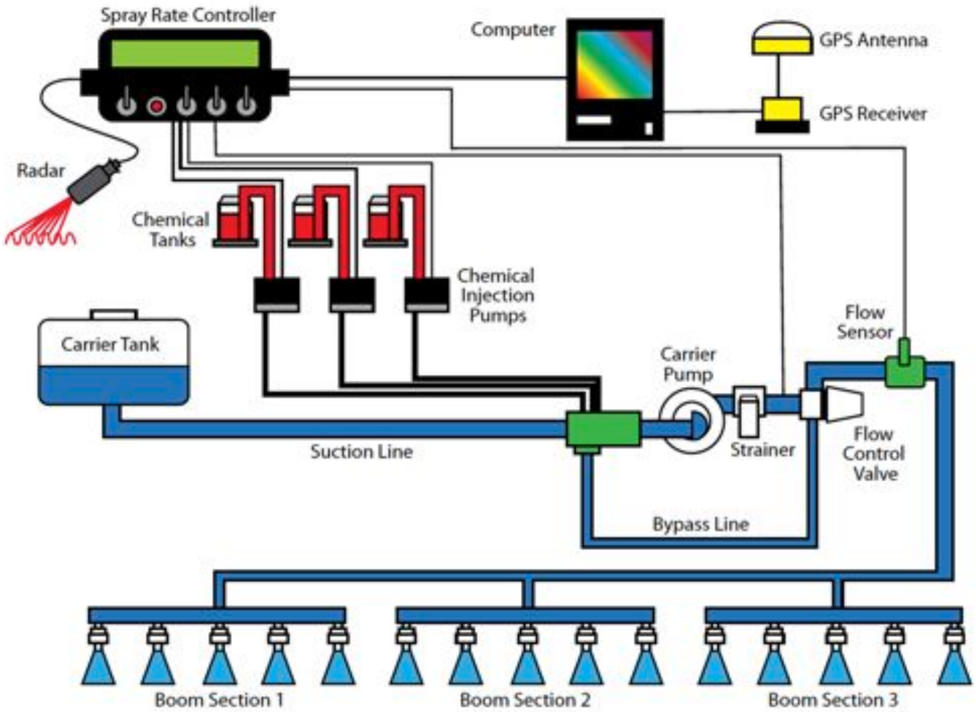

Figure 2.17. VRA spraying that incorporates chemical-injection technology. Three injection pumps and holding tanks are available for three different chemicals to be applied at different rates (from Grisso *et al*., 2011).

Chemical injection eliminates leftover tank mix and reduces operators exposure to chemicals during tank mixing. A major advantage of direct injection systems is the wide range of application rates according to the used metering device and the possibility to change not only the application rate but also the a.i. on-the-go. An additional advantage of this system is that the constant flow of carrier can be adjusted to operate the boom nozzles in order to provide the optimum desirable size and distribution of droplets. The main disadvantage for variable-rate control is the long transport delay between the chemical-injection pump and the discharge nozzles at the ends of the boom. The volume within the

spray plumbing (hoses and attachments) must be applied before the new rate reaches the nozzles. This can cause delays in the rate change and “christmas tree” patterns of application as the new concentration of chemical works its way out through the boom. These problems can be solved using systems based on both carrier and injection control (Grisso *et al*., 2011).
System based on chemical injection and carrier control require the control system change both the chemical-injection rate and the water-carrier rate to respond to speed or application-rate changes. One control loop manages the injection pump while a second controller operates a servo valve to provide a matching flow of carrier. A perfect system of this type would deliver a mix of constant concentration as in the case of use of a premixed tank. Changeover from one rate to another occurs as quickly as both chemical and carrier controllers can make the change, which is usually very fast. Disadvantages include a more complex system with higher initial cost and the problem of delivering varying amounts of liquid through the spray nozzles as rates change, with the resulting changes in droplet and spray characteristics (Grisso *et al*., 2011).

2.6.4.3 Modulated Spraying-nozzle control systems

Modulated spraying-nozzle control systems allow to perform VRA with drift control under a wide range of operating conditions. These systems are able to control the timing and duration of discharge from nozzles. High-speed valves are used to regulate the amount of time in which spray is delivered from conventional nozzles. These systems allow changing flow rate and droplet size distribution on the go. Modulated spraying-nozzle control-equipped sprayers use conventional nozzle assemblies that work in conjunction with direct acting, in-line solenoid valves. In figure 2.18 is reported a scheme of a spraying system that incorporates modulated spraying-nozzle control. The system operates under the direction of a microprocessor and an application controller that responds to signals from flow and pressure sensors. The basic concept of modulated spraying-nozzle control systems is to operate each nozzle at full design pressure and flow when a flow control valve is open. The key is to vary the time in which the valve is open in order to produce variation in the flow rate without changing droplet size distribution or spray pattern. A fast acting, electrical, solenoid-controlled nozzle assembly is mounted directly on a conventional nozzle assembly. Modulated spraying-nozzle control systems are equipped with solenoids that operate at a frequency of 10 Hz. This means that solenoid position can be cycled between open and closed 10 times per second, as directed by a controller that responds to input from a computer and a set of sensors. A cycle of events (valve open/spray/valve close) takes place in one-tenth of a second. In order to operate effectively, valve response must be quite rapid. An electrical signal to each valve is used to produce one of two flow conditions: full flow (completely open valve) or zero flow (completely closed valve). The solenoid-operated valves take only about 0.004 second to respond to an electrical signal (Grisso *et al*., 2011).

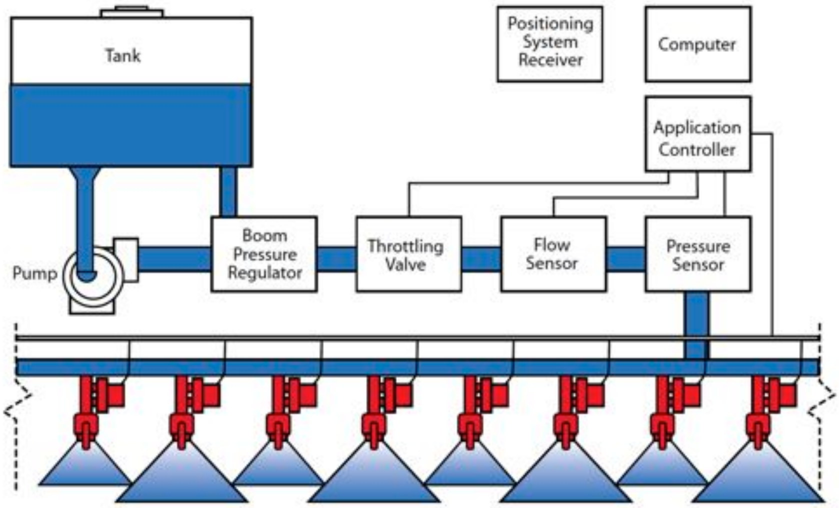

Figure 2.18. VRA spraying system using modulated spraying-nozzle control technology. The controller can control individual nozzles or a single signal for the entire boom (from Grisso *et al*., 2011).

Moreover, the modulated spraying-nozzle control system can be operated at reduced pressures to increase droplet size and reduce drift especially in windy conditions. Application rates could be maintained, even if the system pressure is lowered, by increasing the amount of time in which the nozzle is open. The potential benefits of using a chemical-application system that permits the tailoring of both application rate and droplet-size distribution throughout a field, include the ability to: produce a broader range in flow rates with much more consistent spray characteristics than conventional sprayers, vary nozzle flow rates and/or travel speeds over a wide range without affecting spray pattern or droplet-size distribution, and vary droplet-size distribution without changing application rate in order to minimize drift (increasing drop diameter) or to increase spray coverage (reducing drop diameter) needed for some contact-type formulates (Grisso *et al*., 2011).

2.6.5 Fertilize distributors VRA

Fertilizers applications can cover a wide area of application devices. Many of the VRA technologies for fertilizer applications are similar to those used for herbicide spraying (liquid applications). Their effectiveness is influenced by impacts, nutrient availability and seasonal cycles (Grisso *et al*., 2011).

Every season, maize producers must decide the correct amount of nitrogen to apply in their fields. GPS-enabled application and related precision farming technologies allowed the farmers to choice either to apply nitrogen at a uniform rate or to use VRA within fields. Tailoring nitrogen application rates to more exactly meet crop needs should increase profitability, reduce environmental risk, and may result in higher and more consistent grain quality (Grisso *et al*., 2011).

The key to success and eventual adoption of variable-rate nitrogen management will be the development of decision-making criteria that can accurately predict nitrogen rates for sub-regions of maize, wheat, rice, cotton, and other crops that are economically optimum and environmentally sustainable. The first variable-rate nitrogen strategies took a proactive, prescriptive approach. Fields were divided into smaller sub-regions and methods developed for whole field nitrogen management were applied to these individual "management zones". The variable nitrogen rate prescription map was developed prior to the growing season and fertilizer was applied at the usual time. A second approach to VRA nitrogen management involves reacting to actual nitrogen levels in crop fields during the growing season. Crop nitrogen status is monitored in near real-time, and nitrogen is applied only when and where it is needed. With this method, plant or canopy reflectance of light or chlorophyll content is used to indicate plant nitrogen stress. This approach can utilize remotely sensed crop canopy imagery and typically requires the presence of an adequately nitrogen-fertilized "reference strip" within the field. Interestingly, these optical methods create in-season nitrogen prescription maps that are based on crop nitrogen stress rather than predicted yield levels (Grisso *et al.*, 2011).

For the variable rate application of other fertilizers like phosphate and potassium maps based on soil test information from grid soil sampling are commonly used. Predominantly spreaders with additional controller are used for map-based variable rate fertilizer application as well as for sensor based application (Sökefeld, 2010).

2.6.6. Irrigation VRA

Normally, centre pivot irrigation systems apply a more or less uniform amount of water to a whole field or even several fields with no respect to non-uniform environment like variable soil types, multiple crops or changing topography. To divide fields in management zones according to their estimated water application rate inputs like aerial images of soil or crops, soil and yield maps and farmers' knowledge of field were used. The created application maps were realized by a special variable rate irrigation controller, which varies the application rate by cycling sprinklers on and off and by varying the travel speed of centre pivot irrigation system. Application rates between 0 and 200% were achieved by using this technique (Sökefeld, 2010).

2.7 Yield monitoring systems

Yield is ultimate indicator of variation of different agronomic parameters in different parts within the field. So, yield mapping and maps interpretation and correlation of with the spatial and temporal variability of different agronomic parameters helps in development of next crop management strategies (Mondal *et al.*, 2011).

Farmers, consultants and researchers utilized yield monitors to map yield of many crops. However, majority of precision agriculture practice adoption occurred in grains, oilseeds and cotton. Generally combines grain harvesters use physical sensors to measure grain flow (i.e. impact sensor), whereas cotton yield monitors use microwave or near-infrared sensors to measure amount of cotton. GPS device is a key part of the yield monitor as position data is critical to determine spatial variability in crop yield. Other sensors such as forward speed sensor (i.e. radar, ultrasonic sensor or magnetic pickup on the drive shaft) crop moisture sensor and header height sensor are also mounted on the combines. This way, it is possible to map spatial variability in yield data and create yield maps and track

field performance year after year. These maps are very useful to create different management zones for various inputs within a field (Perez-Ruiz & Upadhyaya, 2012).
A yield monitor was tested at the University of Cordoba (Spain). The yield monitor consists of four optical flow sensors located in the ducts and a DGPS receiver (Fig. 2.19). It was mounted on a four-roe cotton harvester and was calibrated. The aim of the study was to investigate the relationship between yield variability and spatial variability of some soil properties (texture, organic matter, phosphorus and potassium). Maps of each soil property and crop yield were generated. The main cause of spatial variability in cotton yield was the spatial variation in soil texture (Perez-Ruiz & Upadhyaya, 2012).

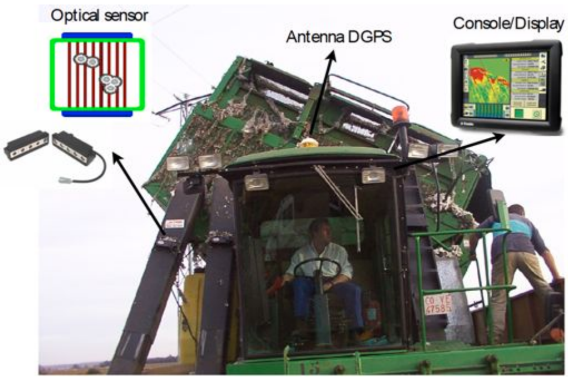

Figure 2.19. Yield monitor mounted on a cotton harvester. The combine is equipped with four optical flow sensors, a DGPS receiver and a display (from Perez-Ruiz & Upadhyaya, 2012).

Vilde and colleagues equipped a grain harvester with a devise for the determination of grain yield and moisture content by fixing the GPS coordinates to produce digital maps of the grain yield (Fig. 2.20). The yield maps showed great spatial yield variability (Vilde *el al*., 2012).

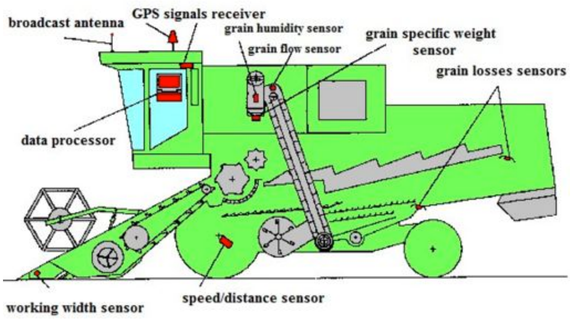

Figure 2.20. Equipment for the determination and mapping spot yields in GPS coordinates mounted on a combine grain harvester (from Vilde *el al*., 2012).

Singh and colleagues mounted an automated yield monitoring system on a combine grain harvester for real-time yield mapping. The automated yield monitoring system consisted of one yield sensor, global positioning system (GPS), field computer with custom software, and header cut off switch. The yield maps were generated by using ArcGIS software from the data collected for four different wheat fields. On average, yield variations recorded for the four fields had coefficients of variation ranging from 17 up to 22% (Singh *et al*., 2012).

CHAPTER 3. SITE-SPECIFIC WEED MANAGEMENT

The heterogeneous distribution of weeds in agricultural fields allows actuating site-specific weed management, resulting in significant herbicides save as well as economic and ecological benefits. The aim of weed management is to keep the density of weed communities on an acceptable level for both the current and forthcoming vegetation periods. The acceptable weed density level depends on several biological, agronomical and economic conditions that have to be taken into account in order to define decision rules for site-specific weed management. Commonly decision support systems give a recommendation for uniform weed control applications across the total field based on the average weed infestation level. Since weed populations have been found to be heterogeneous in their time and location in most arable fields, decision rules need to be developed taking into account the spatial and temporal variability of weed populations (Gutjahr & Gerhards, 2010).

One of the aims of precision agriculture is to minimize the amount of herbicides used to perform weed control. In this respect, two main factors must be considered: the similarity in terms of shape and texture between weeds and vegetation and the irregularity in the distribution of weeds in the vegetation (Gomes & Leta, 2012). The distribution of herbicides with fixed point and quantitative spraying is becoming one of the major research directions of precision weeding technology (Wu *et al*., 2011). Weed-specific chemical application can reduce the amount of chemicals by about 25-50% thus reducing cost and protecting the environment (Perez-Ruiz & Upadhyaya, 2012).

Weed seedlings distributions were found spatially and temporally heterogeneous within agricultural fields. They often occur in aggregated patches of varying size or in stripes along the direction of cultivation (Gerhards & Christensen, 2003). For this reason a uniform treatment of the entire fields can result in unsatisfactory weed control or unnecessary use of herbicides (Grisso *et al*., 2011). Patch spraying, based on the real need for weed control, reduces costs as well as risks of environmental pollution and herbicide presence in the food chain (Gerhards & Oebel, 2006). Site-specific weed management includes spraying weed patches only and/or adjusting herbicide applications according to weed density or weed species composition (López-Granados, 2010). This strategy fits well with European goals of minimising herbicides use and tracing farm products (López-Granados, 2010). Site-specific weed management comply with the aims of the directive 128/2009/EC (OJ, 2009) fitting with the contents of integrated pest management (Bàrberi, 2013).

Site-specific weed management represents a four-step cyclical process that includes (1) weed monitoring consisting of ground sampling or detection of weeds, (2) decision-making (also called management planning), refers to the design of an action based on the diagnosis and other available information (e.g. farmer experience), (3) precision field operation, which is the execution of site-specific weed management and (4) evaluation of the economic profitability, safety and environmental impacts of the field operations for the next season (López-Granados, 2010).

There are two approaches, “off-line” and “on-line”, for site-specific weed management in arable crops (Gutjahr & Gerhards, 2010). Remote sensors are helpful for off-line site-specific weed management, whereas proximal sensing is useful for both off-line and on-line (López-Granados, 2010). In the off-line (or map based, i.e. weed monitoring and management in two separate operations) approach, weed distribution is first measured at georeferenced points. Interpolation methods are applied to create weed distribution maps (Fig 3.1a) (Gutjahr & Gerhards, 2010). The creation of weed maps has the potential to improve the accuracy and sampling rate of weed infestation measurements in the field (Weis *et al*., 2008). A weed threshold is set to determine sections in the map where weed control methods will be applied (Fig. 3.2b). Those application maps are then used to direct a patch sprayer or machines and tools able to perform physical weed control. In many studies, this map-based approach of site-specific weed management was successfully applied resulting in herbicide savings ranging from 20 up to 90% (Gutjahr & Gerhards, 2010).

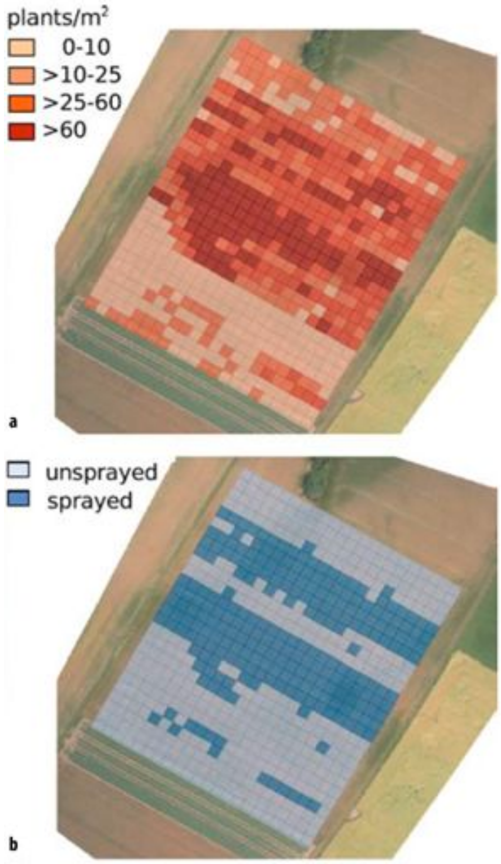

Figure 3.1. Example of weed distribution map (a) and relative application map (from Weis *et al*., 2008)

However, for a broader acceptance of site-specific weed management in practical agriculture, an on-line system (or real-time, i.e. weed monitoring and management in one operation), which combines the detection of weed species and herbicide application or physical weed control in one operation would be needed (Gutjahr & Gerhards, 2010). In an on-line system, the vision system needs to automatically determine where the crops and the weeds are. The major problems that can occur using computer vision are occlusion and variations in plant appearance. Occlusion occurs when leaves from crops and weeds partially overlap, resulting in two or more plants being interpreted in the image as one plant. The variations in plant appearance are variations between different samples of the same plant species. The leaves do not face the same direction and are different in size. Furthermore, variations in the soil conditions and the amount of sunlight can result in colour variations and differences in size between crops and weeds. Moreover, when the image is segmented into plants and soil, the resulting plant objects can be single leaf objects or multiple leaf objects (Fig. 3.2). The multi-leaf objects can contain leaves from the same plant, but it is also very likely that leaves from different plants are included (occlusion). When the objects are merged into plants it can be difficult to discern which objects contain leaves belonging to the same plant (Persson & Åstrand, 2008).

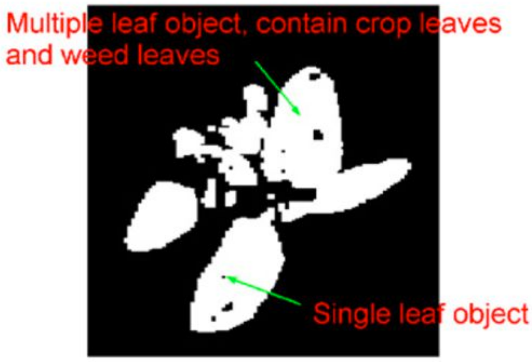

Figure 3.2. The image was segmented into plant material (white) and soil (black); the plant material consists of both single leaf objects and multiple leaf objects (from Persson & Åstrand, 2008).

A general-purpose autonomous robotic weed control system has four core technologies: guidance (RTK-GPS or machine vision), weed detection and identification (machine vision, hyperspectral imaging, possibly assisted by RTK-GPS), precision in-row weed control (i.e. micro-spraying, cutting, mechanical, thermal, electrocution), and mapping (GPS & machine vision) (Slaughter *et al.*, 2008).
Weed monitoring in crops is still one of the critical components for the adoption of site-specific weed management (López-Granados, 2010). At the moment, the main limitations of weed monitoring and mapping tools are: (1) their ability to identify weeds at species level, which would be required for optimized their control, (2) their high cost, and (3) the lack knowledge of farmers and technicians (Bàrberi, 2013).

3.1 Automatic row detection and implement for row position centring

As most crops are cultivated in rows, an important step for site-specific weed management is the development of a row-recognition system, which will allow a robot or an operative machine to accurately follow a row of plants (Åstrand & Baerveldt, 2005). In row guidance, the problem is to find an accurate and stable guidance signal under different environmental conditions. The use of a guidance signal derived from living materials is quite difficult (i.e. the rows can be incomplete because there are missing plants and/or plants of different size along the field). Moreover a large amount of weeds can disturbs the

appearance of a clear row of green plant coming from the crop (Åstrand & Baerveldt, 2005).
Most common types of active guidance systems that can be retrofitted to many weeding implements for weed control at post-emergence of crop are based on computer vision or GPS guidance technology (Nørremark *et al*., 2012). Both machine vision and RTK-GPS guidance systems for precise position control are commercially available. These systems have similar levels of positioning precision along straight rows (generally 25 mm of standard error range) and distinct advantages and disadvantages. Machine vision guidance systems require a reasonable view of a pre-existing guidance directrix (typically the crop row), while RTK-GPS systems require a good "view" of the sky and an RTK-GPS base station located nearby. Currently, equipment costs for machine vision guidance systems are considerably lower than RTK-GPS equipment costs due to the requirement that a base station be located within 10 km at all times (Slaughter *et al*., 2008). GPS service providers and government institutions are working to mitigate this challenge by developing networks of base stations that provide access to RTK correction signals over a wider geographic region via mobile phone or radio modems or satellites (Leandro *et al*., 2011).
Guidance systems that are commercially available include Eye-DriveTM (AgroCom GmbH, Bielefeld, Germany), RobocropTM (Garford Farm Machinery, Peterborough, UK), RoboVator (Frank Poulsen Engineering, Hvalsø Denmark), AutoFarmTM (Novariant, Inc., California, USA) and AgGPS TrueTrackerTM (Trimble Navigation Limited, CO, USA), where the last two are based on GPS guidance technology (Nørremark *et al*., 2012).
Åstrand & Baerveldt developed a method for robust recognition of plant rows based on the Hough transform (a computationally efficient procedure for detecting discontinuous lines or curves in pictures) that is able to guide agricultural machines. The system is not restricted to a specific crop. They used a grey-scale camera with a near-infrared filter to detect plants and derived a binary image in which plant material from both weeds and crops is white and the rest, coming from soil, stones and residues is black. The crop rows were detected in the binary image as the weeds are uniformly distributed in the field, whereas the crop grows exactly in the rows, thus leading to a peak in the Hough-space. The accuracy of the position estimation relative to the row proved to be good with a standard deviation between 0.6 and 1.2 cm depending on the plant size. The vision system is also able to detect other situations as the occurrence of the end of a row (Åstrand & Baerveldt, 2005).
The system was tested on both an inter-row cultivator and a mobile robot. The row recognition system implemented on the inter-row cultivator consisted of a tractor that the farmer drives along the rows with the cultivator mounted at the rear. A steering-unit based on a very thin steering wheel, which cuts through the soil, was used to control the position of the cultivator according to the input of the row recognition system (Fig. 3.3). The controller was designed as a PID-controller. The robot implemented with the row recognition system was able to follow a row guided by the row-following vision system (Fig. 3.4). The camera for the row recognition system was mounted at the front of the robot. This is also the control point of the robot. In order to perform intra-row cultivation, the robot has an intra-row-weeding tool mounted at the rear. At the weeding position, a

second camera was mounted to measure the actual position of the robot (Åstrand & Baerveldt, 2005).
Extensive field tests showed that the system is sufficiently accurate and fast to control the cultivator and the mobile robot in a closed-loop fashion with a standard deviation of the position of 2.7 and 2.3 cm, respectively. The tests also showed that the system is able to deal with incomplete row structures due to missing plants combined with high weed density (up to 200 weeds m^{-2}) (Åstrand & Baerveldt, 2005).

Figure 3.3. Tractor coupled to the row-cultivator (from Åstrand & Baerveldt, 2005).

Figure 3.4. Mobile robot (from Åstrand & Baerveldt, 2005).

Kise and colleagues developed a near infrared stereovision guidance system. The lateral error of the system was 30-50 mm depending upon speed and row curvature. The method required some weed-free areas to provide sufficient information to support the stereovision-based system to detect the navigation points (Kise *et al*., 2005).
Tillett and Hague used computer vision to locate crop rows. They developed an integrated vision-based system that allows the input from multiple cameras to be fed into one system. This provides an opportunity to track rows from more than one drill, or transplant bout at a

single pass. Colour images from each camera were converted to grey scale using a ratio of red, green and blue that exhibited good contrast between live plant material and background, but reduced illumination effects. The mono-chrome image was then divided into eight horizontal bands in which parallel crop rows appeared as a periodic variation in grey level according to their position. This periodic amplitude variation was extracted by the application of a digital band pass filter to each horizontal band in turn. The filter was derived to match the frequency of the crop rows whilst attenuating the lower frequency effects of shadows and spurious higher frequency features such as weeds. The derivation of that filter f (x), which can be considered as a template for matching crop rows, was given by Hague and Tillett (2001) as $f(x) = \frac{127}{\omega_b x}$ [cos ($\omega_c x$) sin ($\omega_b x$)] where: ω_c is the angular frequency corresponding to the nominal row spacing (radians/pixel); ω_b is a tolerance band to allow for some inaccuracy in row spacing (assumed value of $0{\cdot}05\omega_c$) and x is the horizontal distance across the image (pixels) (Tillett & Hague, 2006).

Observations of row location from each camera were then passed to an extended Kalman filter (EKF) and a recursive least-squares estimator. The Kalman filter estimated three states for each camera relating to individual sections and one that is a measure of tractor steer rate. The first two, camera lateral offset and heading angle with respect to the crop rows, are the states necessary for dynamic tracking. A third state, the camera steady-state angular misalignment was also estimated as well as to avoid the need for very accurate mechanical alignment. It was the estimate of lateral error for each individual section that was used to make lateral control corrections. The advantages of this centralised approach, as opposed to multiple independent units, included an opportunity for a simplified user interface and reduced component costs. The estimated rate of tractor steering was used to couple each of the sections leading to improved overall tracking (Tillett & Hague, 2006).

The integrated vision-based system was tested in two cases. The first one was an inter-row hoe used in cereals with three independently guided 4 m wide sections, each with its own camera, operating on 12 m tramlines (Fig. 3.5). Trials showed that the standard deviation in the lateral position was 10 mm at 10 km h^{-1}. The second case concerned with a precision band sprayer for vegetables spanning five 4 m wide beds (Fig. 3.6). Trials indicated that the standard deviation in lateral position was 22 mm at 12 km h^{-1} (Tillett & Hague, 2006).

Figure 3.5. Experimental vision guided hoe spanning 12 m with three independently controlled 4 m wide sections (from Tillett & Hague, 2006).

Figure 3.6. Experimental vision guided band sprayer spanning 20 m with one fixed and four independently controlled 4 m wide sections (from Tillett & Hague, 2006).

As an alternative, RTK-GPS can provide a level of lateral positioning accuracy along the row comparable to machine vision guidance systems, trading the need for a visual guidance directrix for an unobstructed "view" of the sky from all parts of the field. GPS systems provide an absolute guidance system and in contrast to the relative guidance provided by machine vision, require that the crop is planted using an RTK-GPS guided system or the crop rows mapped using some type of georeferenced mapping technique. RTK-GPS systems also require that a GPS base station is located within approximately 10 km of the RTK-GPS guided tractor or agricultural robot. However, since they do not depend upon the visual appearance of the crop, they are not adversely affected by weed density, shadows, missing plants or other conditions that degrade the performance of machine vision guidance systems. Another advantage of GPS guidance systems is that they can be easily programmed to follow curved rows (e.g. centre pivot irrigated fields). Commercial RTK-GPS automatic tractor guidance systems are generally able to steer with precision errors of 25 mm from pass to pass in a row crop field where the RTK-GPS guidance system was used to form the beds and plant the crop. To achieve optimum guidance performance RTK-GPS systems should be used in fields where there is a minimum amount of radio frequency interference, multipath errors (due to reflection of GPS signals near the antenna) are minimal and minimum of four common satellites are available on both tractor and base station. Also satellite geometry (distribution of satellites in the sky) could be affecting the performance since agricultural operations typically cannot be scheduled according to optimum satellite availability (Slaugther *et al*., 2008).
Perez-Ruiz & Upadhyaya designed and built a fully automatic electro-hydraulic side-shift frame for row centre positioning controlled by RTK-GPS location to perform a precise mechanical (between rows) and narrow band spray (on the rows) weed control. The frame is shown in figure 3.7. It is placed between the tractor and the operative machine that allowing to properly performing the narrow band treatments with a minimum lateral drift (Perez-Ruiz & Upadhyaya, 2012).

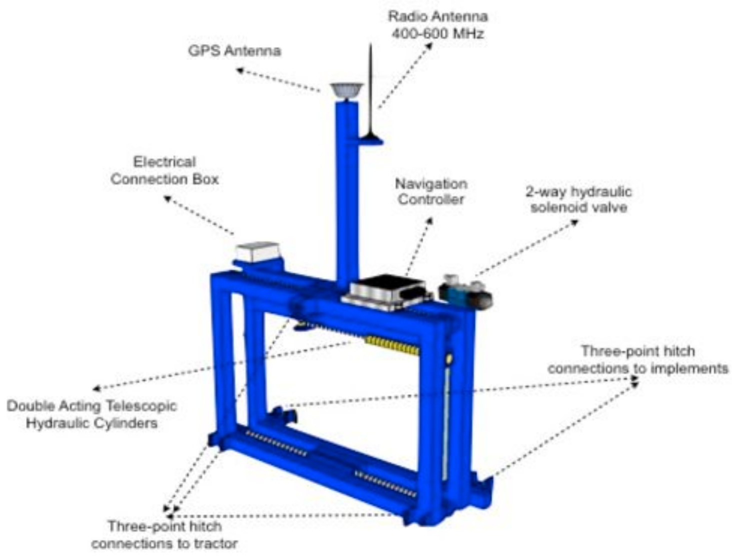

Figure 3.7. Schematic diagram showing the side-shift frame system developed for row position centring controlled with a RTK-GPS geopositioning system (from Perez-Ruiz & Upadhyaya, 2012).

3.2 Automatic weed detection and weed/crop discrimination

The detection of weeds is a prerequisite in order to perform a successful site-specific weed management. The spatial and temporal variation of weed populations needs to be assessed, if the treatment should vary within a field. Commonly weed density and/or weed coverage for each species are measured. These data can be used to estimate the expected yield loss and to decide for each part of the field that weed control method is warranted (Weis & Sökefeld, 2010).

In agricultural automation, the expected outputs of a weed detection system are weed plant detection, classification and stem centre localization (Kazmi *et al*., 2011). Slaughter and colleagues started that robust weed detection and identification was the primary obstacle toward commercial development and industry acceptance of robotic weed control technology (Slaughter *et al*., 2008).

Site-specific weed control methods can be realized when automatic sensor technologies for weed detection and patch spraying technologies are combined with precise decision algorithms (Gerhards, 2010). In addiction to this practical benefit, weed mapping helps to understand weed-crop interactions and population dynamics of weed species. It allows quantifying yield effects of different weed infestations in the field and modelling the spatial and temporal variability of weed populations under different crop management systems (Gerhards, 2010).

A major step towards a practical solution for site-specific weed management was the development of precise and powerful sampling techniques to automatically and continuously determine in-field variation of weed seedling populations (Gerhards, 2010). The application of image processing technology can accurately identify the weeds present in a field (Wu *et al*., 2011). Sensor technology was already used to apply herbicides site-specifically, resulting in 30-70% reduction. Depending on the application technology the sensor design has to be adapted (Weis & Sökefeld, 2010). Airborne remote sensing was

used to identify weeds. Optoelectronic sensors and digital cameras were mounted on the tractor to detect weeds in the near-range. Optoelectronic sensors were used to measure the reflectance in the green, red and near-infrared light wave bands in the inter-rows area (Gerhards, 2010; Andujar *et al*., 2011b). However, the most promising approach for weed detection is a continuous ground-based detection method based on image analysis. With this method, weeds and crops were segmented from digital images in real-time using a bi-spectral camera system connected to DGPS. Weed species as well as crops were identified and counted based on automatic classification of shape features (Weis *et al*., 2008). Sensor fusion and integrative analysis of multiple sensors data could improve the weed detection rate and also influence other precision-farming technologies (Weis & Sökefeld, 2010).
To distinguish the different species certain characteristic properties have to be identified. These properties can be measured automatically and can be divided in four typologies: spectral properties, biological morphology, texture features and location and temporal properties (Weis & Sökefeld, 2010). However, the high cost of weed detection technologies is a major deterrent for their commercial introduction (Andujar *et al*., 2011b).

3.2.1 Spectral properties

The spectral response of plant species at the canopy or single-leaf scale is unique and is known as spectral signature. It varies according to the phenological stage and it can be measured by proximal or remote sensors. The main principle is that if differences in reflectivity based on external factors or distinctive phenological stages can be measured or recognised, automatic weed detection can be performed (López-Granados, 2010).
A large number of research studies investigated the use of colour or spectral reflectance techniques for plant species identification (Slaugther *et al*., 2008). The chromatic properties describe the colour or the spectral composition of the radiation emitted or reflected from objects, quantified by the intensity of pixels in different spectral bands (Gomes & Leta, 2012).
One of the greatest potential of pixel based colour or hyperspectral classifiers are robust to partial occlusion. In addition, the methods that use spectral properties tend to be less computationally intensive than shape-based techniques (Slaugther *et al*., 2008).
There are a large number of studies that have used various types of vegetation indices, typically ratios of broadband reflectance values in the visible and near infrared, to measure crop properties. Broadband colour, or chromaticity values have been widely used to segment plant material from soil backgrounds (Slaugther *et al*., 2008).
Only few researchers found high levels of success in using colour segmentation alone to distinguish crops from weeds in ground-based field images (Slaugther *et al*., 2008). One of the most successful machine vision systems using colour was the autonomous robot developed by Åstrand and Baerveldt. In a test of 587 colour images collected in several commercial sugar beet fields they found that the green chromaticity value ($g = G/[R + G + B]$) was very effective in distinguishing crop from weeds. As a matter of fact, a 91% classification accuracy in one-out cross-validation was obtained (Åstrand & Baerveldt, 2002).

Wu and colleagues firstly, separated the plant pixels from the soil background using the colour difference of green plant and soil. Then, taking into account that crops are arranged in rows, they used pixel histogram method to select centreline of crop rows and set it as starting point and crop rows edge as ending point. Finally they filled crop area and eliminated crop pixels. Weed detection was completed via the feature that weeds tend to grow in small associations and distribute closely. This system allowed to obtain the correct detection rate between 92% and 95% while the false detection rate in the range of 3% to 5% (Wu *et al*., 2011).

Recently, several studies investigating the use of ground-based hyperspectral machine vision systems for plant species recognition were carried out (Slaugther *et al*., 2008). Alchanatis and colleagues extracted plant material from the soil using the difference in multi-spectral images at 660 nm and 800 nm. The cotton plant was extracted from the weed using the local inhomogeneity of the pixel values. For both cotton and weeds 86% of the pixels were classified correctly (Alchanatis *et al*., 2005).

Integrating narrow-banded contiguous spectral fingerprints with spatial registry of each pixel in an image array, hyperspectral imaging seems to be promising for plant identification and localization in the context of automated intra-row control (Zhang *et al*., 2012). Zhang and colleagues investigated the use of hyperspectral vision identification system and a multi-spectral image processing technique for accurately identifying and mapping weeds within the seedline at the early growth stage using tomato (*Lycopersicon esculentum* Mill.) as target crop. A prototype of hyperspectral imaging system was developed to identify processing tomatoes versus weed species *Solanum nigrum* L. and *Amaranthus retroflexus* L.. The core component of the system was a 12-bit, temperature-controlled, monochrome area camera equipped with a hyperspectral spectrograph, which had a nominal spectral wavelength range of 384-810 nm and half band-width of 5 nm. To improve spectral uniformity and signal to noise ratio, a blue filter was placed on the camera lens. The camera height was adjusted, resulting a field of view of 2.5 mm along and 10.8 cm across the seedline. Scene illumination was provided by two tungsten-halogen bulbs collimated through a light duct and directed onto the plant leaf foliage at a 15° angle to vertical direction to avoid glare. A line imaging configuration was used where the camera line-by-line sequentially scanned the surface of the seedline perpendicular to the travel direction as the system moved along the row. A 4 per 4 binning was operated in the camera before data transfer to reduce noise and minimize image transfer time. The resulted hyperspectral images had a size of 330 pixels in the spatial dimension (perpendicular to the seedline) and 260 pixels in the spectral dimension. The system was calibrated for dark signal noise and responses to an optically-flat reference plate (whose reflectance intensity was nearly uniform in the studied spectral range) before acquiring canopy reflectance of the crop row. The hyperspectral imaging system was mounted in an enclosed chamber, with a black interior and white exterior with rubber sheet draped against the ground along the circumference, to prevent ambient light from entering the system area. The hyperspectral imaging system correctly identified about 96% of plant canopy for tomatoes, *Solanum nigrum* and *Amaranthus retroflexus* (Zhang *et al*., 2012)

The fluorescence effect can also be used to distinguish living plants from other objects and may lead to methods for species discrimination in the future (Weis & Sökefeld, 2010).

Chlorophyll fluorescence of the plant photosystem is an indicator for the effectiveness of the photosynthesis. The fluorescence intensity shows a typical temporal change after saturation of the photosynthesis system with light (Kautsky effect). Kautsky functions indicate healthiness of the plants, but can also be used to distinguish different species due to the different leaf structure and leaf angle of grasses and dicotyledons (Weis & Sökefeld, 2010).

3.2.2 Biological morphology

In biological morphology, shape recognition can be conducted at increasing levels of abstraction: geometric, structural and semantic. Most machine vision research on plant species identification was performed at leaf geometry level or at the whole plant level. Biological morphology is defined as the shape and structure of an organism or any of its parts. On the contrary the term morphology is applied to image processing represents the application of a set of basic operations to an image using a structuring element (Slaughter *et al.*, 2008).

Several researchers used shape features to discriminate weed and crop. The shape features were derived for each connected foreground region. Image processing techniques provide a set of commonly used shape features. One of the simplest features to describe the shape of a region is the size, expressed either in number of pixels or scaled by the ground resolution. They may be objects of different size, but with similar overall shape characteristic (geometrically congruent). Therefore shape descriptors were developed independently from the size of the region (Weis & Sökefeld, 2010). Other features are computed from the outline of a region, given by the border pixels that have neighbouring background pixels. Since the border of an object is a closed contour, a periodic representation can be derived (Weis & Sökefeld, 2010). Also the skeleton (the central line of a region) features are helpful for the discrimination of plant species. As a matter of fact, a combination of a distance transform and a skeletonization of the object are used. They basically represent the thickness and elongatedness of a region. A subset of them is invariant to translation, rotation and scale and are suitable for a shape comparison, since they are normalised and can be compared directly to each other. A vector of the shape features represents the shape of the object, which can be used for discrimination of different species. Also "high level" shape description that involve models and try to fit the model to the shape can be used (Weis & Sökefeld, 2010).

Many of the shape-based studies use colour (spectral property) segmentation as a first step to distinguish plants from soil (Slaughter *et al.*, 2008). Onyango and Marchant used colour and the planting grid to extract cauliflower plants from weeds and background. They found that for cauliflower 82–96% of pixels were classified correctly and for weeds this range was between 68 and 92% (Onyango & Marchant, 2003). The planting grid was also used by Åstrand. In this case the plant material in colour images of sugar beets was extracted from the soil using a linear discriminant in the normalised RGB (red, green, blue) colour space. To distinguish between sugar beets and weeds, features including colour, area and shape were calculated from the extracted plants and combined with a model of the distance between the sown crops. The total classification rate was 90–98% when occluded plants were excluded with the tested data sets containing 5–24% occluded plants (Åstrand, 2005). Weis and colleagues developed and mounted on a vehicle three digital bi-spectral cameras (IR-VIS) for automatic weed detection. Two images were taken at the same time in the near-infrared spectrum (770-1.150 nm) and in the red spectrum (610-670 nm) by means of each bi-spectral camera. The images of both cameras were adjusted in brightness and subtracted (IR-VIS) in real-time. With this camera, a strong contrast between green plants and soil, mulch and stones was achieved even under variable illumination and soil moisture conditions. The cameras were triggered with an exposure time of 1/4,000 s to get well-focused images at a speed of 7-8 km h^{-1}. A grey level threshold was set automatically and all white objects in the picture were extracted. Objects, defined as a connected set of foreground pixels (segments) smaller or bigger than plants were automatically removed from the image. The remaining objects were analysed with image processing and classification algorithms. The features of the shape of each object in the images were calculated and stored in a database. For classification purposes different weed species had to be trained by selecting prototypes from the set of objects. The classes indicate the plant species and growth stage, since the shape change for each species over the time of growth. A prototype definition consists of a region (segment) in an image, the corresponding shape features and a class association. A classifier can be trained based on the prototypes and then used to classify all objects, assigning classes to them (Fig. 3.8). The results are the counts of each class in every image. In combination with the GPS position weed maps are generated, which contain the class counts for the different weed species in an attribute table of points (Weis *et al*., 2008).

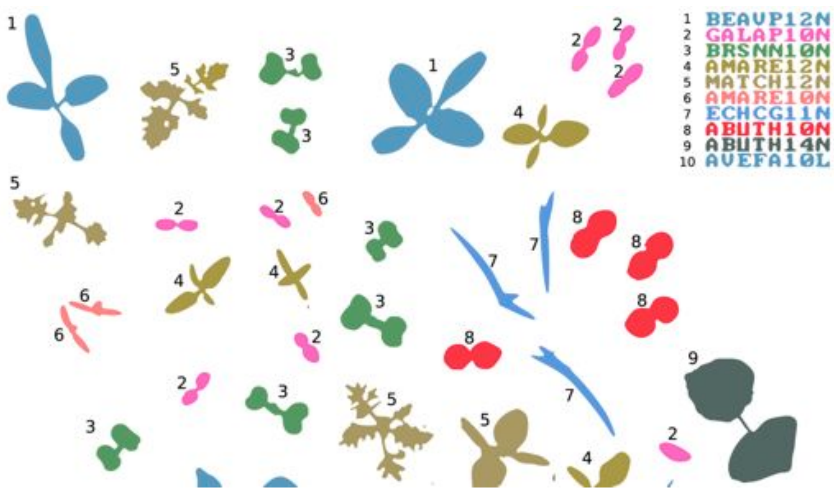

Figure 3.8. Classification examples: each classified region is denoted by a colour and a number for the class (from Weis *et al*. 2008).

Persson and Åstrand classified crops and weeds extracted by an active shape model. Active shape models are deformable templates that can only deform according to criteria defined by a set of training images. The method is suitable for matching objects that can vary in shape, such as hands, insects, plants and medical organs. The method is based on building a statistical model from training images and then using it to search for similar objects (Persson & Åstrand, 2008).

Active shape models were chosen to study the size-independent shape information of plants instead of colour or size information, since they can vary in different fields. Moreover, the active shape model is constructed from a set of training images, and new models can easily be developed for other crop species. Only one model, a crop model, was built and this model was applied to both crops and weeds to extract the plants. The idea was that crops would have been well extracted and give a shape similar to the crop while the weeds would have been poorly segmented resulting in a corrupt shape different from that of the crop (Fig. 3.9). The reason for using only one model, instead of building one model for the crop and one model for each weed species and testing each model on every plant, as tested by Søgaard, was that it would require many different models and too much processing time to be used in an on-line automatic weeding system (Søgaard, 2005). The classification results for the active shape model-extracted plants were compared to classification results for manually extracted plants. It was judged that 81–87% of all plants extracted by active shape model were classified correctly (Persson & Åstrand, 2008).

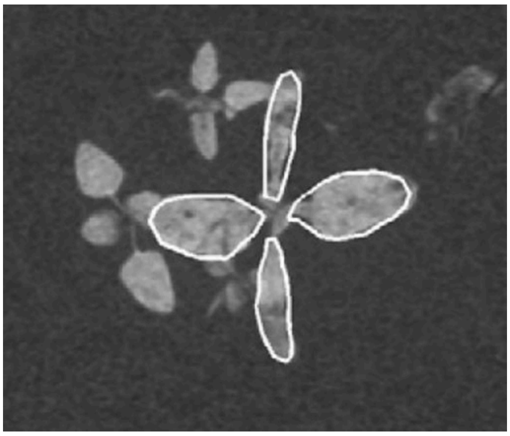

Figure 3.9. Search result of applying active shape model on occluded sugar beets. The deformed model, containing the crop grey pixels, is marked by the white line. Grey pixels outside the white line are weeds (from Persson & Åstrand, 2008).

Kaspersen and colleagues developed a novel image analysis algorithm (Weedcer), based on shape, size, colour and texture. It discriminates young seed-propagated weeds in cereals around the 3-4-leaf stage with row spacing of about 0.125 m in planar view red-green-blue (RGB) images. The leaf cover is the percentage of the observed unit area beneath the plant canopy. Weedcer correctly classified 91-92% of weed leaf in winter wheat and 84-79% in spring cereals (Kaspersen *et al*., 2010) (Fig. 3.10).

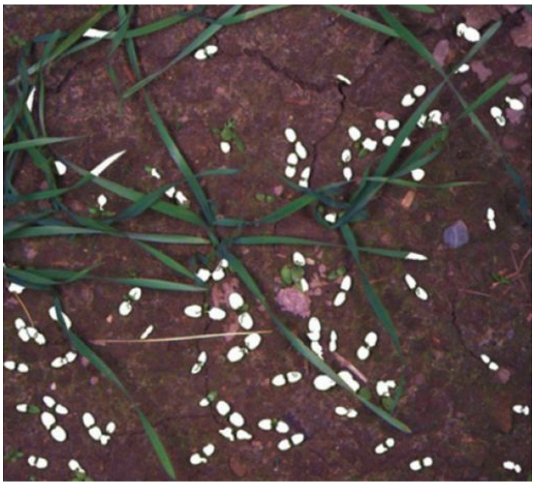

Figure 3.10. Image analysed with Weedcer; white objects = the automatically detected weeds (from Kaspersen *et al*. 2010)

Plant height and biomass are reliable parameters for the assessment of weed stands. These parameters can be estimated using ultrasonic sensors (Reusch, 2009). These sensors could also be used for weed detection and discrimination (Andújar *et al*., 2011a).
Andújar and colleagues discriminated grasses from broad-leaved in the inter-rows of maize based on their heights. An ultrasonic sensor was mounted on the front of a tractor, pointing vertically down in the inter-row area, with a control system georeferencing and registering the echoes reflected by the ground or by the various leaf layers. Static measurements were taken at locations with different densities of grasses (*Sorghum halepense* L.) and broad-leaved weeds (*Xanthium strumarium* L. and *Datura* spp.). The sensor readings allowed to perform the discrimination of pure stands of grasses (up to 81% success) and pure stands of broad-leaved weeds (up to 99% success). Moreover, canonical discriminant analysis revealed that the ultrasonic data could separate three groups of assemblages: pure stands of broad-leaved weeds (lower height), pure stands of grasses (higher height) and mixed stands of broad-leaved and grass weeds (medium height). Dynamic measurements confirmed the potential of this system to detect weed infestations. This technique seems to be really promising for the development of real-time spatially selective weed control technique, either as the sole weed detection system or in combination with other detection tools (Andújar *et al*., 2011a).

3.2.3 Texture features

Some researchers distinguish plant species according to the texture. Ishak and colleagues present a texture analysis for images of two weed species, a broad-leaved and a grass weed, in late growth stage (Ishak *et al*., 2009). Texture-based discrimination between grassy and broad-leaved weeds was also described by van Evert and colleagues. The method was based on the observation that grass leaves are long and narrow (several millimetres), whereas the leaves of broad-leaved weeds are at least an order of magnitude larger. Consequently, image parts with grass contain more colour and intensity transitions than image parts with broad-leaved weeds. This texture information can be used to

discriminate between grass and broad-leaved weeds. With this method 93% of broad-leaved weeds were detected (van Evert *et al*., 2011).
Gebhardt and Kühbauch segmented the image according to a homogeneity criterion and used textural and colour features to find *Rumex obtusifolius* L., *Taraxacum officinale* Weber and *Plantago major* L. in a grassland plant community with an accuracy of over 70% (Gebhardt & Kühbauch, 2007). From 3D sensor data Šeatović segmented broad leaves and classified them as weeds in grassland (Šeatović, 2008). Klose and colleagues developed a robot equipped with a weed detection system able to work in maize using a sensor fusion approach: a vertical laser triangulation sensor measuring the thickness of the maize plant steam was combined with a horizontally mounted camera viewing the maize row from above to find weeds within the row (Klose *et al*., 2008).

3.2.4 Location and temporal properties

Weeds are generally confined to the location and changes in species composition and population size occur slowly over time (Zijlstra *et al*., 2011). The location of a plant is a useful property to distinguish species. On the large scale there are several habitats, while on the small scale there are locations within a field with a higher probability of occurrence, e.g. at the borders of a field (Weis & Sökefeld, 2010).
Most weeds occur in patches within a field and their location was found to be stable over years. This effect is due to persistent seed banks in the soil and variable germination conditions. The germination rate is higher in areas with a high seed density. Perennial weeds have additional vegetative reproduction organs such as rhizomes, tubers and roots, from which the plants regenerate. Therefore, patches of perennial weeds were found to be most aggregated and stable (Weis & Sökefeld, 2010). This means that a weed map (historical map) can be used, to some extent, to predict the occurrence of weeds and patch locations for the following years (Zijlstra *et al*., 2011).
Since the RTK-GPS based seed or transplant map was close to the actual plant map, it was hypothesized that a simple greenness sensor could be used to look for plants. When a plant was detected its coordinates could be compared with the coordinates of plants in the plant map. If there were no corresponding plants on the plant map, it could be assumed to be a weed and an appropriate herbicide could be applied (Perez-Ruiz & Upadhyaya, 2012).

3.3 Automatic implements and autonomous robot for site-specific chemical weed control

Precision application technology opens the way towards operating on smaller treatment units in the field by applying herbicides according to the site-specific demand. With the use of new technologies, site-specific weed control aims at reducing herbicide input and retaining the efficacy of weed flora management (Zijlstra *et al*., 2011).
Over the last two decades, rapid development and implementation of new technologies (such as RTK-GPS, optical imaging and spectroscopy) for precision agriculture encouraged extensive studies on automated weed control in a row crop environment. As a result, researchers have investigated several concepts to apply automated weed control systems in a variety of crops using machine vision for plant species recognition and robotic

actuation mechanisms for in-row weed removal (Zhang *et al*., 2012). Patch spraying in real-time seems to be the preferred approach among the end-users (Lutman & Miller, 2007). Recent experienced carried out on precision targeting of chemical spray demonstrated the ability to target weeds within 1 cm crop plants (Slaughter *et al*., 2008).

The system WEEDit is a spraying technology that actively detects live plant matter on-the-go. Rather than spraying an entire area characterized by 10% weed coverage on average, WEEDit sensors are mounted to the spraying vehicle and can detect weeds up to 25 km h^{-1}, only turning chemical on for a short moment when a target plant is detected. WEEDit detects, measures and applies chemicals to plant matter. WEEDit runs on a standard 12 volt system. Power is connected directly to the battery and runs to an interface box. The interface box does many tasks, among them, it inverts 12 volts up to 30 volts in order to minimize power loss across large 36 m booms. WEEDit uses 30 volt spool solenoids across all of its spray nozzles. This allows higher voltages to be used but most importantly allows the interface box to send a very high signal voltage to that specific solenoid for fast opening times. These solenoids are able to open in 1 millisecond and close in 5 milliseconds. At 25 km h^{-1} the "delay distance" to open the solenoid is only 8 mm. The "smarts" inside the interface box send a high "opening voltage". Thus, the solenoid opens quickly, but then the voltage is lowered to a "holding voltage" should the solenoid need to remain open for longer bursts. One interface box has enough power to run a 36 m system without any additional components (WEEDit, 2013).

Gerhards and Oebel developed a system for site-specific weed control in arable crops with on-line detection system using digital image analysis, computer-based decision-making and GPS-controlled patch spraying. For automatic weed detection, three digital bi-spectral cameras were mounted in the front of a prototype of carrier vehicle. Plants were identified using a shape-based approach. Herbicide application maps were created according to interpolated maps of weed distribution and control thresholds for classes of weed species. Three different application maps were realized at the same time using a multiple sprayer with three separated hydraulic circuits. This allowed the herbicide mixture to be varied during application. Each of the three sprayer circuits had a boom width of 21 m, divided into seven sections of 3 m (Fig. 3.11). Each sprayer circuit and each section were separately turned on and off by a control unit via solenoid valves. The herbicide dose for the full spray boom was regulated by the same control unit via a computer. Three different volume rates were applied by changing the pressure in the system ranging from 200 L ha^{-1} (herbicide doses of 70%) to 290 L ha^{-1} (herbicide doses of 100%). During herbicide application, the spray control system was linked to an on-board computer loaded with the weed treatment maps. A DGPS was used for real-time location of the patch sprayer. The on-board computer compared the actual position of the sprayer with the information in the weed treatment maps and signals were transmitted to the control unit via a data bus in order to properly open each individual solenoid valve when herbicide application was warranted. Similarly, the herbicide dose was adjusted to the recommended rate in the treatment map. The results of some field tests carried out showed that the use of this map-based approach allowed to reduce herbicide spaying in winter cereals by 6–81% in the case of a.i. used to control broad-leaved weeds and 20–79% in the case of a.i. used to control grasses (Gerhards & Oebel, 2006).

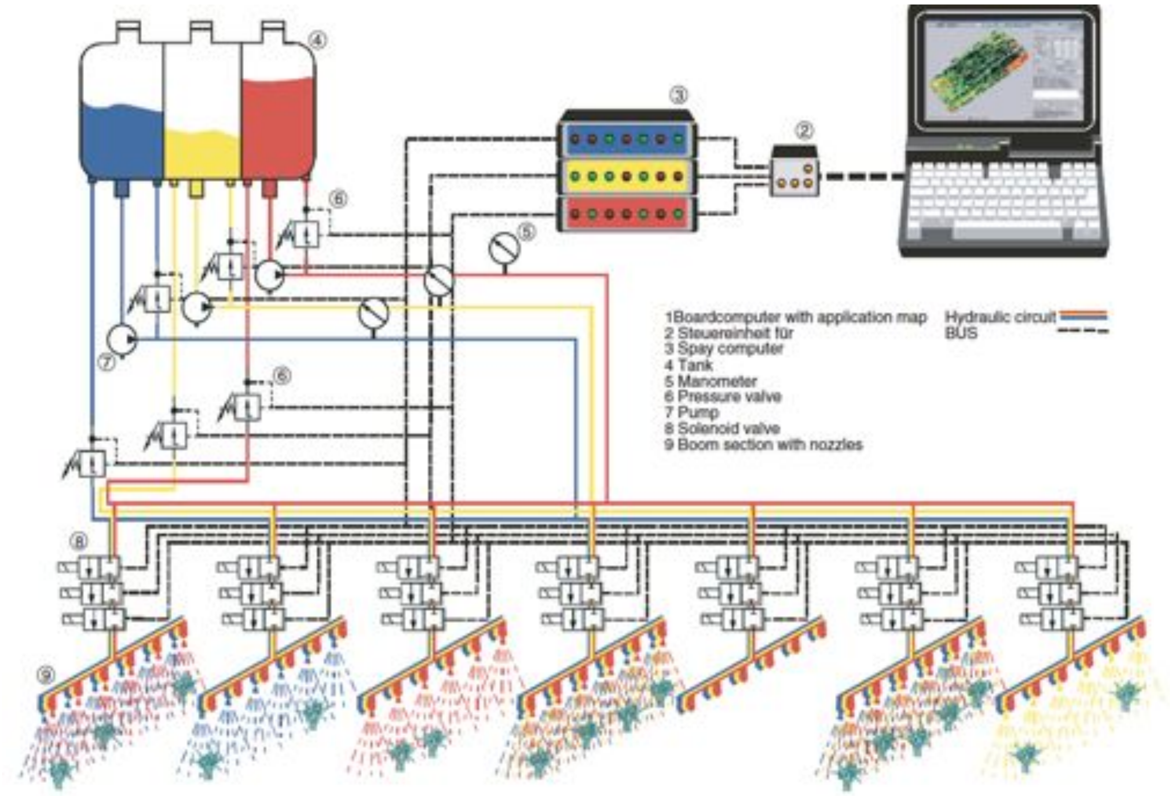

Figure 3.11. Sprayer control system for site-specific herbicide application with three separated hydraulic circuits (from Gerhards & Oebel, 2006).

The HortiBot is an autonomous vehicle developed for the use in agriculture (Jørgensen *et al*., 2007). It is equipped with a commercial downward-looking camera, which enables it to navigate using visible rows in the field. In areas with no rows the robot is positioned by use of RTK-GPS. The HortiBot is a lightweight four-wheeled robot and it is based on a modified framework of commercial available remote-controlled slope mower called "Spider ILD01". The use of a vision-based row guidance system and RTK-GPS ensures that the robot covers the whole field very accurately allowing to work with implement for precision field application, like cell sprayers. A cell sprayer is a vision-based spraying system for field crops, which only sprays in areas (cells) in the field where weeds are detected. All other areas without weed plants are not sprayed at all (Fig. 3.12) (Griepentrog *et al*., 2010).

Figure 3.12. HortiBot with Cell Sprayer (from Griepentrog *et al*., 2010).

Klose and colleagues developed the field robot Weedy (Fig. 3.13), which is able to navigate autonomously through maize fields and perform weed control both in the inter- and intra-row spaces. To achieve robust navigation, the row guidance of the robot has to function for either straight or curved rows even if the soil is wet or if plants are missing in the row. Another important part of the autonomous navigation besides the row guidance is the autonomous turn at the end of one row into the next. According to the definition of weed to be everything green within the field except maize plant, the Weedy robot has to be able to detect plants in the inter row space and it has to identify maize plants and all other plants in the inter- and intra-row. The system splits up into five main parts: the robot control system, the navigation control system, the weed control system, the speed and steering control system and the safety system. These five main systems of the robot are linked via a CAN-bus-system. Cameras, optical and acoustic distance sensors as well as other low-cost sensors (such as position encoder or angular sensors) are used for navigation and weed detection. For the weed control actuator, it is very important to be centred over the plants of the middle maize rows to keep a constant distance from the plants. Since the robot does not always drive perfectly in the middle of the row when passing curves, the weed control actuator needs to be moveable. As the actuator for the weed control unit an assembly of a linear drive, used for centring the actuator over the maize row, and a combination of a pump and different sprayers is used (Fig. 3.14) (Klose *et al.*, 2008).

Figure 3.13. Field robot Weedy (from Klose *et al.*, 2008).

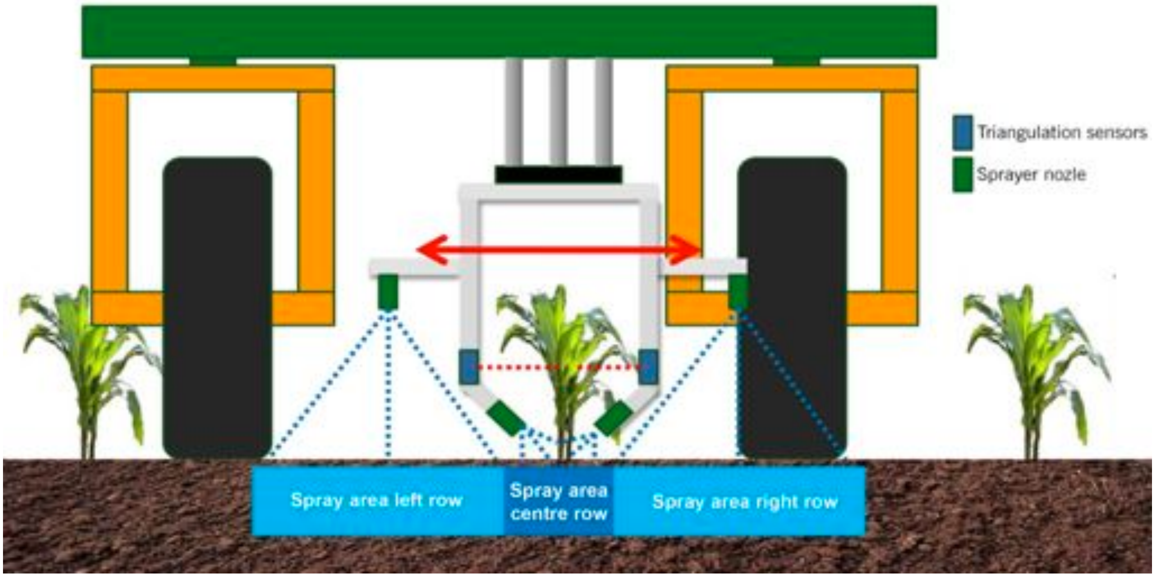

Figure 3.14. Weed control actuator of the robot Weedy. Triangular sensors were used to detect the plants of maize measuring the height profile of the plants and weeds and the thickness of the plant shafts (from Klose *et al*., 2008).

Berge and colleagues tested an autonomous GPS guided robot for real-time weed monitoring and patch spraying of broadleaf herbicides in spring cereals (Berge *et al*., 2012) (Fig 3.15). Weed monitoring was performed with the algorithm Weedcer (Kaspersen *et al*., 2010) (see Chapter 3.2.3) that estimated cereal cover, total broadleaf weed cover and the cover of mayweeds. Weedcer was used as decision system to apply patch spraying. Images were acquired using a colour camera and two custom xenon flashes. The herbicide savings varied from 22% up to 97% (Berge *et al*., 2012).

Figure 3.15. The robot used for weed monitoring and patch spraying; A=box with camera and xenon flashes; B=box with computer, GPS and external disc; C=GPS antenna; D=herbicide tank; E=spray boom (from Berge *et al*., 2012).

Perez-Ruiz and colleagues developed an innovative machine for weed control in inter-row and intra-row areas, with a unique combination of inter-row cultivation tooling and intra-row band spraying in six rows (Fig. 3.16). An electro-hydraulic side-shift frame (Perez-Ruiz & Upadhyaya, 2012) was used for row centre positioning (see also Chapter 3.1). An implement that incorporated tools for mechanical and chemical weeding was attached to

the side-shift frame using an anchoring plate. For the inter-row weed control system, seven units were used to cultivate six crop rows. Five central complete and two half hoeing units were mounted on spring shanks and attached to the implement chassis with an angle plate (90°). In figure 3.17 is shown how a set of beet hoes worked between crop rows, 100 mm from the centre of the row and with a working width of 300 mm. There was a 25 mm overlap between the spray band and the beet hoes on each side to avoid untreated areas. The system had two gauge wheels for controlling the working depth and two folding bars, joined by hinges at both the left and right sides, to allow a larger implement width that was easily compacted for safer field-to-field transportation (Perez-Ruiz *et al.*, 2013).
The hydraulic sprayer components needed to apply herbicide to six crop rows in narrow bands were mounted on the chassis along with a 500 L tank. Before field tests, a specific band width was selected and checked with the appropriate nozzle height for a spray angle of 80° with respect to the crop (band width equal to 250 mm and nozzle height of 150 mm). An RTK-GPS system was used to correct the lateral deviation of the combined row crop cultivator and band sprayer implement (Perez-Ruiz *et al.*, 2013). The machine was tested in sugar beet. The herbicide application rate was approximately 50% compared to a broadcast spraying method, achieving similar weed control rates. Obviously, also a significant reduction in the operating costs of weed management was obtained (Perez-Ruiz *et al.*, 2013).

Figure 3.16. Prototype of six-row mechanical weed control cultivator for inter-row areas and band spraying for intra-row areas (from Perez-Ruiz *et al.*, 2013).

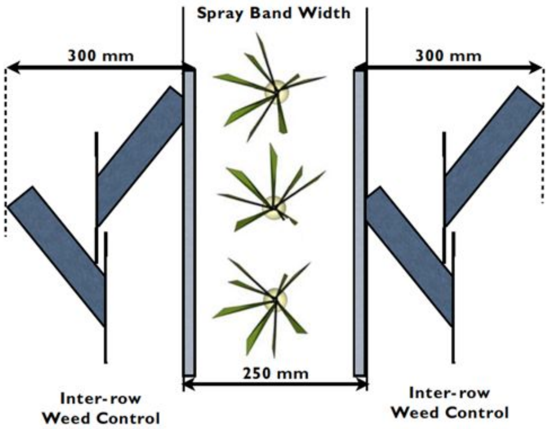

Figure 3.17. Mechanical inter-row weed control and herbicide spray band with the overlapped zones (grey) (from Perez-Ruiz *et al*., 2013).

The ASETA project (acronym for Adaptive Surveying and Early treatment of crops with a Team of Autonomous vehicles) is a multi-disciplinary project combining cooperating airborne and ground-based vehicles with advanced sensors and automated analysis to implement a smart treatment of weeds in agricultural fields. The purpose is to control and reduce the amount of herbicides, consumed energy and vehicle emissions in weed detection and treatment process, thus reducing the environmental impact. The project addresses this issue through a closed loop cooperation among a team of unmanned aircraft system (UAS) and unmanned ground vehicles (UGV) with advanced vision sensors for 3D and multispectral imaging. ASETA project started in 2010 and is the first project of this kind to use a team of both UAS and UGV in agriculture (Kazmi *et al*., 2011).
ASETA has three unmanned mobile robots available for the project (Fig. 3.18). The close cooperation among robots is an important part of ASETA in order to ensure a safe and efficient execution of the tasks provided by the Task Management. The cooperation layer will determine which robot will tackle each task and to some extent in what order. Multispectral aerial imaging can detect hotspot locations and volumes, but on a macro level. It cannot resolve individual plants at intra-row level. Thus, in this project, a ground based imaging system has to be used in order to perform close-to-crop inspection. The major objective in this project consists in utilizing 3D computer vision techniques in weed detection. A shape-based approach is used to distinguish crop from weeds (Kazmi *et al*., 2011).

Figure 3.18. Autonomous vehicles in ASETA, (from left): Vario XLC, Maxi Joker-3 and robuROC-4 (from Kazmi *et al*., 2011).

CHAPTER 4. PHYSICAL WEED CONTROL

Weed control is a significant issue in agricultural crop production. Weeds compete with crop plants for water, nutrients and sunlight and can have a detrimental impact on crop yields and quality if uncontrolled. A number of studies have documented the yield loss associated with weed competition (Slaughter *et al*., 2008).
Currently, for row crops, typical weed control methods include a combination of pre-emergence herbicide application and/or pre-emergence tillage, mechanical cultivation, post-emergence herbicide application (if selective herbicides or crop resistance is available) and hand hoeing. While herbicides based weed control may be both biologically efficacious and economically effective, in many situations it has heavy environmental costs. In many locations, increasing pesticide use regulations, consumer concerns, and a growing interest in organically produced foods limit the long-term acceptability of herbicides application (Slaughter *et al*., 2008).
Physical weed control techniques are non-chemical methods that are becoming increasingly important at legislative level and are promoted in order to ensure lower environmental impact and the health of consumers and operators. Physical weed control is a method that includes mainly the following techniques: soil tillage, direct mechanical and thermal weed control (Cloutier & Lablanc, 2011).

4.1 Soil tillage

Soil tillage is a preventive method to control weeds. Preventive methods are those used before crop establishment whose main goal is to reduce weed emergence in the crop (Melander *et al*., 2005). Tillage refers to the mechanical manipulation of soil for the enhancement of crop production, according to the American Society of Agriculture and Biological Engineers (ASABE, 2009a).
Primary tillage (the first major soil working operation) based upon soil inversion provides some control of annual weed species by burying some of their seeds at depths that prevents them from emerging and can also partially control perennial weeds by burying some of their propagules, thereby preventing or slowing down their emergence. Once on the surface, these propagules will be exposed more directly to weather conditions and then to desiccation (Mohler, 2001). The primary tillage tools are mouldboard ploughs, disc ploughs, powered rotary ploughs, diggers and chisel ploughs (ASABE, 2009a).
Mouldboard ploughs are the most widely used tools to perform primary tillage and allow the control of both actual (weeds present in the field) and potential (weeds that could emerge during the crop cycle) weed flora by means of soil inversion. In order to increase the degree of control of the vegetative and reproductive structures of perennial weeds and/or to reduce the risk of the regrowth of buried weeds near the soil surface the mouldboard ploughs can be equipped with jointers. The diggers produce an incomplete soil turning compared with the mouldboard ploughs and their weeding actions are effective only on actual flora while are not effective on potential flora. Furthermore, the diggers may increase infestations with perennial weeds because the vegetative structures and propagules are cut and not buried in the soil, thus potentially propagating them. Also the

weeding action of the chisel ploughs is effective only on the actual flora while the potential flora is not controlled because there is not soil inversion; however, they help to control perennial weeds as a portion of their vegetative structures are brought to the soil surface where they can be destroyed by being exposed directly to the weather conditions (Peruzzi *et al.*, 2011a).

The secondary tillage (tillage operations following primary tillage) in addition to prepare the seedbed, buries soil amendments and fertilizers and performs weed control (ASABE, 2009b). Secondary tillage implements are various types of cultivators, harrows, and PTO powered machines. PTO powered machines control emerged annual weeds extremely well but can increase perennial weeds by cutting their vegetative and reproductive structures and then causing their multiplication. The use of cultivators equipped with goosefoot tools well control emerged weeds but it could also increase new weed emergence. Harrows equipped with different type of tools (discs, flexible and/or rigid tines, radial blades, etc.) have different weeding actions according to soil conditions, weed type, stage of development, density, and degree of anchorage. For this reason, several implement are modular and can be equipped with a combination of tools of different shapes in order to perform different actions in a single passage (Peruzzi *et al.*, 2011b).

4.2. Direct mechanical weed control

Direct mechanical weed control is mainly associated with "cultivating tillage", often known as tertiary tillage. Cultivating is carried out after crop sowing/transplanting in order to control weeds and consists of shallow tillage performed with a variety of equipment often categorized as hoes or harrows. It includes broadcast, inter-row and intra-row cultivation (Rueda-Ayala, 2010).

4.2.1 Narrow-row crops

Narrow-row crops are usually grown at high densities (> 300 plants m^{-2}) at 100- up to 180-mm row spacing. In organic farming, mechanical methods are mostly used to perform control: harrowing and hoeing. Harrowing treats the whole crop, whereas hoeing mainly control weeds in the inter-row area (Melander *et al.*, 2005).

In narrow-row crops, control can be conducted using a spring-tine (also called flex-tine) harrow or other harrow types. Spring-tine harrows have fine, flexible tines, which control weeds by vibrating in all directions, thus causing uprooting, burying and leaf breaking. Usually the tension on the tines can be adjusted to change the intensity of the treatment. Flex-tine harrowing well controls not only weeds seedlings, but if used after crop emergence, also many germinated and emerged weed species having a poor anchorage to the soil. These harrows are more effective on broad-leaf plants and less on grasses (Cloutier *et al.*, 2007).

Weed harrowing with spring-tine, chain, or drag harrows may be used, but the spring-tine harrow with flexible tines is for sure the most preferred according to its widest range of applications. It can either be used before crop emergence or post-emergence, and it performs weeding on the whole crop. If the crop plants are larger than the weeds, the weeds will be damaged more by the harrow. Crops have different sensitivity to

disturbance; monocotyledons such as cereals are less sensitive than dicotyledons, and high crop density in the rows causes the tines to move away from the rows, thereby making the control selective (Melander *et al*., 2005).
Selective harrowing is possible after tillering stage because the tines operate almost only in the inter-row space. As the crop grows taller, the rows offer increasing resistance to the tines, thus forcing the tines to cultivate the inter-row spaces (Melander *et al*., 2005).
Inter-row hoeing using ducksfoot or "A"-width hoe blades that cultivate the inter-row area of cereals was able to control tap-rooted and erect weed species more effectively than harrowing. Inter-row hoeing is also less sensitive to treatment timing because even well-anchored weeds can be uprooted (Melander *et al*., 2005).

4.2.2 Wide-row crops

Wide-row crops are typically grown at 0.3 – 0.7 m row spacing and present two different situations for direct physical weed control. Inter-row weeds can be easily removed by ordinary inter-row cultivation while intra-row weeds constitute a major challenge (Melander *et al*., 2005; van der Weide *et al*., 2008).
Inter-row cultivation can be carried out by inter-row cultivators, discs, brush weeders, rotary cultivators, rolling cultivators, basket weeders and rolling harrows. (Cloutier *et al*., 2007). Mechanical methods that only work the inter-row space usually work successfully in most situations, mainly because the crop plants are not directly affected by the weeding tools that, moreover, can be shielded in different ways (Melander *et al*., 2005). Unfortunately, the effect is often sub-optimal within the crop rows, because most weeders are non-selective (the weeding tool itself is unable to distinguish between crop and weed plants) (van der Weide *et al*., 2008). Inter-row cultivation is regularly used both in conventional and organic management. Ordinary steerage hoes with hoe blades configured either as a "ducks foot" or "Awidth" shape mounted on either S-tines or shanks are normally used for inter-row cultivation, but other cultivators such as rotary hoes, rolling cultivators, and PTO-driven cultivators are also used. Several new implements were recently introduced where multiple mechanical tactics were included in order to improve effectiveness (Melander *et al*., 2005).
If properly adjusted, inter-row machines can perform also intra-row control of small weeds in many crops and in several growth stages (van der Weide, 2011). The rolling harrow (designed, fully realized and patented at the University of Pisa, Italy) is a multipurpose implement that, depending on the arrangement of the tools (spike discs and cage rolls), can be used both for secondary tillage and for inter-row hoeing interventions. Moreover, the rolling harrow can be equipped with flexible tools (acting as vibrating tines) that can selectively control weeds in the rows and with a manual guidance system that enhance the precision of the weeding action. Young weed seedlings are controlled because they are uprooted from the soil, even if it is very wet and plastic (Peruzzi *et al*., 2007; Raffaelli *et al*., 2011).
Mechanization of the intra-row weed control would not only lower the direct costs for hand-weeding, but also release time and labour to be used elsewhere in the production. Intra-row weeds are those that grow within the line of row crop plants and are not affected

by inter-row cultivation, such as hoeing. If insufficiently controlled, they cause major problems for organic growers in wide-sown crops, such as vegetables, maize, etc. (van der Weide *et al*., 2008).
Several mechanical methods have application for intra-row treatment, primarily controlling weeds by uprooting or burying, or both. As with most other mechanical weeding implements, operator skill, experience, and knowledge are critical to perform a successful intervention (Melander *et al*., 2005).
Intra-row cultivation can be carried out by torsion weeders or other flexible tools (Fig. 4.1) (Cloutier *et al*., 2007; Peruzzi *et al*., 2007). Torsion weeders control weeds less rooted and anchored to the soil than the crop by a pairs of bent spring tines having two short segments that work very closely together and parallel to the soil surface, even overlapping over the crop plants. Torsion weeders, with pairs of tines set on either side of the crop row and lowered 20 to 30 mm into the soil, offer more precise intra-row control but steering becomes crucial, normally including a second operator to specifically steer the implement (Peruzzi *et al*., 2007; Raffaelli *et al*., 2011). Torsion weeders are often used in combination with precision cultivators equipped with a manual guidance system in order to perform a post-emergence, selective, gentle and very precise weeding treatment on the whole surface in only one passage (Cloutier *et al*., 2007; Peruzzi *et al*., 2007; Raffaelli *et al*., 2011).
Peruzzi and colleagues developed a precision steering hoe, able to perform both inter and intra-row weed control. The machine is equipped with rigid tines for inter-row very shallow tillage and spring tools (torsion weeders or vibrating tines) for intra-row weed control (Peruzzi *et al*., 2007) (Fig. 4.2).
Finger weeders, with flexible rubber tines on ground driven-cone wheels, were also developed specifically for intra-row weed control (Fig 4.3). Intra-row brush weeding is another method with similar constraints to those of finger and torsion weeding. A brush is placed on either side of the row and each brush is rotated by a hydraulic engine to create either uprooting or soil coverage of the weeds, depending on the direction of rotation (Melander *et al*., 2005).

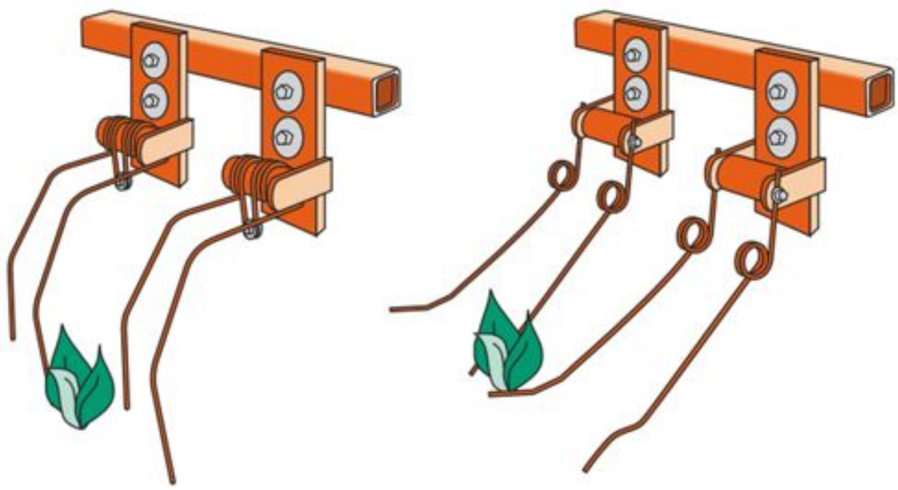

Figure 4.1. Draw of the vibrating teeth (on the left) and torsion weeders (on the right).

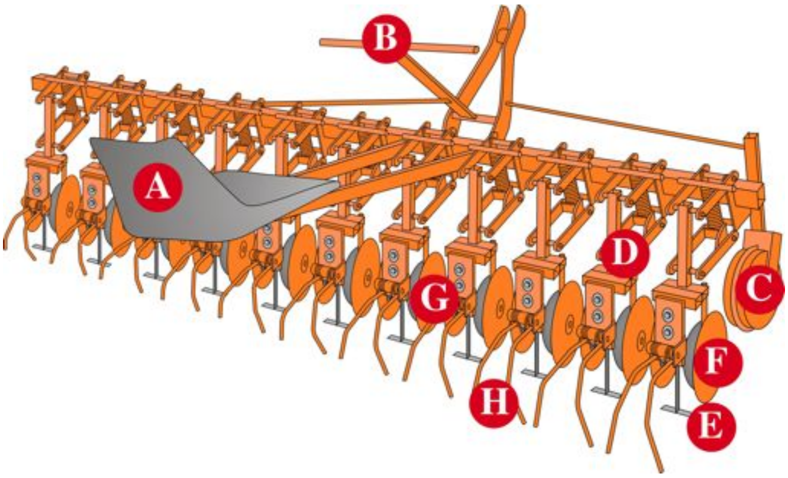

Figure 4.2. Draw of the precision hoe developed by Peruzzi *et al*. (2007) for both inter and intra-row weed control: (A) seat; (B) handlebars for steer; (C) directional wheels (D) articulated parallelogram; (E) blade tools for inter row weed control; (F) side discs; (G) support wheel; (H) vibrating teeth.

Figure 4.3. Finger weeders operating in transplanted tomatoes.

4.3. Thermal weed control in agriculture

The thermal means for weed control in agriculture include open flame, steam, hot water, electrical energy, microwaves, ultraviolet radiations, laser and freezing (Ascard & van der Weide, 2011). These techniques are normally applied in a not selective way. The effect of these techniques is based on the different sensitivity of crop and weeds to the applied dosage (Bakker *et al*., 2013). Thermal weeding does not leave any chemical residue in the environment and does not disturb soil (Hatcher & Melander, 2003).

4.3.1 Flaming

Flaming allows to avoid the use of herbicides and thereby eliminate the risk of chemical pollution of the environment. Flaming allows to control a wide range of annual weed species, sometimes tolerant or resistant to herbicide action. Flaming should not be confused with burning; flaming does not burn the plants but heats them rapidly, in order to cause the rupture of the cell membranes (Ascard, 1995).
The effectiveness of flame weeding is attributed to both a direct effect of the flames on the cell membranes and an indirect effect during the following desiccation (Ellwanger *et al*., 1973a, 1973b). The response to flaming varies among species, growth stage, dose, temperature, and leaf moisture (Ascard, 1995; Ulloa *et al*., 2010b). The degree of

penetration of the flames depends on the used technique (Parish, 1990a). The tolerance of different plant parts to heat injury can be influenced by several other factors, including the presence of protective layers of hair, wax, lignification, external and internal water status of the plant and species regrowth potential (Ascard *et al.*, 2007).

Regardless of the growth stage broadleaf weeds are more susceptible to flaming than grasses (Ulloa *et al.*, 2010b). Such differences are probable a result of the physical position of the growing point at the time of flaming (Knezevic *et al.*, 2009). The tolerance of both grassy and broadleaf weed species increases as plant size increases (Parish, 1990b; Ulloa *et al.*, 2010b). The higher thermal sensitivity of younger plants is likely due to the fact that they have thinner leaves, lower shoot biomass and less protected meristems (Ascard, 1995). The thin and delicate plant tissues at the early vegetative stage is heat sensitive, and the plants cannot regrow fast when they get damaged (Ascard, 1994). Another critical part of the young plant is the growing point in the shoot apex, which also determines the heat tolerance of plants (Ascard, 1994).

Generally flaming cause the desiccation of the annual broadleaf complete few days after treatment whereas the grassy species growth new leaves after a week or two (Ulloa *et al.*, 2010b). The most important factor distinguishing sensitive and tolerant species was not the heat tolerance, but rather the ability of plants to regrow after the flame treatment. A large amount of reserve food in the roots increases the plant ability to regrow (Ascard, 1995).

There are three fundamental types of thermal weeders on the market: the open flame burners with cover (T max=1900°C) (used by Ascard, 1995), the open flame burners without cover (T max=1500°C) (Knezevic *et al.*, 2013; Peruzzi *et al.*, 2007; Raffaelli *et al.*, 2011; Ulloa *et al.*, 2010b), and the infrared weeder (used by Rask *et al.*, 2012), with essentially no visible flame and T max=500°C. All the flaming systems use LPG or similar gas mixtures as fuel (Hatcher & Melander, 2003).

Pre-emergence flaming was the predominant thermal weed control method in slow germinating row crops such as onion, leek, carrots, etc. (Fig. 4.5). Flaming kills weeds that have emerged prior to the crop, mainly by rupturing the cell membranes and the indirect effect of subsequent desiccation (Hatcher & Melander, 2003; Peruzzi *et al.*, 2007; Raffaelli *et al.*, 2011).

Post-emergence broadcast flaming weed control in heat-tolerant crops (i.e. maize, soybean, sunflower, onion, garlic, etc.) represents an alternative to mechanical weed control (Knezevic, 2009; Ulloa *et al.*, 2010b). Knezevic and colleagues applied a propane dose of 50 kg ha^{-1} parallel to the soybean rows at an operating speed of 4.8 km h^{-1}. The obtained results indicate that soybean could tolerate a maximum of two flaming treatments at unfolded cotyledon and fifth trifoliate growth stages per season without any yield reduction (Knezevic *et al.*, 2013). Ulloa and colleagues tested the response of maize to broadcast flaming. 5-leaf stage was the most tolerant one for broadcast flaming, whereas 2-leaf stage was the most susceptible resulting in the highest visual crop injury ratings, dry matter reductions and largest loss of yield. They also investigated the response of sorghum to broadcast flaming as influenced by propane dose and crop growth stage. The results empathized that the maximum yield reductions caused by the use of the highest propane dose of 85 kg ha^{-1} were 11%, 6%, and 9% for 3-leaf, 5-leaf, and 7-leaf growth stages, respectively (Ulloa *et al.*, 2011a).

Figure 4.5. Pre-emergence flaming performed with four open burners.

4.3.2 Soil steaming

Soil steaming is a preventive method to control weeds. Mobile soil steaming was recently taken into close attention because of its potentially very high effectiveness leading to almost complete weed control for long periods (Melander *et al*., 2005). Soil steaming can allow to strongly reduce laborious intra-row hand weeding in row crop systems where herbicides are not used. Steam is applied to the whole soil bed area at a depth of 50-100 mm in the soil depending on the steaming time. Steaming causes high mortality of weed seeds, which could lead to effective and long-term weed control (Ascard & van der Weide, 2011).

Van Loenen and colleagues treated with steam soil samples containing the seeds of *Chenopodium album* L. and *Agropyron repens* L. in controlled conditions at temperatures ranging from 40 to 80°C. Steaming at 50 or 60°C for 3 minutes, followed by an 8-minutes resting period in the steamed soil and immediate removal from the soil thereafter, resulted in 100% kill of seeds (Van Loenen *et al*., 2003).

Peruzzi and colleagues developed an innovative self-propelled machine for soil steaming and tested the effect of soil steam injection on the natural weed seedbank. Treatments were carried out using steam alone or in addition of compounds (KOH or CaO) that increase weed control by boosting soil heating through exothermic reaction with the steam, reaching peak temperatures higher than 80°C at 7 to 15 cm of depth. The effects of the treatments on seedbank were analysed using the seedling emergence technique at three different soil depths (0-7, 7-14 and 14-21cm). Non-linear dose-response curves were used to correlate weed emergence with soil temperature sum. Surface steaming was the most effective treatment (up to 100% weed control at 0-7cm depth). At the deepest soil layer, steaming depleted the weed seedbank up to 95%. The most homogeneous weed control effect across the soil profile was obtained with the addition of KOH or CaO, with differences depending on their distribution ratio (Peruzzi *et al*., 2011 and 2012).

However, extremely high fuel consumption and low work rates are major disadvantages of current soil steaming technology. This led the idea of band-steaming where only a limited soil volume is steamed corresponding to the intra-row area (Melander *et al*., 2005).

Band steaming is a new technology with the potential to radically lower the burden of hand-weeding intra-row weeds in organic vegetable cropping. Preliminary studies with band-steaming have shown effective control of viable weed seeds when the maximum soil temperatures reach 60-80°C (Melander & Kristensen, 2011). Two soil types (sand *versus* sandy loam) and two moisture levels (moist *versus* dry) were studied in one experiment while two levels of structure of a sandy loam (coarse *versus* fine) were included in a second experiment. A third experiment was focussing on the significance of heat duration expressed as the speed of cooling-down after steaming had been stopped. Weed control was generally greater in sand than in sandy loam and with soil irrigation. Steam application to the finely structured soil improved weed control. The rapidity of cooling from the maximum temperature did not affect the effectiveness of the treatment on weed seed mortality. A maximum soil temperature of 80°C should ensure satisfactory weed control under moist soil conditions, especially if the soil is cultivated prior to steaming (Melander & Kristensen, 2011).
Peruzzi and colleagues developed a prototype of machine able to perform band-steaming after CaO incorporation into the soil (Fig. 4.6). The machine is equipped with a water tank, three hoppers containing CaO and an industrial steam generator providing an outflow of about 1300 kg h^{-1}. The steam generator unit is connected to PTO-driven small rotary hoes 0.18 m wide placed on three foldable sections at a distance of about 0.35 m. Each section of the frame treats four bands of soil. The machine present a large working width that reduces the operative times needed to perform the steaming treatments. The total working width is about 5 m. The steam injection is superficial in order to kill weed seeds till a depth of 5-7 cm (Peruzzi *et al*., 2012).

Figure 4.6. Operative machine realized by Peruzzi and colleagues to perform band-streaming and incorporate CaO into the soil (Peruzzi *et al*., 2012).

4.3.3 Hot water

Hot water can be used where flaming is not desirable because of fire hazards. However the use of hot water requires large amount of water and energy, which makes the method not much interesting on arable land (Ascard & van der Weide, 2011). Using hot water as a foliar spray, the energy used to obtain 90% reduction of *Sinapis alba* L. plant number in the 2-leaf stage was 3970 MJ ha^{-1}, corresponding to 110 kg ha^{-1} of diesel fuel, and 10,000

L ha^{-1} of water. The plant stage is important because a very high amount of energy is required to control plants at the six-leaf stage in comparison with that used to control plants at two-leaf stage (Hansson & Ascard, 2002).
The energy use in hot water treatments is high and attempts were done to improve application efficiency. The control efficiency was improved and the effective travel speed increased by using a long insulated shield with nozzles or an insulating shield behind the nozzles (Hansson & Ascard, 2002).

4.3.4 Electrical energy

Also electrical energy was used to kill weeds. The control equipment consists of a generator, a transformer, electrodes, and rolling coulters. Two systems was developed; the spark discharge method that uses short-duration, high-voltage pulses with two electrodes around the plant, and the electrical continuous contact method that uses a high-voltage electrode touching the unwanted plant resulting in a current passing through the plant. The technology requires that the weeds are taller than the crop in a mixed weed-crop population in order to allow selective electrode contact with the weeds. Some damages are reported also on roots and rhizomes of weeds as the current flows through the plants into the root system before it dissipates into the soil. Plant with large below-ground parts are damaged to a lesser extent, and the root damage is greater in drier soils. While electrocution appears to be an interesting option in some situations, the commercial use is limited by several factors, including high equipment cost, inefficient control of small weeds, and a concern for the application safety (Ascard & van der Weide, 2011).

4.3.5 Microware radiation

Microwaves for dielectric heating have been investigated to kill weed seeds. However, the effectiveness of microwaves in killing soil-borne seeds under field conditions is limited, because much energy is wasted in heating a large volume of soil to damage seeds. Microwaves do not penetrate enough deeply according to their quick attenuation, especially if the soil is characterized by high water content. Furthermore, the travel speed of the application equipment is extremely slow. The energy use of microwave-based weed control system in a field ranged from 10 to 34 GJ ha^{-1}, corresponding to a fuel consumption of between 1000 and 3400 kg ha^{-1}, respectively (Ascard & van der Weide, 2011).

4.3.6 Ultraviolet radiation

High levels of ultraviolet radiation (1 to 100 GJ ha^{-1} range) seemed to be able to control weeds. When plants are irradiated with UV, energy is absorbed by the plant tissue, damaging plants similarly to flaming. Experimental equipment to apply high doses of UV was developed by the Danish company Electro Light (Ascard & van der Weide, 2011).

4.3.7 Laser

Laser is considered as a cutting device for physical weed control. Such lasers are available in the visible range (wavelengths of 750 - 400 nm), and in the infrared range (IR) (wavelengths of 1 mm - 750 nm). Visible and IR lasers applied to plant material act via explosive ejection, i.e. ablation of plant tissue generated by multiphoton and avalanche electron ionisation (Mathiassen *et al*., 2006).
When *Solanum nigrum* L. seedlings were cut below the meristems, about 10 J mm^{-1} of CO_2 laser energy was needed to obtain 95% reduction of plant dry weight (Heisel *et al*., 2002). Mathiassen and colleagues showed that laser treatment of the apical meristems caused significant growth reduction and in some cases had lethal effects on weeds. The biological effectiveness of the laser control method varied among weed species and was related to wavelength, exposure time, spot size, and laser power (Mathiassen *et al*., 2006).

4.3.8 Freezing

Freezing with liquid nitrogen (-196°C) and CO_2 snow (dry ice, -78°C) were compared with flaming. Freezing affected the weeds in a similar way to flame weeding, but it required 6000 and 12,000 MJ ha^{-1}, for liquid nitrogen and CO_2 snow, respectively. Freezing, therefore consumed about three to six times more energy to obtain the same level of weed control as flame weeding (Ascard & van der Weide, 2011).

4.4 Combinations of physical weed control methods

Mechanical post-emergence methods have to be combined with methods applied in pre-sowing/transplant or pre-emergence to overcome or lower the problems connected with poor selectivity. Approaches in which two or more methods are combined into a specific control strategy adapted to the actual weed problem provided some promising results. Pre-emergence methods control the first flushes of weed seedlings that emerge before the crop and thus delay their further emergence and growth, allowing the crop to gain a size advantage (Melander *et al*., 2005). Pre-emergence harrowing is usually gentle on the crop, provided that the crop is sown deeper in the soil than the soil layers from which most weed species emerge (van der Weide *et al*., 2008).
False and stale seedbed techniques are preventive management options able to kill the nondormant weed seeds in the germination zone (about 6 cm soil layer) before crop planting or transplanting (Boyd *et al*., 2006). In false seedbed technique the preparation of the seedbed is followed by one or more superficial secondary tillage with appropriate implements at about one-week intervals prior to sowing or transplanting the crop (Mohler, 2001). When soil conditions and time allow performing shallow soil tillage this procedure can be repeated several times prior to sowing or transplanting the crop (Cloutier *et al*., 2007). Implements like flex-tine harrows and rolling harrows can be properly used for this purpose (Peruzzi *et al*., 2011). Pre-emergence soil cultivation after sowing and before crop emergence has the potential to control early germinating weeds. At the same time, it may cause problems by stimulating subsequent weed germination (Melander *et al*., 2005). The stale seedbed technique is realized almost in the same way of false seedbed technique, but

it includes before transplanting or crop emergence the control of the emerged weeds without disturbing the soil (Mohler, 2001). Traditionally herbicides were utilized for this purpose, but in organic agriculture flaming can be properly used (Rasmussen, 2003).
Baumann achieved 90% weed control in maize on a sandy soil by combining two passes of pre-emergence harrowing with eight passes of post-emergence harrowing with no associated yield decline (Baumann, 1992). Combination of inter-row hoeing and weed harrowing at 240-mm row width gave better weed control in winter wheat than harrowing alone at 120-mm spacing (Rasmussen, 2004).
Lundkvist used a spring tine harrow on oat and spring wheat and achieved the higher weed density reduction when a late pre-emergence harrowing was combined with one or two post-emergence harrowing treatments, although this also resulted in a decrease in cereal yield of about 10% on average (Lundkvist, 2009).
Flaming is used mostly as one part in a weed control programme that involves other methods that are usually applied later. Pre-emergence flaming followed by post-emergence hoeing of weeds was found particularly promising (Peruzzi *et al*., 2007; Raffaelli *et al*., 2011; Fontanelli *et al*., 2013). Pre-emergence flaming followed by post-emergence vertical brush weeding gave 90% intra-row weed control over 2 year of experiments in leek but only 39 to 74% effectiveness in onion (Melander & Rasmussen, 2001).

CHAPTER 5. PRECISION PHYSICAL WEED CONTROL

Both increasing cost of chemicals and soil pollution caused by herbicides residues ask for alternative methods of weed management. On the other hand, there is a strong political interest in the European Union to increase the amount of organically grown products as organic farming is not only a political goal, but it also represent a need from the market. As more and more customers ask for organically grown products many companies need to increase this kind of supplies (Åstrand & Baerveldt, 2005). Autonomous mechanical or thermal weed control systems could contribute to increase the available of organic products allowing to replace hand weeding and reducing agriculture current dependency on herbicides and improving yields, product quality and economical incomes of the farmers (Bakker *et al*., 2010).

5.1 Automatic operative machines and autonomous vehicles for mechanical weed control

Mechanical methods of removing weeds within the seedline, including the use of tools such as mechanical knives and rotating hoe are suited to be employed as robotic weed control actuators (Slaughter *et al*., 2008). Automation of mechanical weed control in arable farming could contribute to sustainable food production at lower cost (Bakker *et al*., 2010). Several developments and investigations were carried out in order to automate the lateral control of hoes. Actually the most promising automation principles are based on GPS and computer vision. A fusion of both surely represents the most promising strategy, because advantages of absolute and relative referencing principles compensate each other (Griepentrog *et al*., 2010).

Experiments on selective harrowing were carried out at the University of Hohenheim under the sensor based mechanical weed control approach. The intention was to combine real-time sensors for weed detection, positioning and measuring soil compaction with different tools able to perform mechanical weeding (Weis *et al*., 2008). The setup of the experimentation used to automatically control the intensity of harrowing operations is shown in figure 5.1. All measuring and weeding tools are attached to the tractor (t). With a bi-spectral camera (bc), images of crop and weeds are taken in order to compute the plant coverage as a percentage before and after flex-tine harrowing. A soil sensor (ss) measures soil compaction allowing to quantify the resistance to mechanical action. Positions are detected with a real time kinematics differential global positioning system (RTK-DGPS). All data are received, stored and computed within a control unit (cu) in order to generate the appropriate algorithm to automatically set up the machine. A more aggressive (strong) or less aggressive (light) treatment is directed through a motor (m), which changes the angle of the flex tines (ht). This adjustment is defined taking into account crop and weed soil coverage aiming to obtain the highest weed control and the least crop damage. Data coming from soil sensor are measured to generate a function that controls how many soil resistance force units define either a smaller or a greater angle of the tines. The images taken by means the bi-spectral cameras are used to determine total plants (crop and weed) coverage in percentage. Then soil coverage can be calculated by simple subtraction. Image classification procedures allow to create weed maps in order to identify patches where the harrow must work with higher or lower intensity. Image based weed maps are used to define the increasing harrowing frequency (Weis *et al*., 2008).

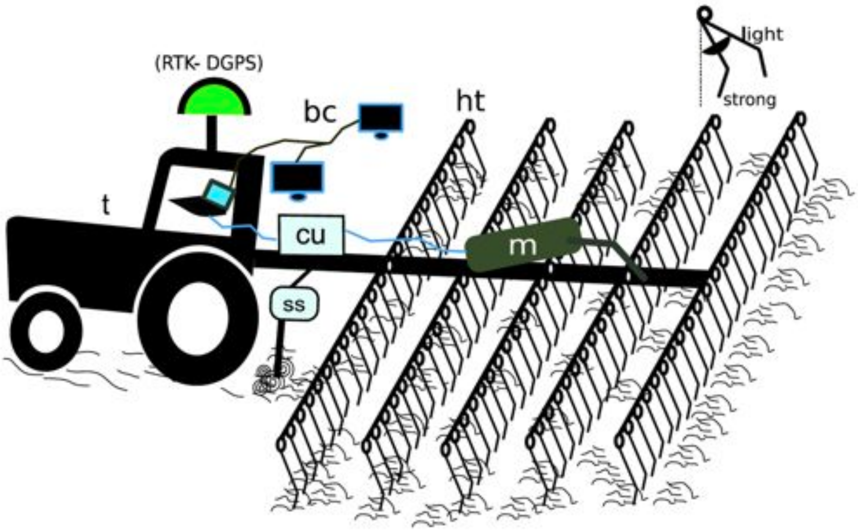

Figure 5.1. Scheme of an automatically controlled real-time flex-tine harrow (from Weis *et al*. 2008).

Tillett and colleagues developed a tractor-mounted cultivation system based on a commercially available steerage hoe (equipped with common inter-row cultivation blades) fitted with two novel discs rotating on a vertical axis. The discs were mounted on a depth control wheel and set to cultivate at a shallow depth (typically 20 mm) within the crop rows. Crop damage was avoided by cutting out a section from the disc's plan profile and rotating it in synchrony with forward movement in order to make the cut-out always coinciding with the regularly spaced transplants (Fig. 5.2) (Tillett *et al*., 2008). A computer vision system (Hague & Tillett, 2001) detected the phase of approaching plants and that information was combined with measured disc rotation to calculate a phase error between the next plant and disc cut-out. Variability in plant spacing along the row was accommodated by making small adjustments to the rotational speed of the disc via a phase-lock loop. This system minimised the relative speed between the cultivation device and the soil, thus reducing soil throw and possible contamination of the crop by stones and soil. Field trials in transplanted cabbage indicated that under normal commercial growing conditions, crop damage levels were low with weed reductions in the range 62-87% measured within a 240 mm radius zone around crop plants (Tillett *et al*., 2008).

Figure 5.2. Cultivation disc incorporating a cut-away section to accommodate crop plants (from Tillett *et al*., 2008)

A plant map can be utilized for intra-row weed-specific cultivation. As a matter of fact, a geospatial crop seed or plant map may be a good alternative to real-time weed sensing in order to remove intra row-weeds (Perez-Ruiz & Upadhyaya, 2012). Perez-Ruiz and colleagues developed an automatic weeding system using cultivator knives that remove the weeds within the crop rows of transplanted processing tomato using RTK-GPS based plant map obtained during transplanting operation. A RTK-GPS based real-time control system was mounted on the cultivator to determine the geospatial position of the knife blades with respect to each mapped tomato plant in the field. A pair of intra-row mechanical knives has two operating positions: close for intra-row weed control, and open where tomato plants were mapped to avoid crop damages (Fig. 5.3). The intra-row implement consisted of a pair of concave disks and a pair of sweep-style knives (Fig. 5.3). The three weeding zone are shown in figure 5.4. On the left side of the figure, the intra-row knives are shown in the closed position where they touch each other, and they kill all plants present in zone B. In the centre of the figure, the knives are shown in the open position, leaving the gap in zone B uncultivated in order to bypass the tomato plant previously mapped. A high-speed pneumatic actuator was used to quickly reposition the pair of knives between the intra-row control state. Field test results indicates that this RTK-GPS based automatic weeding system did not damage tomato plants while performing intra-row cultivation at working speed of 0.8 and 1.6 km h^{-1}. Knife path control was good, with a mean error of 0.8 cm in centring the actual uncultivated close-to-crop zone about the tomato main stem. This system seems to be very advantageous because it does not require a weed sensor (Perez-Ruiz *et al*., 2012).

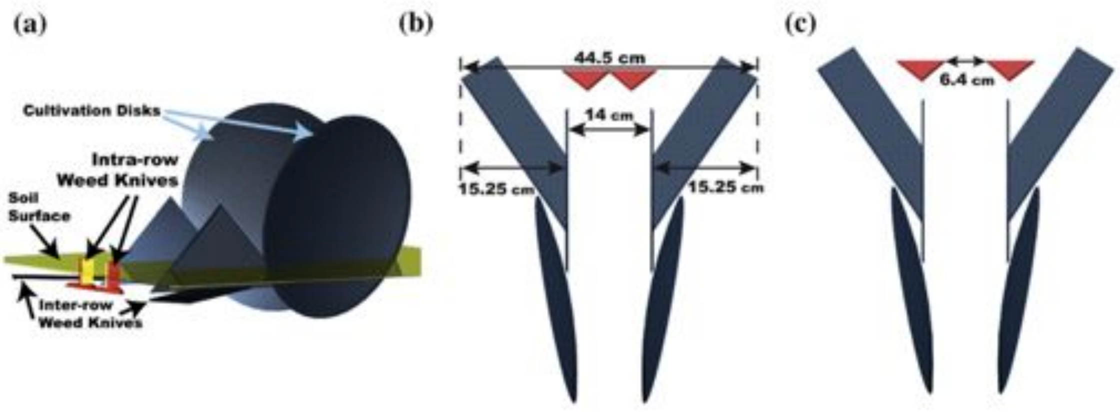

Figure 5.3. Weed knife system for row crops. (a) Side perspective view showing the inter-row disks (gray) and sweep knives (gray), the soil surface (yellow), and the intra-row knives (red) in the closed position about 2.5 cm below the soil surface. (b) Top view showing the intra-row knives (red triangles) in the closed position, killing any weeds in the central 14 cm seedline region. (c) Top view showing the intra-row knives (red triangles) in the open position, creating a 6.4 cm uncultivated gap to allow crop plants to pass unharmed (from Perez-Ruiz *et al*., 2012).

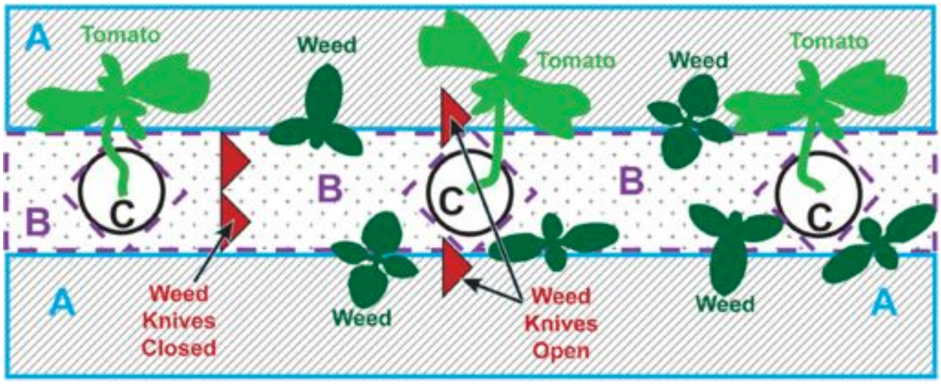

Figure 5.4. Scheme of the three weeding zones (A=inter-row, B=intra-row, and C=close-to-crop) and the ideal path of the intra-row knives (red triangles) (from Perez-Ruiz *et al.*, 2012).

The new technologies for sensing crop and weeds in real-time with image analysis, by GNSS receivers, mapping tools in a GIS and robotics using autonomous vehicles allow a precise operation of mechanical weeding tools (Rueda-Ayala *et al.*, 2010).

Åstrand and Baerveldt developed a vision-guided mobile robot, able to carry out mechanical weed control between plants in outdoor environments. The robot has two main sensors, the vision system for row detection and the vision system for plant identification. Each of these systems has industrial PC-based hardware for grabbing and processing the images. A third computer, the main computer, runs under QNX, a real-time operation system, and controls all the robot systems and actions. The row-recognition system is based on the Hough transform (Åstrand, & Baerveldt, 2005) (see also Chapter 3.1) and was tested extensively proving to be able to guide the robot with an accuracy of ±2 cm. A forward-looking camera with a near-infrared filter is used to find the position of the row (Fig. 5.4). A colour camera system is then used for single plant identification. This is mounted inside the robot in order to control the illumination, as shown in figure 5.5. Colour, shape features and planting grid were used to classified weeds. The colour camera system controls a tool that removes weeds within the row of crops (Åstrand & Baerveldt, 2002).

The length of the robot is about 120 cm and the steering mechanism is an Ackerman steering controlled with a DC–servo motor. A potentiometer is used for calibration and an encoder, which has an approximate resolution of 700 pulses degree^{-1}, determines the current position of the steering motor. To prevent any damage of the steering mechanism there are two end switches able to block the steering motor if the angle is out of range. The robot has two driving wheels at the rear, equipped with encoders with an approximate resolution of 24000 pulses m^{-1}. For safety reasons the driving motors are equipped with electrically controlled brakes. The robot is powered by a endothermic engine driven generator for field tests. The mechanical tool is a wheel that is rotated perpendicularly to the row line. The tool processes only the area between crops in the seedline. If a plant crop is detected, the tool is quickly lifted by a pneumatic cylinder and lowered directly after its passage. The downward-looking camera identifies and localizes the position of every crop plant. The position is then sent to the controller of the tool. To minimize the delay between position estimation and tool real position close to the plant, the tool should be located as

close as possible to the border of the field of view of the camera. The tool is therefore located at the rear of the robot directly after the rear driving axle (Åstrand & Baerveldt, 2002).
The system as a whole was verified, showing that the subsystems are able to work together. The robot was able to recognize all the sugar beet plants and the weeding tool worked well (Åstrand & Baerveldt, 2002).

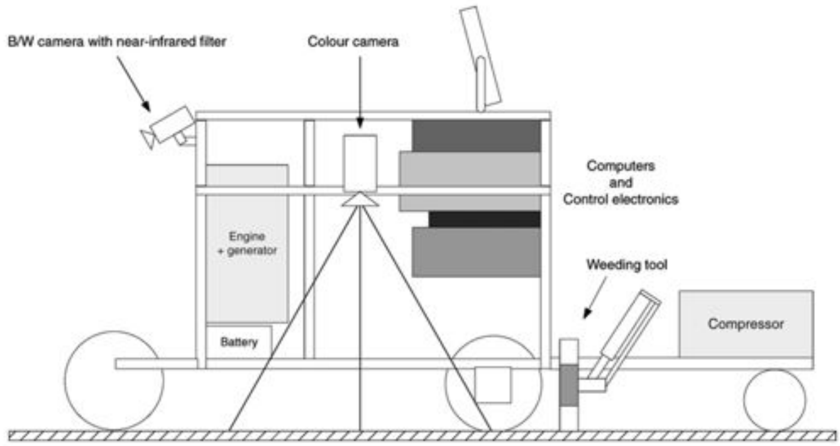

Figure 5.5. Mobile robot equipped with a weeding tool mounted at the rear (from Åstrand & Baerveldt, 2002).

van Evert and colleagues developed a robot that can navigate in grassland, detect *Rumex obtusifolius* L., and remove all the detected weeds. The base of the robot consists of a rigid frame carrying four independently driven wheels. Power was provide by a 36-kW diesel engine. A programmable logic controller (PLC) receives inputs from incremental encoders mounted on the wheels, a remote control receiver, and the PC that provides overall control of the system. The wheel encoders are used to regulate robot driving speed. The PC provides overall control of the system and functions as a pre-processor of the signals from the GPS receiver and the vision system. Weeds are detected using machine vision with a texture-based method. The vision system consists of a camera attached to a boom in front of the robot (Fig. 5.6). Weed control was actuated with a vertical rod weeder. The tool consists of a single 0.20 m blade that rotates around a vertical axis and is pushed into the ground at the location of any weed. To facilitate the penetration of the blade into the soil, the vertical axis extends below the blade and ends in a sharp point. An important feature of this weeder is the cylindrical cover that is lowered with the blade and remains on soil surface while the blade penetrates. The cover ensures that the loose soil forms a mound on top of the hole. When the loose soil settles, it refills the hole (Fig. 5.7). This robot allowed to obtain a 60%-80% control of *Rumex obtusifolius* L (van Evert *et al*., 2011).

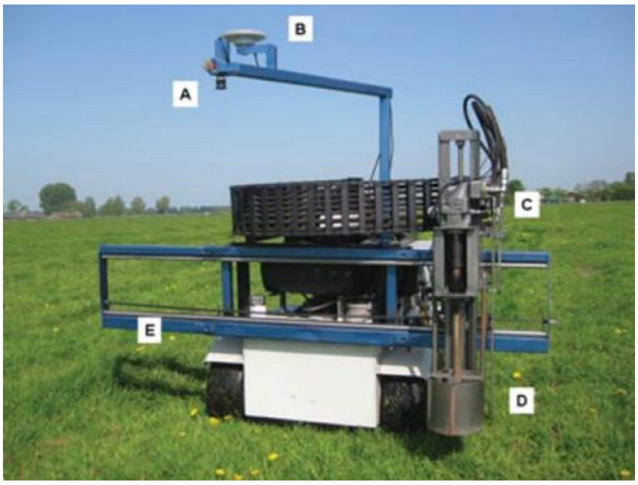

Figure 5.6. The completed robot: (A) boom-mounted camera, (B) GPS antenna, (C) hydraulic motor, (D) weeder, (E) rail that allows lateral movement of the tool (from van Evert *et al*., 2011).

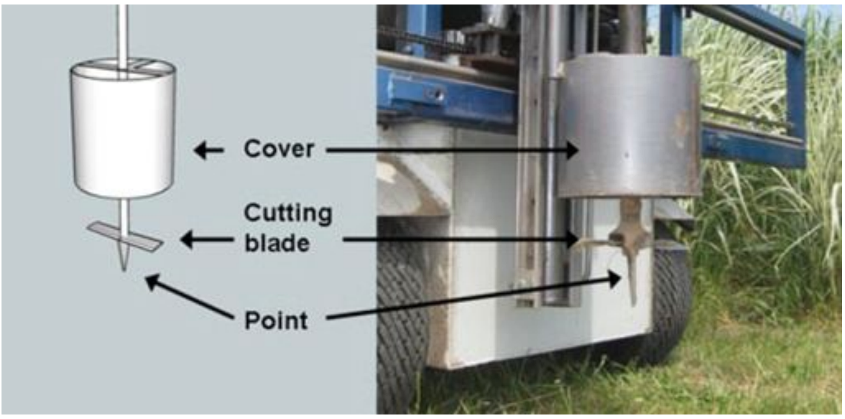

Figure 5.7. Diagram (left) and photo (right) of the weeder. The cover has been propped up to expose the cutting blade (from van Evert *et al*., 2011).

Nørremark and colleagues developed an autonomous guided tractor based on real time kinematic GPS (RTK-GPS) and an automatic rotary hoe able to perform inter- and intra-row weed control. The autonomous tractor was able to follow a predefined route parallel to crop rows, make turns at the end of rows, provide hydraulic and electrical power to mounted implement and pull, lift and lower the implement at predefined waypoints. The cycloid hoe consisted of a tine-rotor that was mounted onto a vertical parallelogram attachment and driven by a hydraulic motor. The parallelogram was mounted on the side-shift rear frame and with a ground wheel in order to control tillage depth of the tines. The sigmoidally curved tines were mounted on individual spindles that enabled switching the tools into two trajectory modes (Fig. 5.8). In the locked mode, the tines moved into the row when there was enough space between plants. In the released mode, the tines were still soil-engaging and pulled by the tine-rotor but stayed outside the row if it was likely that they would strike a plant. The individual tines can be released for individual rotation in order to avoid collision with geo-referenced crop plants. The system navigated with reference to pre-defined waypoints to till in a way parallel to crop rows and around individual crop plants (Nørremark *et al*., 2012).

The system evaluation was based on quantification of treated areas for uprooting and burial and the corresponding prediction of weed control efficiencies. A single pass of an 80 mm wide row band provided tillage of 30-49% of the intra-row area, with highest coverage at a speed of 0.32 m s^{-1} and at even plant spacing. A double pass (on each side of the row in opposite directions) provided higher soil disturbance intensity and resulted in tillage of 31-58% of the intra-row area with highest coverage at a speed of 0.32 m s^{-1}. The intra-row weed reduction was predicted to be up to 20% for a single pass and up to about 30% for a 2-way pass treatment both at white thread and two-leaf stage of weeds (Nørremark *et al.*, 2012).

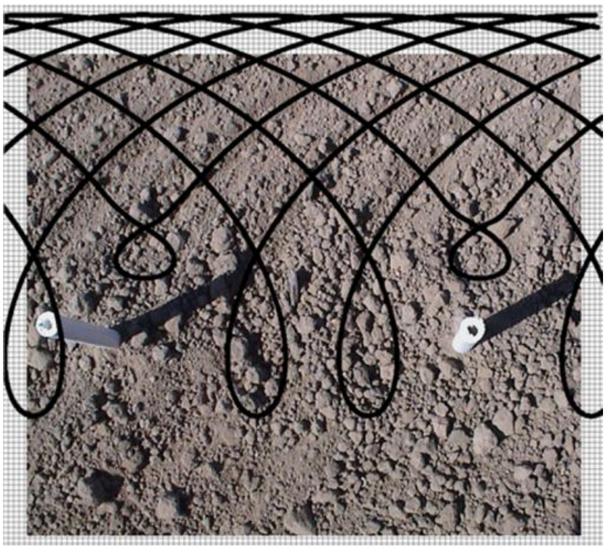

Figure 5.8. Photo of soil upheaval and cycloid hoe tine trajectories with simulated tine trajectories layer placed on top (from Nørremark *et al.*, 2012).

5.2 Automatic operative machines for thermal weed control

Thermal methods represent a good tool to perform selective weed control in automated management systems (Zhang *et al.*, 2012). Zhang and colleagues developed a system for intra-row weed control in high-valued crops using hyperspectral imaging for species identification and a pulsed-jet thermal micro-dosing to perform weed control. The thermal micro-spray system, coupled with a hyperspectral imaging system, selectively delivers high-temperature, organic, food-grade oil for intra-row weed control in early growth tomatoes. The thermal micro-spray system utilizes pressurized nitrogen gas (providing a pressure head) to deliver the heated oil to the spray manifold through an internally pressurized chamber. The nozzles can apply heated oil to a rectangular area approximately 0.64 cm per 1.27 cm and deliver 85 mg cm^{-2} of heated food-grade oil based on a ground travel speed of 0.04 m s^{-1}. The travel speed of the system is constrained by the hyperspectral image transfer rate from camera to computer. The average oil temperature during application was approximately 160 °C. The outer reservoir heating oil (flashpoint higher than 204°C) was 75% biodegradable, non-toxic and had no expected adverse affects on humans and the environment including fish and wildlife. Thermal “treat-by-species” tests were carried out both indoors and outdoors. In these tests, tomato cultivars and weed plants, except the ones selected for control, were intermingled by species and the system

was set to detected weeds and apply thermal treatment exclusively to the their foliage. The hyperspectral imaging system correctly identified and mapped the majority of the weed canopy both in indoor and outdoor tests and the thermal micro-dosing treatment was effective on weeds. The results of the outdoor test demonstrated that this technology of integrating thermal micro-dosing of high-temperature food-grade oil for weed control with hyperspectral imaging for plants species identification has the good potential to be translated into real-world applications to improve the weed control effectiveness in row crops (Zhang *et al*., 2012).
Frank Poulsen developed a new robot (Patent No PCT/DK2005/000311) for intra-row flame weeding. The machine is able to remove weeds between crop plants placed in a row. The robot can operate at 1-6 km^{-1}. A computer with a camera detects the individual plants in the row and the software calculates their position. A specific algorithm allows to distinguish between crop and weed. When a crop plant is passing, the camera records its position. When the same plant a moment later is passing under the array of burners, signals are sent from the computer, which causes the plasma jets adjacent to the plant to be switched off whereas other jets are kept on. This pattern of ON-and OFF jets are moving along the array with the same speed as the machine is driving forward (Fig. 5.9). The result is that the pattern of hot plasma jets is stationary with respect to the ground while the machine is passing allowing to kill weeds without damaging crop plants (Frank Poulsen ApS Engineering, 2013).

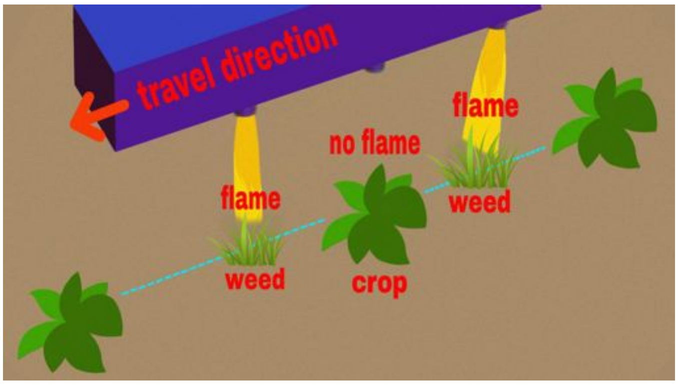

Figure 5.9. Principle of operation of the robot for intra-row flame weeding (redrawn from Frank Poulsen ApS Engineering, 2013)

A laser beam directed towards weeds can be an efficient weed control method as an alternative to herbicides. Lasers may deliver high-density energy to selected plant material, raising the temperature of the water in the plant cells and thereby stop or delay the growth (Mathiassen *et al*., 2006). A laser weed control system was developed by Mathiassen and colleagues. A laser tool was used together with computer vision system able to detect weeds and identify their apical meristems from a top-down point of view. The laser is pulsed with a required dose of energy and uses a mirror, directed towards the targeted plant tissue (Fig. 5.10). The effect of laser treatment directed towards the apical meristems of selected weed species at the cotyledon stage was investigated. Experiments were carried out under controlled conditions, using pot-grown weeds. Two lasers and two spot sizes were tested and different energy doses were applied by varying the exposure time. The biological effectiveness was examined on three different weed species: *Stellaria media* (L.), *Tripleurospermum inodorum* (L.) and *Brassica napus* (L.). The results emphasized that laser treatment of the apical meristems caused significant growth reduction and in some cases had lethal effects on the tested weed species. The degree of control guaranteed by this method was related to wavelength, exposure time, spot size and laser power. It also varied in the different tested weed species (Mathiassen *et al*., 2006).

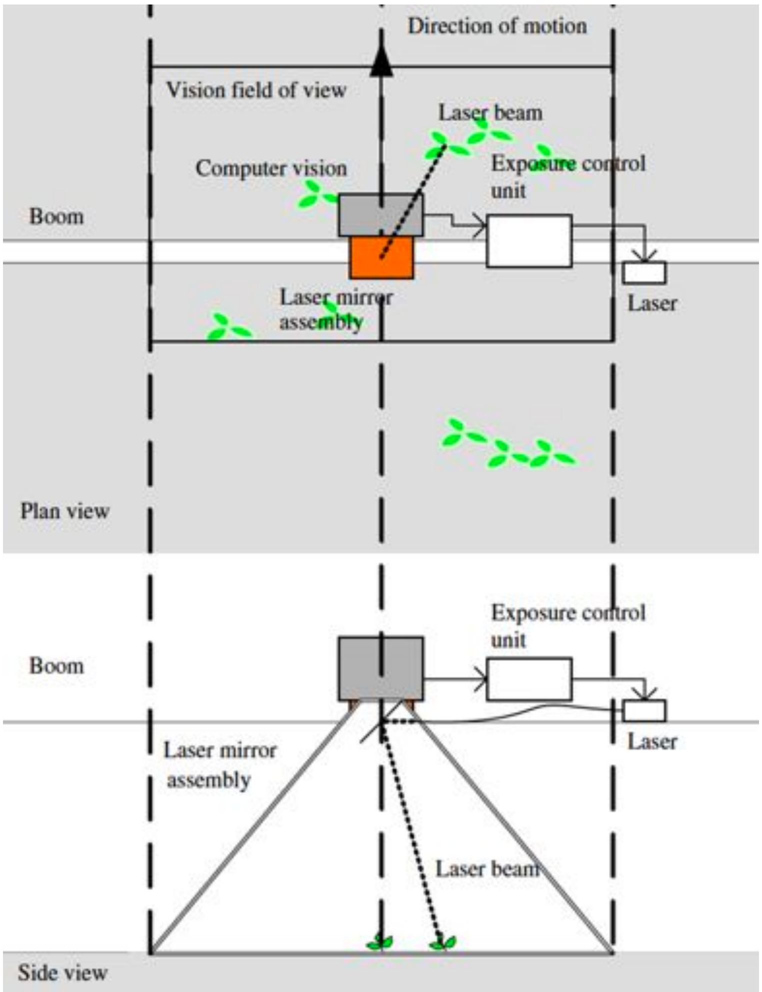

Figure 5.10. Laser weed control system and its components (from Mathiassen *et al*., 2006).

CHAPTER 6. THE RHEA PROJECT

The RHEA (Robot fleets for Highly Effective Agriculture and forestry management) Project is an European Project funded under the Seventh Framework Programme. The RHEA Project is focused on the design, development and testing of a new generation of automated and robotized systems able to both chemical and physical effective weed management and crop protection covering a large variety of European products including narrow and wide row crops and forestry woody perennials.

RHEA aim at diminishing the use of agro-chemicals by 75%, improving crop quality, health and safety for humans and reducing production costs by means of sustainable crop management obtained using a fleet of small, heterogeneous robots (ground and aerial) equipped with advanced sensors, enhanced end-effectors and improving decision control algorithms. RHEA can be considered as a cooperative robotic system.

The project involves 15 European partners: (1) Agencia Estatal Consejo Superior de Investigaciones Cientificas (CSIC, Spain), (2) CogVis Software und Consulting GmbH (CV, Austria), FTW Forschungszentrum Telekommunikation Wien GMBH (FTW, Austria), (4) Cyberbotics SARL (CY, Switzerland), (5) Università di Pisa (UP, Italy), (6) Universidad Complutense de Madrid (UCM, Spain), (7) Tropical S.A. (TRO, Greece), (8) Soluciones Agricolas de Precision S.L. (SAP, Spain), (9) Universidad Politecnica de Madrid (UPM, Spain), (10) Airrobot GMBH & CO KG (AR, Germany), (11) Università degli Studi di Firenze (UF, Italy), (12) Centre National du Machinisme Agricole, du Genie Rural, des Eaux et des Forets (CE, France), (13) CNH Belgium NV (CNH, Belgium), (14) Bluebotics SA (BL, Switzerland) and (15) C.M. Srl (CM, Italy).

In order to accomplish the project aim, the RHEA Project is organized in 11 work packages (WP) focused in research into advanced perception systems to detect and identify crop status and innovative actuation systems to both applying insecticides and herbicides precisely and remove or eliminate weeds directly. Additionally, a fleet of small, safe, low cost, reconfigurable, heterogeneous and complementary mobile units will guarantee the application of the procedures to the entire operation field. This scientific activity must be complemented with technical developments in novel communication and location system for robot fleets, enhanced simulation systems, collaborative graphic user interfaces and pioneering fuel cells to built up clean and efficient energy sources.

6.1 Work package 1 (WP1) - Technical requirements, specifications and system breakdown

The objectives of WP1 were (1) the definition of the technical requirements and the specifications of the final system, (2) the description of the final tests to proceed with the project assessment, and (3) performing system breakdown into different modules to facilitate the definition of interfaces between modules and the management of the project from the scientific and technical points of view.

The essential requirements of the project are: (1) the development of a system consisting of a fleet of mobile units (three ground and two aerial) capable of scanning the mission field with a perception system in order to detect and discriminate weeds and crops. An overall scanning of the terrain of at least 95% under any condition is expected. (2) The fleet management is centralized in a Base Station. An operator can supervise the mission state thorough a Graphical User Interface (GUI) tool running in the Base Station computer. (3) The aerial units are controlled either manually or automatically by an aerial controller running in the Base Station. (4) The aerial mobile units carry a payload of about 2 kg with autonomy of about 30 minutes. The unit weight is about 8 kg. (5) The ground mobile units are powered by an engine and are controlled autonomously by an on-board controller. (6) The ground mobile units carry a payload of about 500 kg and fulfil the normative for autonomous outdoor vehicles. The unit weight is 1200 kg. (7) A mission manager, running in the Base Station computer, establish an *a-priori* treatment plan for the 3 ground mobile units and an *a-priori* inspection plan for the 2 aerial mobile units. The mission manager also supervises the mission in real time and will be capable of re-planning the mission after the failure of a number of robots. (8) The electronic equipment on-board the ground mobile units are powered by a system based on solar panels and fuel cells. (9) The aerial units are equipped with vision and NIR cameras to detect weed patches. It is expected to detect at least 90% of the weed patches by using off-line methods and algorithms. (10) One ground mobile unit is equipped with a ground perception system based on RGB cameras to distinguish weeds from crops. It is expected to detect at least 90% of the weed patches in real time. (11) All 3 ground mobile units are equipped with a 3D vision system to detect crop rows (in wide row crops) and to detect objects in the vehicle trajectory. This system allows to the unit controller to follow the rows at a speed of about 6 km ha^{-1} with a positioning accuracy of about ±2 cm. (12) Every ground mobile unit is also equipped with a different actuation system for physical and chemical treatments. The target is a reduction of chemicals of about 75%. (13) One ground mobile unit is equipped with a spray boom that applies herbicide based on the information from the perception system on board the aerial units. The goal is to apply herbicide to at least 90% of the detected patches. (14) One ground mobile unit is equipped with tools developed to destroy weeds witch are based on both thermal and mechanical devices. The goal is to control at least 90% of the detected weeds. (15) One ground mobile unit is equipped with a spray system to apply insecticide in olive trees. The goal is to apply the pesticide al least on 90% of the tree canopy. (16) Robot location modules (position accuracy of about ±2 cm at 20 Hz) and communication modules (among robots, operators, Base Station, and personal mobile units) allow monitoring/controlling the robot fleet in real time. (17) The assessment of the whole system will be performed on three scenarios (two major herbaceous crops and an orchard). The selected crops are wheat as a representative of the narrow crop, maize as a representative of the wide crop and olive trees as a representative of the woody perennial scenario.

6.2 Work package 2 (WP2) - Mission Manager

The Mission Manager is the system in charge of defining and controlling the mission and will run in the Base Station computer system. This manager is divided into two modules: Mission Planner and Mission Supervisor. The Mission Planner is in charge of devising the mission, while the Mission Supervisor is in charge of governing the operation.

The objectives of WP2 are: (1) the definition of the Mission Planner, (2) the definition of the Mission Supervisor, (3) the development of the Mission Planner, (4) the development of the mission supervisor, (5) the assessment of the Mission Planner.

A seven-step procedure is proposed for the development of a weed control program based on the use of a robot fleet. The seven steps are (1) field inspection, (2) strategic decisions, (3) tactic decisions, (4) online decisions, (5) unit distribution and path planning, (6) mission execution, and (7) mission supervision.

The main operational states that have been identified in the Mission Manager are (1) mission definition for field inspection (performed using aerial mobile units), (2) mission definition for field treatment (performed using ground mobile units), (3) mission supervision of the field inspection, (4) mission supervision of the field treatment. States (1) and (2) will be accomplished by the Mission Planner while states (3) and (4) will require the use of the Mission Supervisor. Mission Manager (both Mission Planner and Mission Supervisor) runs in the Base Station computer and they will use the GUI for communication with the operator (Fig. 6.1).

The Mission Planner is mainly focused on collecting data related with the type of mission (treatment) and field specifications (crop type, dimensions of mission fields, geographical position, etc.) from the operator, deciding on the number of aerial units for inspecting the mission field, selecting the number of ground mobile units to accomplish the task, selecting the type and number of sensorial systems and actuators on-board the ground mobile units and providing an action plan for each mobile unit. The Mission Planner is the responsible of planning the mission and to generate the plan it requires inputs about: (1) the type of task to be performed, (2) the number and features of the available robots, (3) field features including previous information on the field acquired by remote and ground sensing, farmer’s knowledge, etc. With these data, the Mission Planner has to define the distribution of units as well as the appropriated sequence of mobile unit actions to accomplish the mission. In the context of RHEA, a crop inspection or a crop treatment are missions. Concerning the timing, the Mission Planner runs before the mission begins, thus it has not high response requirements. For this reason some optimization methods as those based on evolutionary computations can be used to find the best planning in each situation. The Mission Planner elaborates the plans for both ground and aerial vehicles and sends them to the GUI to be simulated and shown to the operator(s). Once the operator accepts a plan, orders have to reach either the AUHLC (Aerial Unit High Level Controller) or HLDMS (High Level Decision Making System).

The Mission Supervisor is in charge of monitoring the overall system status. The Mission Supervisor performs: (1) the supervision of the mission, in real time, helping the operator(s) in detecting problems, (2) the definition of a new plan wherever any type of emergency appears. The Mission Supervisor runs during the mission execution. The Mission Supervisor identifies malfunctions in the execution of both the inspection (performed by aerial mobile units) and treatment missions (performed by ground mobile units). To restore proper system operation as soon as possible, the identification and the diagnosis of faults must be associated with adequate fault management. Thus, notification of the faults must be sent to the operator or other modules of the system capable of repairing the problem.

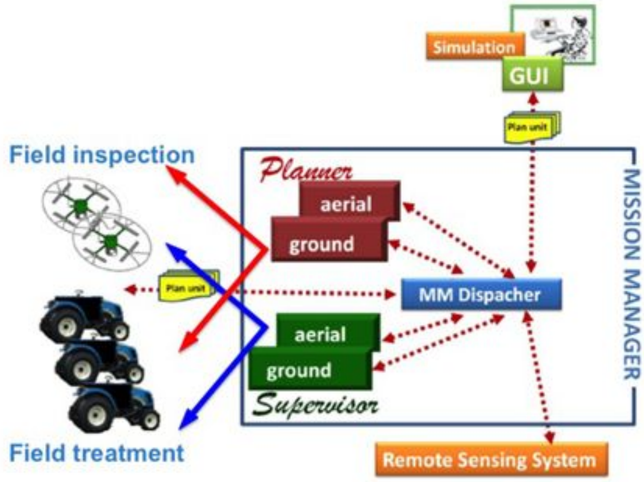

Figure 6.1. Mission Manager architecture.

6.3 Work package 3 (WP3) - Perception System

The objectives of WP3 are: (1) the definition of the Remote Sensing Equipment, (2) the definition of the Ground Sensing Equipment: camera based devices and laser, (3) the development of the Remote Sensing Equipment, (4) the development of the Ground Sensing Equipment: texture identification and 3D system. Perception system is the most challenging activity of the project and permit to improve site-specific application of herbicides as well as mechanical/thermal actuation on specific weeds.

The role of the Remote Sensing Perception system is to achieve the preliminary aerial survey, which relies on two pillars: (1) the implementation on the aerial units of appropriate imaging devices, (2) the development of efficient imaging processing software for parcel survey and weed patch detection.

For inspection purpose (Mission Manager) two DP2 Merril cameras (Sigma, Kawasaki, Japan) were installed on the drone (Fig. 6.2). The first camera is a VIS camera and the second one was modified as a NIR camera in order to obtain final multispectral images. The nominal usage conditions are a flight elevation of 60 m and 120 m, giving respectively spatial resolutions of 1 cm $pixel^{-1}$ (wheat crop parcel) and 2 cm $pixel^{-1}$ (maize crop parcel). Pictures are stored on the camera SD cards.

The inspection missions with aerial units provide image acquisition. Subsequent mosaicking and image processing for weed detection are needed.

Several images are grabbed successively, and these images have to be stitched together in order to get a unique, large image of the whole parcel. This process is known as "mosaicking". Mosaicking consists in gathering overlapping pictures of a scene to build a global orthorectified and geo-referenced image. The mosaicking process requires image acquisition with a high spatial resolution (a few centimetres) and large ground coverage (several ten meters in each dimension). Only a very high-resolution sensor (more than 10 million of pixels) can combine these two requirements. The resulting stitched images have also to be georeferenced. This means that each image pixel is associated to its absolute geographic coordinates through a georeferencement equation, in order to specify the exact location of weed patches for further ground unit operations.

As a first step, pictures issued from the camera SD cards are automatically selected and synchronized with the flight log data provided by the Aerial Mission Planner, using their time stamp. This allows to roughly determining the spatial position of each picture according to the drone GPS coordinates and heading at the shooting time. Thus it is possible to visually control the completeness of the aerial mission by displaying the whole set of pictures. In case some pictures are missing, a complementary aerial mission can be demanded through the communication protocol with the Mission Manager System.

Because they represent different species, weeds and crops in the field should theoretically exhibit slight differences in their reflectance spectra. However, the limited spectral resolution of the images provided by the acquisition hardware (four spectral bands R, G, B and NIR) is not sufficient to detect such differences, especially in variable natural outdoors lighting conditions. For this reason, the spectral information is mainly used to separate the vegetation as a whole (weeds plus crop) from the soil, and the crop is discriminated from the weeds according to its spatial organisation: crop lines are detected as drawing parallel lines in the field, and weeds are detected as vegetation not included in these lines (segmentation). For row-crop discrimination the normalized difference vegetation index (NDVI: NIR-R / NIR+R) is used to classify objects of vegetation. A customized merging operation is then performed to create lengthwise vegetation: objects, following the shape of a crop row. For weed/crop discrimination the vegetation objects entirely located along the rows are classified as crop plants, and otherwise as weeds. A more complex decision is taken in the case of objects located below the edge of the rows. In this case, the objects in contact with or very close to other weeds are classified as weeds (an aggregation among weeds is generally observed). The weed map identifies free and infested zones, where latter are categorized in three different levels of infestation: low (<5% of weed coverage), moderate (5 ‑ 20%) and high (>20%). Both grid dimensions and weed ‑ infestation categories can be customized according to cropping patterns and to the specifications required by the sprayer.

Figure 6.2. Sigma DP2 Merril camera and implementation on the drone.

The design of the Ground Sensing Equipment pursues two goals: to perform a perception that allows both optimal and safe navigation and accurately detect the natural elements to be treated. The physical elements conforming the Weed Detection System and the Guidance Navigation Systems, particularly the cameras, are installed on-board the Ground Mobile Units (Fig. 6.3). Therefore, they are designed considering working conditions of Ground Mobile Units. Ground Mobile Units guidance is achieved by combining computer vision and a GPS system. In the first stage, the GPS is used to provide information to the tractor to place it at the beginning of the crop rows as much aligned as possible. Once the tractor is placed and aligned, it starts moving along the crop lines. While the tractor moves along the crops, the guidance is made by the information provided by the computer vision system.

Figure 6.3. Position of the camera on the Ground Mobile Units.

The safe navigation is performed by detecting obstacles. The algorithm is designed to distinguish between persons and other, general obstacles. Both, persons and obstacles are then projected in 3D space. This allows calculating the distance between the Ground Mobile Unit and these persons/obstacles and thus deciding whether or not to stop the vehicle. Obstacle detection is performed using a laser scanner (Laser Imaging Detection and Ranging - LIDAR) fusing camera data. A safety laser scanner is an optoelectronic device, which uses, as the laser ranger finder, diffused reflection of emitted light to guard personnel working around hazardous machinery. This small optical sensor uses pulsed laser light to scan its surroundings and then compare the scanned information to its predefined zones. If the scanner detects an intrusion into that area, it sends a stop signal to the machinery being guarded. LIDAR is installed on the middle of the front of the vehicle and with a push–broom configuration for the detection of obstacles along the vehicle trajectory (Fig. 6.4).

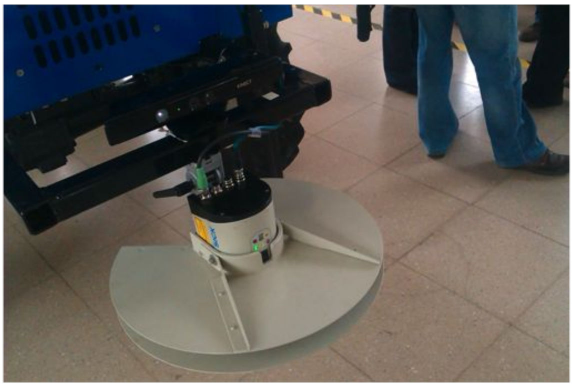

Figure 6.4. LIDAR configuration for obstacle detection.

In olive trees applications, the perception system will allow identifying and locating the structure of the trees. The Laser sensor (LIDAR) was connected to Ground Mobile Unit Ethernet for the detection of tree volume and tree localization, but orientation incompatibility has made it impossible the characterization of the trees. The Kinect (motion sensing input device), on the contrary, can detect, in real time, presence and absence of canopy.

A complementary weed detection system using computer vision was also developed for weed detection in wide row crops. The weed detection system (WDS) is placed on board the Ground Mobile Unit (Fig. 6.5). The goal is to analyse the Region of Interest (ROI) in front of the Ground Mobile Unit with the aim of gathering information on the green plants to detect crop lines and weeds, this last computing densities of green (Romeo *et al*., 2013).

The geometric configuration of the WDS is displayed in figure 6.5. The housing is set up with a inclined pitch angle (α) (approx. 27º) with roll (θ) and yaw (β) angles set to 0º; h is the height from the ground to the centre of the Charge Coupled Device in the camera, set to 230 cm. Two systems are associated with this configuration: OXYZ (world coordinate) and oxyz attached to the plane of the image, i.e., coinciding physically with the Charge Coupled Device (CCD) (Romeo *et al*., 2013).

The WDS consists of a camera and accessories (lens and UV-IR filter) and an Inertial Measurement Unit (IMU), both placed inside a commercial housing and very close to each other (Fig. 6.6). The housing is equipped with a fan and a thermostat for cooling the camera. This fan runs on 12V DC. The housing consists of a fixed base and a removable top, which allows direct access to the camera, IMU and fan. The base is attached to a bracket with a joint mechanism, which can be used to set the pitch angle by means of screws. The bottom of the bracket has a circular piece with screws for attaching the housing to the tractor. The power required by the camera, the IMU and the fan are supplied by the Ground Mobile Unit general power supply. The camera is protected against voltage peaks by a DC-DC voltage regulator, placed inside the Ground Mobile Unit. The camera consists on a CC-based device which is a Kodak KAI 04050M/C sensor with a Bayer colour filter with GR pattern and a resolution of 2,336 × 1,752 pixels and a 5.5 × 5.5 µm pixel-size (Romeo *et al*., 2013).

The Ground Mobile Unit moves along the crop lines and it processes in real time the images determining the percentages of weeds and the crop lines location. Ground Mobile Unit speed is a critical factor since more faster the tractor moves along the crop lines, more faster the algorithms for detection have to be or else the further away the selected area to be focused has to be, with the resulting unavoidable loss of accuracy. A panel with four colours is placed in front of the Ground Mobile Unit and inside the field of view of the camera for knowing the position of the panel in the image and also the distribution of colours on it (Fig. 6.7). The white part of this panel serves as reference for controlling the exposure time (Romeo *et al*., 2013).

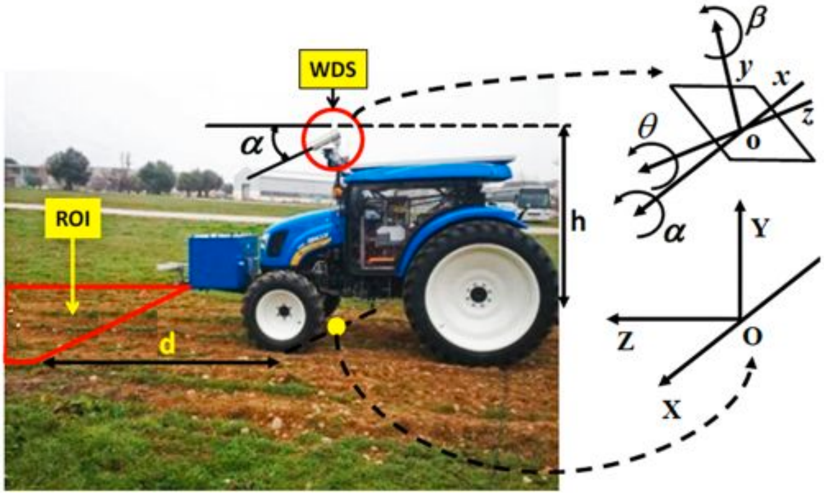

Figure 6.5. Geometric configuration of the WDS (from Romeo *et al.*, 2013).

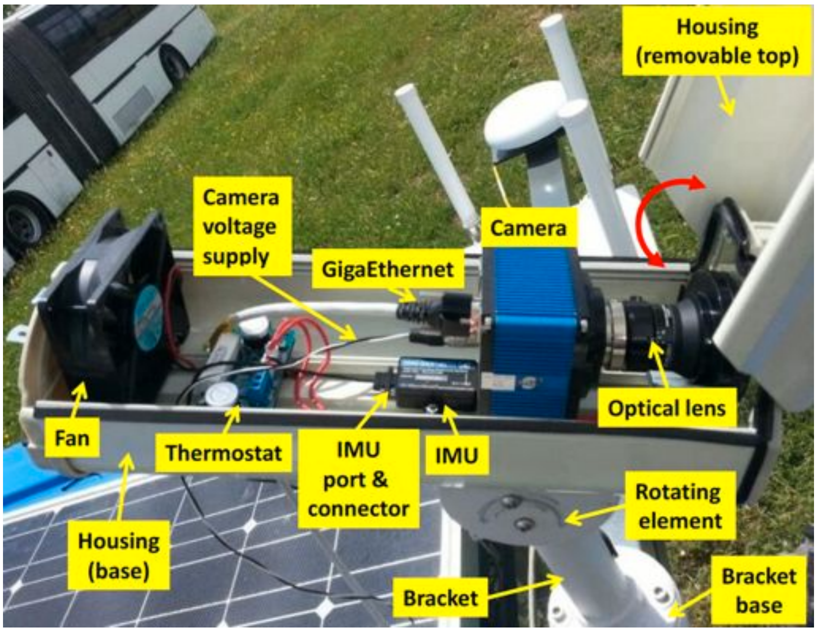

Figure 6.6. Distribution of the WDS components inside the housing (from Romeo *et al.*, 2013).


Figure 6.7. Colours panel placed in front of the GMU (from Romeo *et al.*, 2013)

The camera is directly connected to the High Level Decision Making System (HLDMS) via Gigabit Ethernet. According to this connection the image acquisition can be triggered and the image can be transmitted to be processed by the HLDMS. The HLDMS redirects the images captured by the camera according to the needs: to the WDS for extracting information (weeds and rows) or to the Base Station (BS) to display them on the operator screen (Romeo *et al*., 2013).

The assessment consists of two parts: crop lines detection and computation of weed densities. The WDS is evaluated by verifying the weed densities in different cells, obtained from the partition of the Region of Interest. During the normal WDS on-line operation, both the original images and the processed ones are stored in the HLDMS, which are off-line recovered for subsequent analysis. The densities of the cells are also stored as numerical values. The set of analysed cells are annotated as cells with low, medium and high density of green plants. Thus, the range of possible values for weed density is discretized in three different levels: low, medium or high. The cells are partitioned in equal size areas, considering the crop lines. Therefore, crop lines must be detected with the highest accuracy. The first stage of assessment is the detection of four crop lines. With such a purpose all images are processed and the four crop lines detected are drawn. Once the first stage of assessment is completed, the second stage that consists in weed identification is started. This is carried out by computing the green plants identified inside each cell. Each cell is limited by a detected crop line, a central line between two consecutive crop lines and two horizontal lines specified by the user. Currently the horizontal lines in the image correspond to lines in the field spaced with 0.5 m covering 2 m long. Around each crop line an area is considered as crop. Around each crop line an area is considered as crop. The width of this area depends on the growth stage of the crop, it can be specified by the user. An indicative value in pixels of the image is obtained as the 10% of the length between two detected crop lines. The pixel identified as green plants inside this area are discounted from the computation of the densities. The algorithms are also designed trying to exclude from the computation of the densities the maize leaves that cover the inter-crop lines (Fig. 6.8). The crop rows identified are also found as an aid for guiding the vehicle.

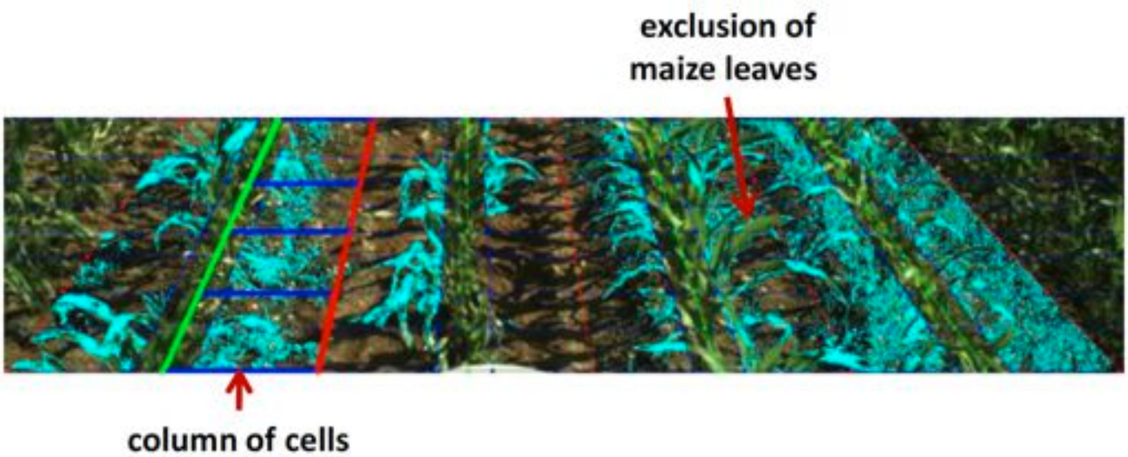

Figure 6.8. Identification of cells and maize leaves excluded from the weeds density computation

6.4 Work package 4 (WP 4) - Actuation System

The objectives of WP4 are: (1) the definition of the High-Level Decision Making System (HLDMS), (2) the definition of the Low Level Actuation System and Device System (LLASDS), (3) the design and development of the HLDMS, (4) the design and development of advanced end-effectors and actuators for treatment applications, (5) the design and development of enhanced tools for thermal and mechanical weed control, (6) the design and development of the tools positioning system, (7) the design and development of the ground mobile unit controllers.

The HLDMS is a module (hardware and software) of the mobile unit controller, which is in charge of deciding (1) what process to apply, (2) where to apply it, (3) the optimum dose, (4) time of application. These four basic functions make the HLDMS to interact among the Mission Manager, the perception system, the actuation system and the location system. The HLDMS takes as inputs a local (or total) plan generated by the Mission Manager, commands from the user portable device, data from the perception system and the status from the Ground Mobile Units. The HLDMS produce as outputs a set of local trajectories for the Ground Mobile Units, commands for the LLAS and reports for the Mission Manager and the User Portable Device.

However, in the RHEA fleet the decision making is shared among different modules depending by the way the perception is carried out. For instance, in narrow-row crops, the information about the weed types and positions is obtained by the Mission Manager through the Remote Sensing System, and generates the mission taking into consideration all available data. In this case, the Mission Manager passes the whole plan to the HLDMS. Therefore, this last module does not really perform the decision making. However, it is in charge of generating local trajectories for the Ground Mobile Unit Controller (GMUC), taking into account the information provided by the Row and Obstacle Detection System (RODS). In the case of wide row crops, the perception is achieved by the Weed Detection System (WDS), which is a local system, and then the HLDMS performs the decision-making, although it can be reinforced with data from the Mission Manager if the remote perception system is also used. Finally, in olive orchard, the Mission Manager gives a theoretical trajectory to the HLDMS, which computes local trajectories taking into account the information from the RODS and sends them to the GMUC. The GMUC is responsible of the motion of the vehicle. The localization, as well as the planning information, is communicated by the HLDMS and Localization System. The GMUC follows trajectories with an error in the range ±5 cm.

The LLASDS are the actuation systems (implements) for herbicides distribution in wheat, physical weed control in maize and insecticide distribution on olive trees canopy. The Low Level Actuation System Controller is embedded on each implement. The Actuation Controller is connected to the GMUC via Ethernet. Relays may be found between the Actuation Controller and the actuators to adapt the voltage and/or the power. The HLDMS sends commands to the GMUC, which follows the necessary information to the Actuation Controller. The Actuation Controller is an industrial PLC (Programmable Logic Controller). It is composed of a CPU module coupled with inputs and outputs modules.

Sensors are connected to the inputs (analog or digital). Actuators are connected to the outputs (analog or digital).
The implement for herbicide application in wheat is a commercial central direct injection system equipped with a water tank and a separate container for the herbicide to be injected according to the prescription information from the HLDMS. The HLDMS program uses the RTK-GPS position and the application rate map information to determine the desired application rate. The injection system controller supplied a variable voltage to the gear motor to power the injector pump. This voltage caused the injector pump to turn at the appropriate speed to generate the desired flow rate of active ingredient. An encoder integrated in the system measured the flow rate of active ingredient from the injector pump speed. The controller used this flow rate to determine if a change was required. The flow rate was verified using a mini-flow meter. The implement is made up of twelve high-speed solenoid valves mounted on a stainless steel sprayer boom with an equidistant spacing of 0.5 m. These solenoid valves consists of a ¼” barb brass inlet for incoming liquid, a spray nozzle, a nozzle cap, a LED indicator, a 3-pin electrical connector (signal, negative and positive), and two captive screws. The boom sprayer was divided into twelve sections, each containing one-solenoid valve. Each one of these valves was powered by a 12 V sources that allows the spray from each section to be controlled independently. A LED indicator is lit when the solenoid is open. In figure 6.9, a drawing of the spray boom is shown. The boomer has been developed to exhibit two states: folded, for transportation between working places and to allow the Ground Mobile Unit to perform rotations in the field heads, and unfolded for normal operation. The fold/unfold mechanism is performed by two electrical actuators (Carballido *et al*., 2012).

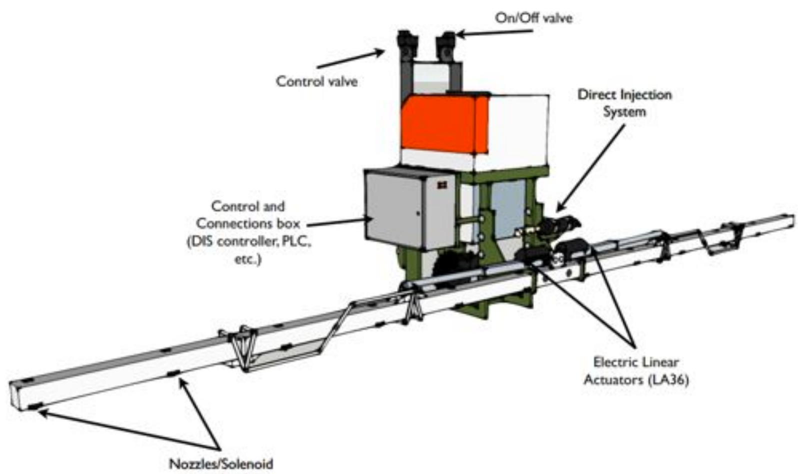

Figure 6.9. Sketch of the sprayer boom (from Carballido *et al*., 2012).

The implement for insecticide applications in olive trees was design starting from an Oktopus (Nobili-Khun) airblast sprayer with independent modules, double side configuration and a semi-loaded complete equipment. The sprayer was modified in order to guarantee a variable pulse control of the flow rate for VRA of insecticide based on the olives canopy thickness. Each module presents an airblast flow control. The terminal two modules have a variable inclination. The sprayer is equipped with ultrasonic sensors able to detect the canopy width and consequently control the air blast flow rate on each module (Fig. 6.10). At a canopy detection of 100%, 50%, <50% and 0% correspond a dose of insecticide of 100%, 50%, 25% and 0% (Vieri *et al*., 2012).

Figure 6.10. Airblast sprayer for VRA of insecticide in olive trees (from Vieri *et al*., 2012).

The implement for physical weed control in maize field will be closely described in Chapter 7 as this description represent the central part of this PhD thesis.

6.5 Work package 5 (WP5) - Mobile units

The objectives of WP5 are: (1) the definition of the Ground Mobile Unit (GMU): vehicle, actuation system and controller, (2) the definition of the Aerial Mobile Unit (AMU): vehicle, actuation system and controller, (3) the definition of the safety system of the Mobile Units, (4) the development of the safety system of the Mobile Units, (5) the definition of the alternative power systems for mobile units, (6) the development of the alternative power systems for mobile units, (7) the development, integration and assessment of the GMU modules, (8) the development, integration and assessment of the AMU modules, (9) the integration, test and assessment of the robot fleet.

The three GMUs are based on commercial CNH compact tractors Boomer 3050 CVT. One of those tractors is equipped with SuperSteerTM system that reduces the turning radius from 3.24 m (common tractors) to 2.87 m. They were mechanically, electrically and hydraulically modified and programmed with a dedicated software. The GMUs can follow a trajectory based on commands received from the Ground Mobile Unit Controller (GMUC). The other functions of the GMUs, as the PTO, the three-point hitch and the electro-hydraulic valves were also tested through GMUC commands in order to control the three different implements.

Different hydraulic and mechanical modifications were made on the units to install new systems (Fig. 6.11). The seat, the brake pedals, the throttle pedal and handbrake were removed, as they were not used anymore also in order to have free space in the cabin for

the electronic parts. The cabin of the original tractor was cut and the roof lowered. The roof can be easily removed from the cabin structure to access the electronics inside the cabin. The modification of the cabin required new doors and new windows to keep some sealing. Three supports were made to attach the alternative energy system box (hydrogen proton exchange membrane fuel cells system) at the front of the GMUs. The weight of each box is around 190kg. An horizontal bar was fixed to the front support of the cabin in order to support the antenna bar, that contains different supports to attach the GNSS receiver, the communication router, the vision camera and the safety antenna.
A new steering motor (Sauer-Danfoss OSPF 80 LS) with load sense capability was installed on the machine to allow the adoption of an electro-hydraulic steering valve (Sauer-Danfoss EH20 + HIC, with a PVED-CL controller able to control electronically the steering). A wheel angle sensor was also installed on the front wheel king pin. After configuration and calibration, the PVED-CL controller can read and apply curvature GMUC command.
A 12 V 200 A alternator and a 24 V 120 A alternator were installed in order to provide enough electrical power to all the additional systems installed on the GMUs aiming to facilitate power distribution to the devices installed on GMU (sensors, Ethernet switch…), as well as the ones attached on the implement (actuators, PLC, sensors…), a centralized power distribution system was developed. This centralization was composed of two power distribution boxes for devices in the GMU, for equipment both at 12 VDC and at 24 VDC and another box in the back of the GMU with a connector for implement power supply at 12VDC and 24VDC.
A touch screen display was installed in the cabin of the GMUs. The cabin contains also the HLDMS and GMUC boxes. A remote control system, with a range of about 2 m, is used to manually control the displacement of the vehicle. Three emergency stop buttons were installed on the GMUs: one at the front, one at the front right and one at the rear left. Each of these buttons has two relays and is connected to the safety controller, which activates the brake and shut down the engine of the vehicle if one of them is pressed. The safety controller sends pulses through the connection of those emergency buttons to ensure that they are not short-circuited to ground or to supply.
The three implements used in the RHEA project are connected to the GMUs using the three-point hitch connection. To control the height of the implement, an electrical actuator was attached to the original lever controlling hitch position and a rotation sensor was installed at the back to measure the position of the hitch.

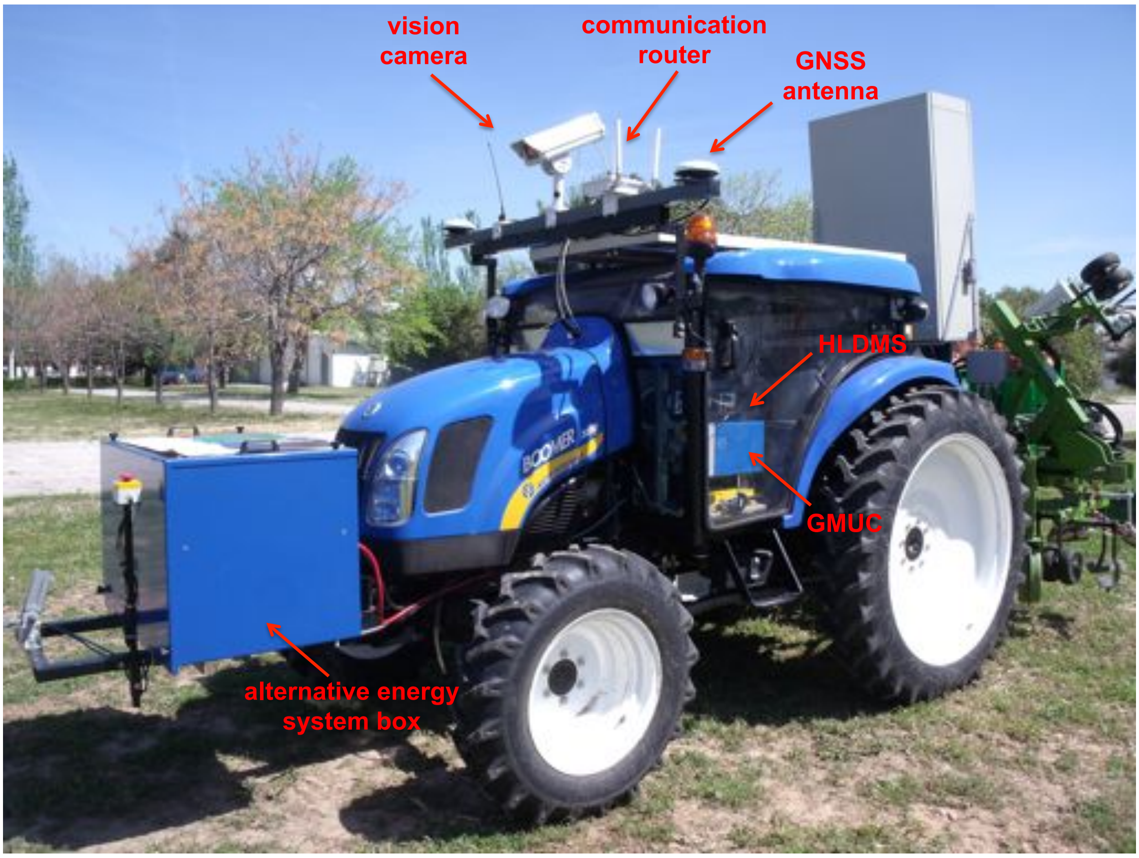

Figure 6.11. Ground Mobile Unit.

The aerial fleet consist of two hex-rotors prototypes (AR200 units). AMUs were developed (Fig. 6.12) and integrated with the remote sensing system. The unmanned aerial vehicles are suitable for taking images of farmland as basis for creating high-precision weed maps. The six-rotors aerial units have sensor-payload up to 1.5 kg, big reach and long flying time (about 40 minutes). They rely on digital data transmission and control on a real-time basis. An importance feature of the drones is their innovative folding system that allows a space-saving and comfortable transport to the field. Moreover, using six-rotors allows certain redundancy, reducing in this manner the accident risk in case of fail of one motor. Drones allow way-point programming as well as some payload control commands. Thus, the mail part of the program includes a list of ordered way-points where the drone has to take a picture. Drones are able to fly this program in fully autonomous mode. Drones provide with telemetry information during the flight, including information required for supervision such as position estimation, battery level, etc.

Figure 6.12. Aerial Mobile Unit (AR200).

6.6 Work package 6 (WP6) – Communication and localisation systems

The objectives of WP6 are: (1) the definition of the Communication and Localization Architecture, (2) the design of the Infrastructure, (3) the definition and development of Localization System, (4) the definition and development of the On-board Network functions, (5) providing the specification of the communication services that facilitates robust communication within the fleet, (6) the implementation of the personal mobile unit connectivity and Internet access.

The purpose of the fleet communication system is to establish a robust, wireless interconnection of distributed application components of the RHEA robotic fleet. The logical connections are present between the GMU and the Base Station (BS). The wireless links have to be resilient to interference and fading effects. In addition, they have to fulfil tight timing requirements for the real-time control and monitoring of the robotic fleet. The Base Station is located at a know point close to where the vehicles operate and communicate with the fleet through a Radio or Wi-Fi transmitter.

Four different configurations are used to locate the components in the field: Base Station, Ground Mobile Units, Aerial Units and Operators. The Trimble BX982 GNSS receiver was installed on the Base Station. The Trimble BX982 supports GPS L1/L2/L5 and GLONASS L1/L2 signals. In addition, Trimble is committed to the next generation of Modernized GNSS configurations by providing GALILEO compatible products available for customers well in advance of GALILEO system availability. In support of this, the Trimble BX982 is capable of tracking Galileo signals for evaluation and test purposes. This receiver offers centimetre-level accuracy based on RTK solutions and sub-meter accuracy code- phase solutions. The main task of this GNSS receiver was to provide and transmit the GPS correction signal to each mobile unit, in order to determinate the location of the GMU accurately, getting centimetre accuracy on RTK receivers and decimetre precision on DGPS receivers.

Currently two of the RTK-receivers are mounted on the GMU and fully operational for field trials (BX982-1 and BX982-2). The rover GNSS receiver is similar to the base station unit, but it has enabled the calculation heading derived from dual-antenna GNSS

measurements, unlike the Base Station calculates that the heading with a single GPS antenna.
Field operators may interact with the fleet in different roles (remote supervision and operation, maintenance, joint work) depending on the robotic task, but also on the level of robot autonomy. Therefore, to know the location of the field operator is critical. A rugged tablet PC (model Algiz 7), the User Portable Device, equipped with DGPS receiver is used to record and display this location that is integrated with all data generated from the components moving through the working area (Fig.6.13). This information is sent to the Base Station and the GMUs in order to avoid crashing.
To improve positioning accuracy (sub-metric) on the AMUs a DGPS receiver is installed on-board.

Figure 6.13. Rugged tablet PC for field operators.

6.7 Work package 7 (WP 7) - Base station and graphical user interface

The objectives of WP7 are the definition of the Base Station configuration, the design and development of the Graphical User Interface, the simulation of the operational setup and the integration of Base Station and Graphic User Interface.
The Base Station is the point of interaction between the RHEA mobile units and the human operator. The Base Station is located in a cabinet next to the mission field, with a view on the fields. The Base Station is equipped with several computers and different software modules specially designed to plan and control the missions of the ground and flying units. BX982 GNSS receiver and GNSS antenna (Zephyr) are installed on base station cabinet (Fig. 6.14).
The base station is based on Graphical User Interface (GUI) for system operation, monitoring, information record-keeping and operation optimization (Fig. 6.15). The GUI is based on the Webots 7 robot simulator. The GUI system is connected in real time with the real system and display in 3D the current state of operation (i.e., position, orientation, speed, and status of every robot). This allows the user to send instructions to the fleet of robots and include a simulation system that can be used to perform quick tests of new operations before the instructions are actually sent to the real system or simulate an emergency procedure started from the current real situation. This helps to manage

emergency situations where the user has to define rapidly new operations in case of problems (e.g. the failure of one robot).

Figure 6.14. Base Station cabinet. A communication router and a GNSS antenna are installed on the cabinet.

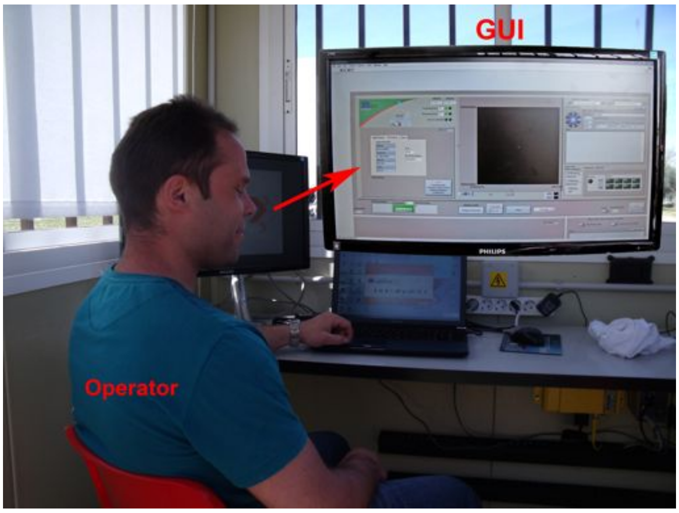

Figure 6.15. Inside of the Base Station; an operator supervises the mission state thorough GUI tools running in the Base Station computer.

6.8 Work package 8 (WP 8 RTD) - System integration and project assessment

The objectives of WP8 are performing the intermediate integrations of equipment, completing the integration of the robot fleet, performing tests to identify any part that may require modifications, and executing an exhaustive assessment program.

6.9 Work package 9 (WP 9) - Dissemination, exploitation and training

The objectives of WP9 are: (1) ensuring an effective dissemination of project achievements and transfer of the technology implemented within the project, (2) addressing Confidentiality and Intellectual Property Rights (IPR) handling, (3) organizing the exploitation of the results, (4) managing the project web site, (5) offering a training on the system operation.
The goal is to disseminate the results of the project among the interested communities. Thus project outcomes are timely presented using traditional and electronic means. Dissemination plan activity includes the planning of the events, the generation of broad-public material and the interchange of students and personnel between the partners.
Exploitation plan outlines the path towards the exploitation of the results of the project. Information generated within the WP1 are taken into account and related to the analysis of market opportunities. The possibilities to launch new spin-offs within the consortium are also considered.
A project web site started at the beginning of the project. The web site contains general information for partners and interested people. A restricted access area is available to partners for exchanging reserved information. Training is devoted to promote the use of the final system among the potential users. Training is to be performed at the very end of the project, when the system is fully tested and operative.

6.10 Work package 10 (WP 10) - Management

The objectives of WP10 are centralizing and handling all project related matters with the Commission, being responsible for the timely availability of all reports, cost statements and deliverables, coordinating and distributing responsibilities amongst persons and groups, decision process and information flow, as well as reporting, releasing rules and methods allowing managing risks with respect to the general performance, and launching and maintaining the project web site.

6.11 Work package 11 (WP 11 DEMO) – Final demonstration

The objectives of WP11 are to carry out the final demonstration of the system and evaluate the project with the EC project officer.

CHAPTER 7. DESIGN AND REALIZATION OF AN INNOVATIVE AUTOMATIC MACHINE ABLE TO PERFORM SITE-SPECIFIC PHYSICAL WEED CONTROL IN MAIZE

A new implement able to perform site-specific physical weed control in maize was developed at the University of Pisa according to the work package 4 of the RHEA project. The operative machine was design and fully realized as one of the three Device Systems closely related to the Low Level Actuation System (drivers and algorithms that control the implement) (see also Chapter 6.4).
The aim was to design an automatic operative machine able to perform mechanical non-selective weed control in the inter-row space and site-specific flaming weed control on the rows of heat-tolerant crops. According to work package 1.1 of the RHEA project the machine was adjusted in order to properly work in maize planted at 0.75 m of inter row. The preliminary tests carried out in order to verify the correct coupling to the Ground Mobile Unit (see Chapter 6.5) were successful.

7.1 Machine structure

The machine structure is realized by assembling a rigid elements hoeing machine to the flaming system. The hoe was constituted by a 3.46 m wide steel frame, supporting 5 articulated parallelograms on which the hoeing tools were placed (Fig. 7.1). The LPG feeded flaming system, consisting in a steel frame (0.76 m x 1.46 m) supporting four LPG tanks and the open flame burners installed on the articulated parallelograms, is integrated (Fig. 7.2).
According to the inter-row space of maize in the RHEA project, which is equal to 0.75 m, the machine is adjusted in order to have a working width of 3 m in order to treat 4 intra- and 5 inter- rows in a single pass. The three central articulated parallelograms bring a couple of burners and rigid tines that till a 0.5 m space between the rows. Each couple of cross burners generates a flame able to control weeds on a strip 0.25 m wide with the maize plants placed in the middle (Fig. 7.2). The two external articulated parallelograms bring only one burner. Whole the side tines are removed to avoid overlapping in machine pattern (Fig. 7.2).
Each articulated parallelogram was designed in order to maintain the correct working depth of the tines and the proper distance of the burners from the soil surface during the treatment. This task is guarantee by a spring and two free pneumatic wheels (Fig. 7.3).

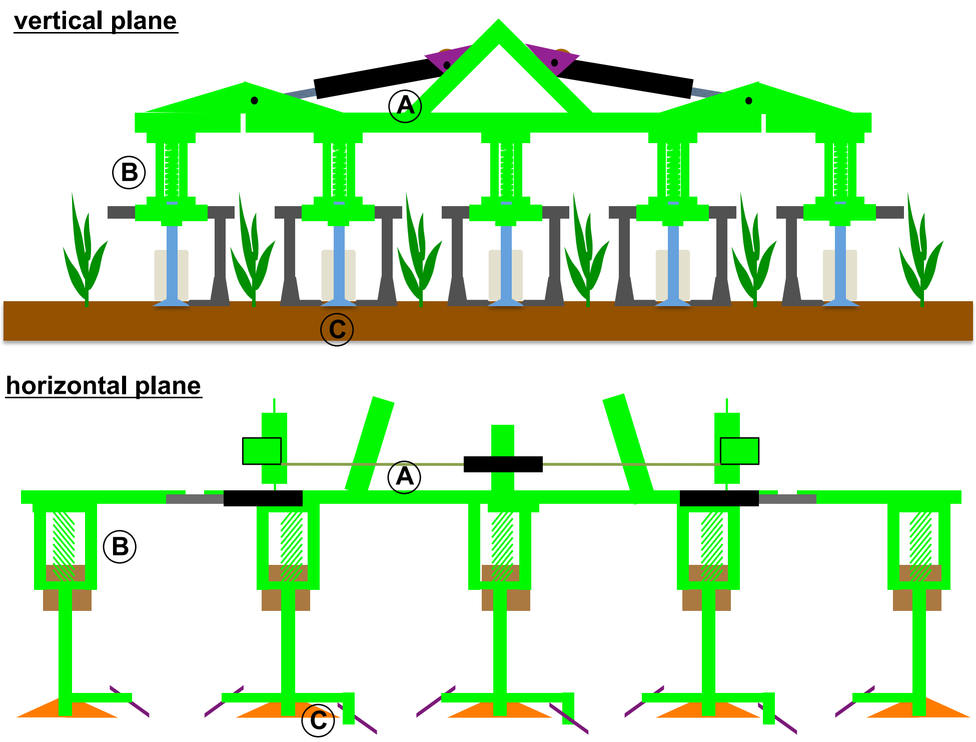

Figure 7.1. Vertical and horizontal plane of the initial machine structure. A: steel frame; B: articulated parallelogram; C: tines.

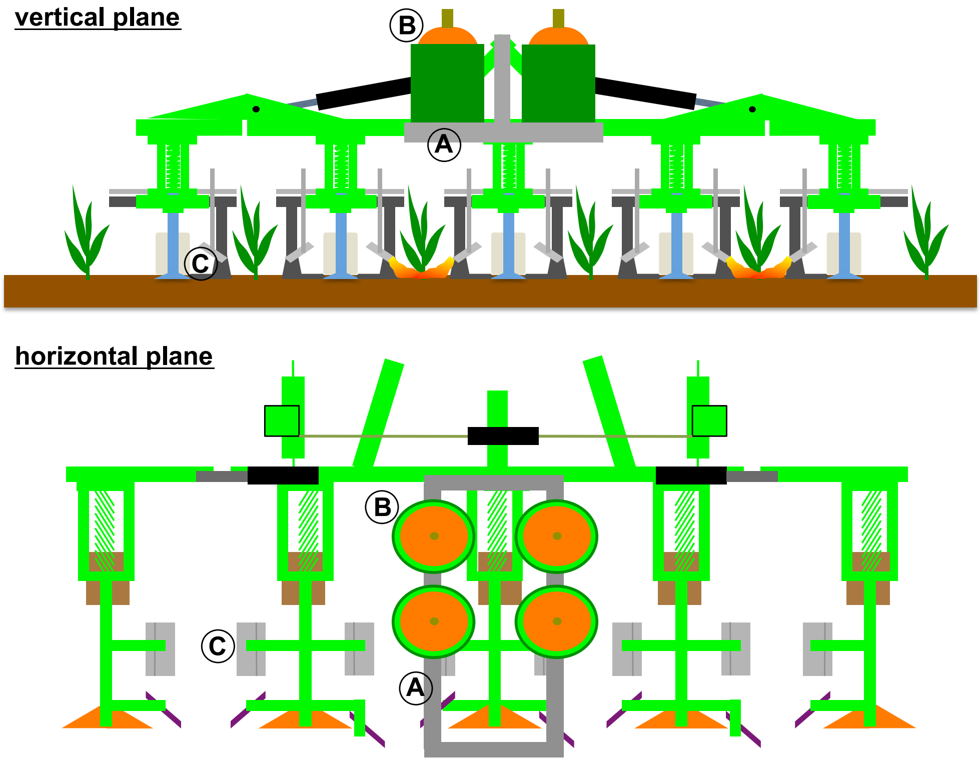

Figure 7.2. Integration between steel frames and flaming system. A: steel frame supporting LPG tanks, B: LPG tanks, C: burner.

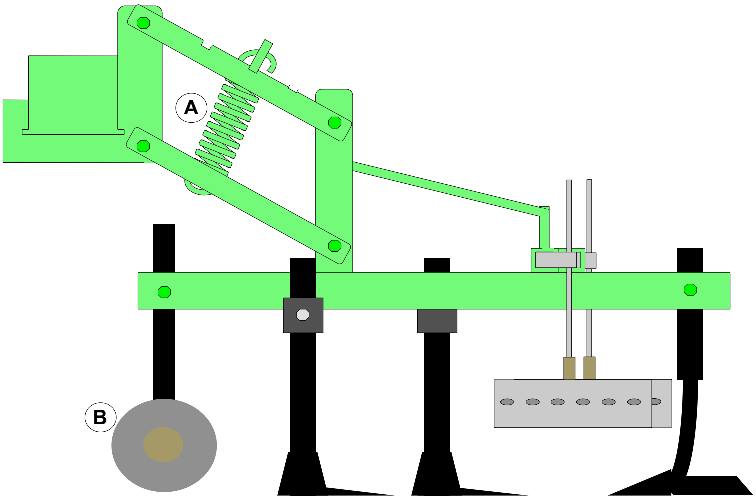

Figure 7.3. Scheme of the articulated parallelogram. A: spring, B: free pneumatic wheel.

7.2 Mechanical tools

Mechanical tools are placed on the articulated parallelograms. The external parallelograms are equipped with a goose-foot tine and only one "L" shaped sweep (Fig. 7.4a). On the other hand, the central parallelograms are equipped with a goose-foot tine and two sweeps (Fig. 7.4b). These rigid tools control weeds in the inter-row space, performing a shallow tillage (3-5 cm depth). The choice to perform hoeing was due to the agronomical importance of this practice. As a matter of fact, hoeing allows to break soil crust soil capillaries, preventing water evaporation under dry conditions. In addition, it improves water infiltration into the soil (Cloutier & Leblanc, 2001). Goose-foot tines are 0.24 m wide (Fig. 7.5), while, "L" shaped sweep tools are 0.15 m wide (Fig. 7.6).

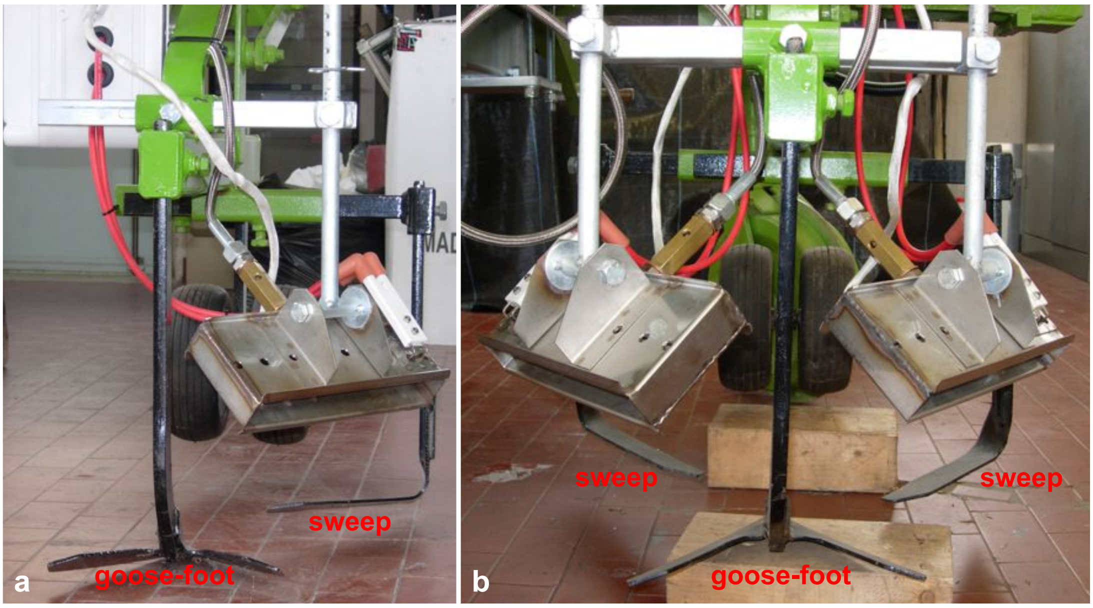

Figure 7.4. Mechanical tools installed on lateral (a) and central (b) parallelograms structure.

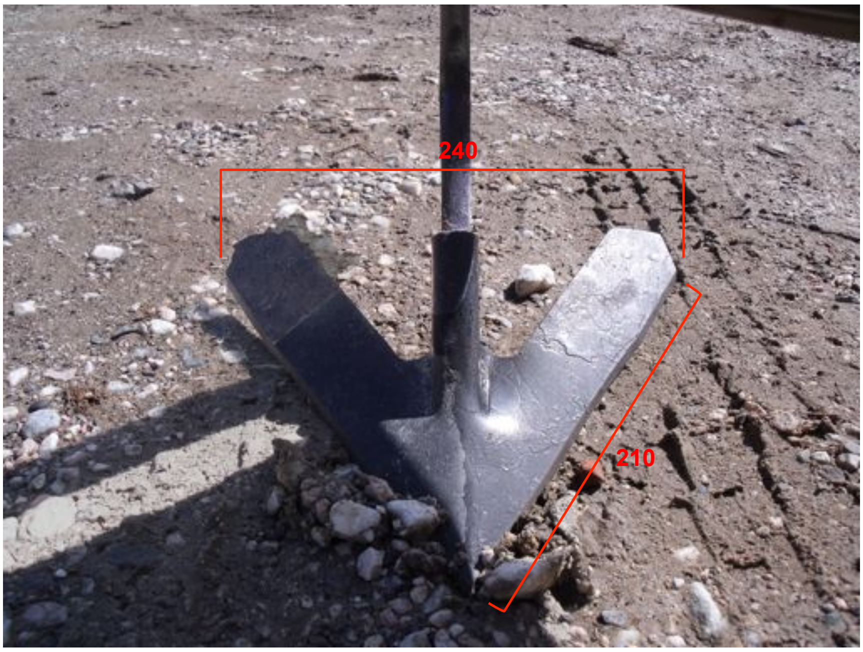

Figure 7.5. Goose-foot tine (dimensions are expressed in mm).

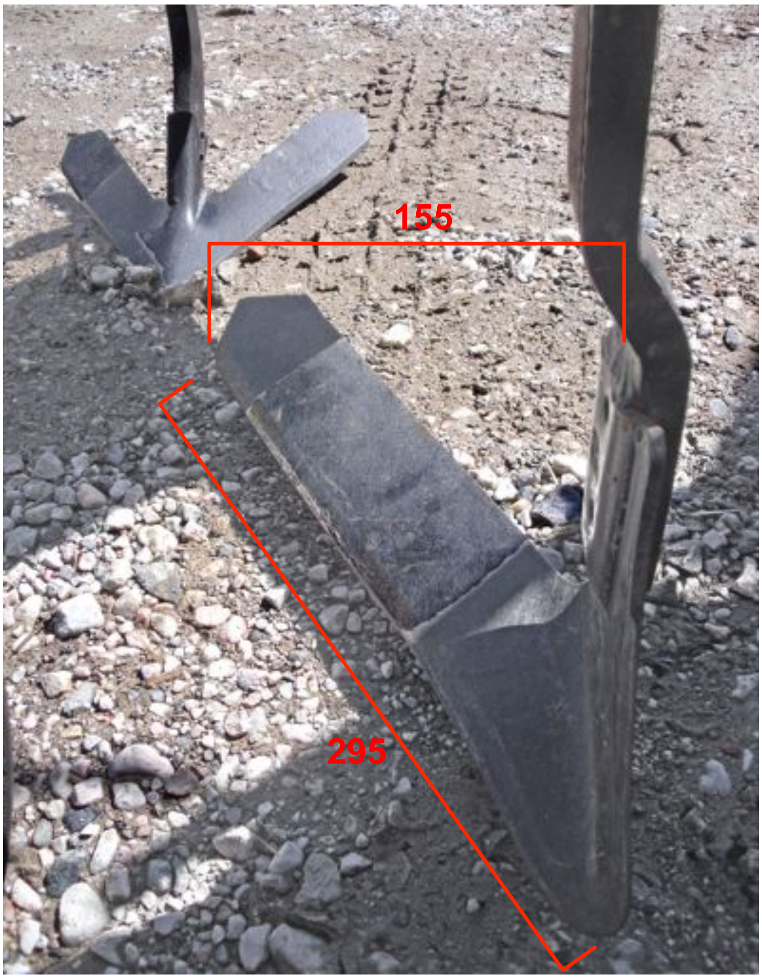

Figure 7.6. “L” shaped sweeps (dimensions are expressed in mm).

7.3 LPG feeding system and burners

The flaming system is composed by a LPG feeding system, 8 burners and an ignition system. Flaming system is completely automatic and based on a weed detection system (see Chapter 6.3.1).
Open flame is generated mixing air and LPG. Four LPG tanks are supported by a steel frame placed in the middle of the frame of the machine (Fig. 7.2). LPG tanks have to be manually inserted into proper hoppers (Fig. 7.7) containing the heat exchanger, that consists in water heated by the exhausted gases of the endothermic engine of the tractor that flow into the hoppers through a pipe. No-heated water has to be manually put in the hoppers. Exhausted gases exit from a proper chimney installed near the hoppers (Fig. 7.8). The heat exchanger allows to perform continuously flaming treatment at high pressure as LPG needs to be heated to pass from the liquid to the gas phase and the heat coming from the environment is not enough. As a matter of fact, if the temperature of LPG is lower than the vaporization one, the gas stops flowing switching off the burners.

Figure 7.7. Insertion of a LPG tank in the hopper.

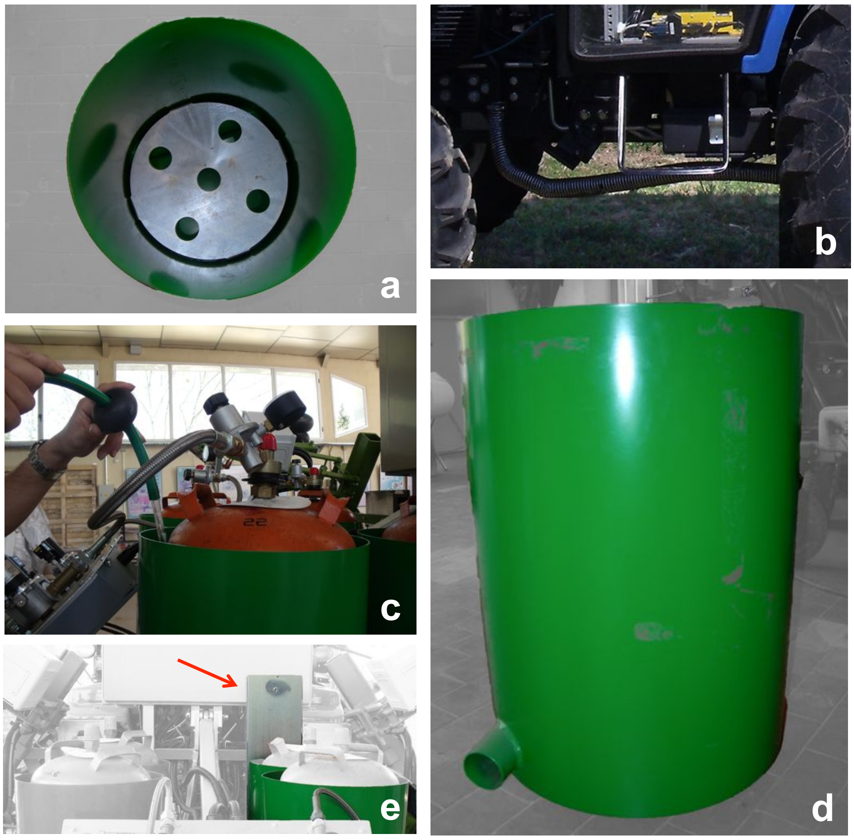

Figure 7.8. Heat exchanger. a) view of horizontal plane of the hopper with the internal holed support for tanks: b) Pipe for the transport of the exhausted gases from the engine to the hoppers; c) hoppers half filled with water (about 70 dm^3 $hopper^{-1}$); d: hole for the proper insertion of the pipe; e: chimney.

Gas flow from the LPG tanks to the burners is controlled by a PLC (Programmable Logic Controller) composed of a CPU coupled with inputs and outputs modules. Pressure sensors and thermocouples are connected to the inputs, while electro-valves and transformers are connected on the outputs. On the machine are placed four 15 kg LPG tanks. Each tank feeds a couple of burners. The scheme of the LPG feeding system for a couple of burners is shown in figure 7.9. On each tank there is a manual pressure regulator with a gauge set at 0.5 MPa. A pressure sensor (Aplisen® PC29) supplied with a 12 V DC voltage, monitors the pressure status of the LPG tank and transmits an analog signal to the PLC. When the LPG in the tank is going to finish and the pressure falls below 0.4 MPa, the PLC closes the adjacent electro-valve. All the electro-valves are normally closed solenoid valves (Madas® EV6 DN15) enabling the gas flux when they are supplied with an electrical 24V DC input. The LPG route is then split into two branches, one for each working pressure adjusted by two manual regulators. The choice between the two LPG pressures is made in real-time according to weed cover detected by the weed detection system. The PLC sends the signal to the electro-valve that has to be open according to detected weed cover (Fig. 7.10). In any case the LPG reaches two external mixers, placed on the pipes close to the two burners. The external mixer provides to mix LPG with air acting as a Venturi pipe. The external mixer is a hallow brass hexagonal prism mounted coaxially onto the LPG feeding pipeline upstream of the burner. The brass structure of the mixer has three circular inlets (ø 7 mm) on the lateral walls and a coaxial screwed nozzle

(ø 1.1 mm) placed inside (Fig. 7.11). The primary air intake is followed by a second air intake within the burners on which holes (ø 9 mm) are present and again exploit the Venturi effect. The LPG/air mixture then reaches the ignition electrode. Secondary air intake increases the efficiency of the combustion. Each burner is connected with a K thermocouple, which checks the presence of the flame and sends a low voltage output signal to the PLC. If the flame accidentally switches off, PLC activates the transformers in order to reignite the burners. If the ignition fails after 10 s the PLC closes the electro-valve placed near the tank, thus avoiding LPG efflux (Fig. 7.12). The wires of the thermocouple are coated in fiberglass in the part close to the burner in order to prevent any damage caused by high temperatures (Fig. 7.13). Burners are made in stainless steel and are composed by an external carter and an internal pierced-rod. The internal rod is 25 cm wide and 3 cm long and has pierces (ø 2.5 mm) placed 3.5 cm apart (Fig. 7.14). The presence of these pierces allows to obtain a flat flame. The external carter (10.5 cm long) presents holes on the main sides for the secondary air intake. The carter is reinforced with steel "wings" in order to avoid deformations (Fig. 7.15).
The preliminary tests performed in order to verify the proper functioning of LPG system and management carried out by the PLC were successful.

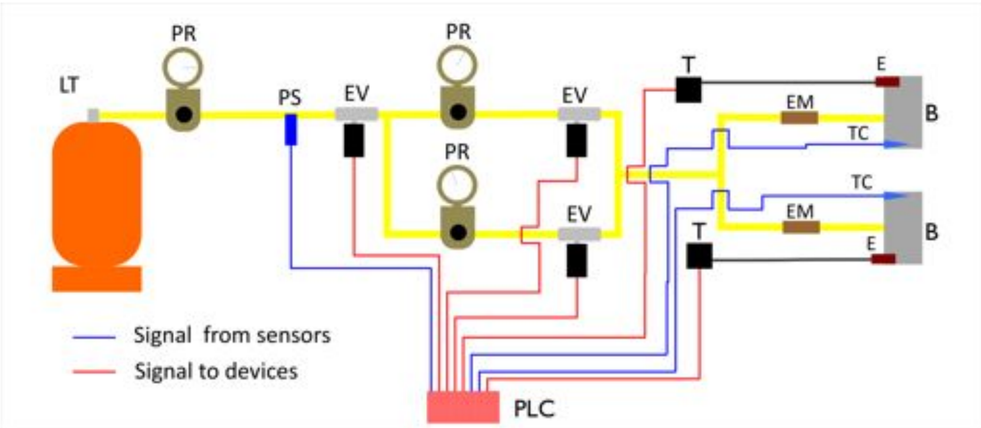

Figure 7.9. LPG feeding system. LT) LPG tank; PR) manual pressure regulator; PS) pressure sensor; EV) electro-valve; T) transformer; EM) external mixer; TC) thermocouple; E) electrode; B) burner; PLC) Programmable Logic Controller.

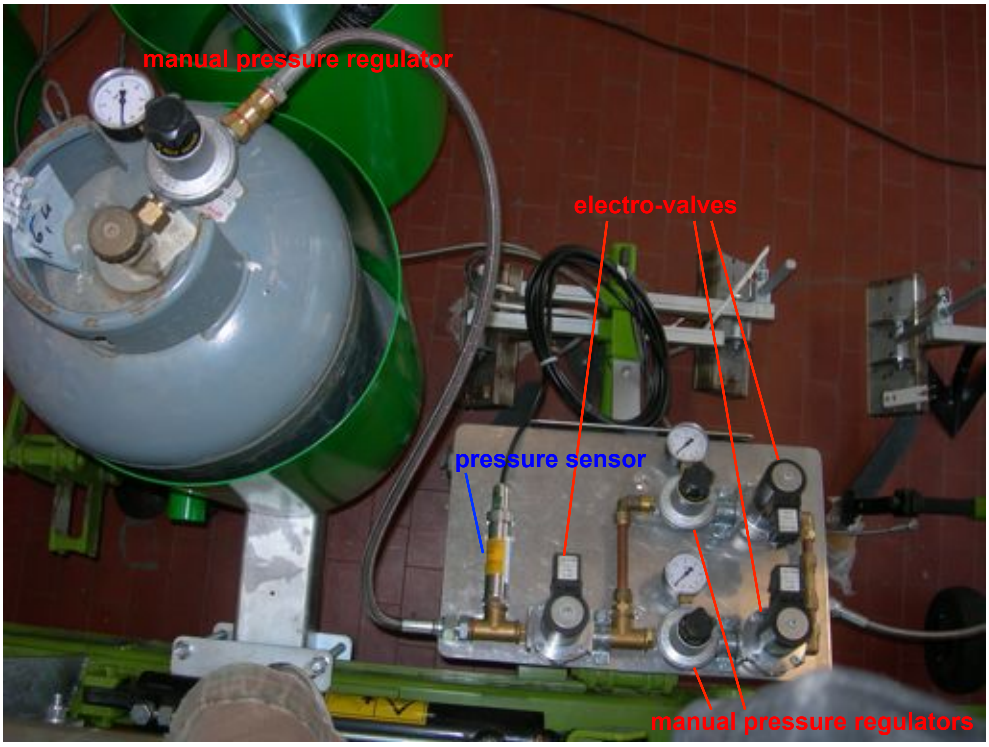

Figure 7.10. First part of the LPG feeding system.

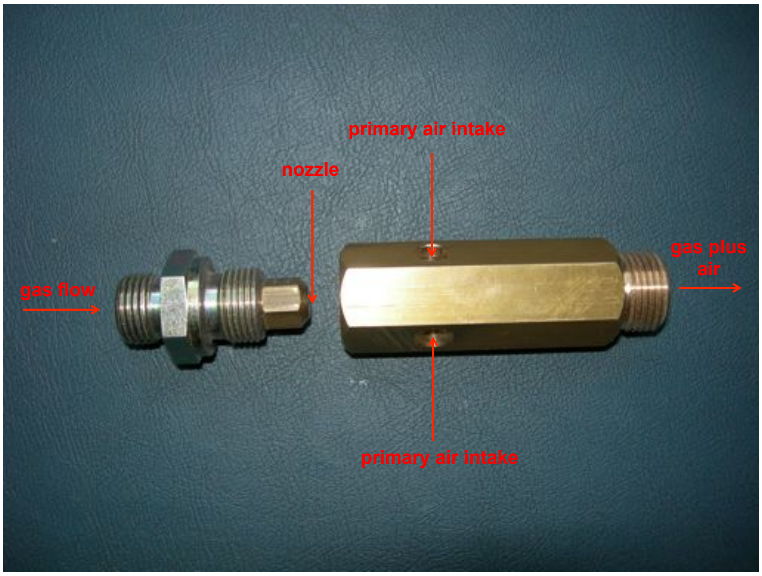

Figure 7.11. Disassembled self-aspirating external mixer.

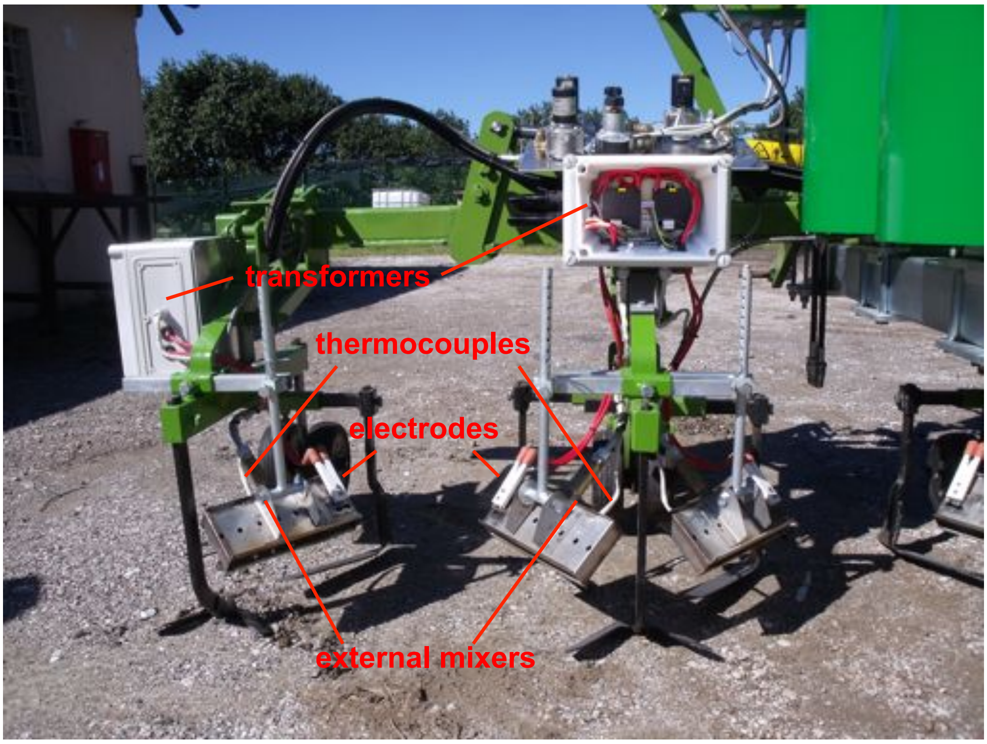

Figure 7.12. Second part of the LPG feeding system.


Figure 7.13. Type K thermocouple mounted onto the burner.


Figure 7.14. Internal view of the burner.

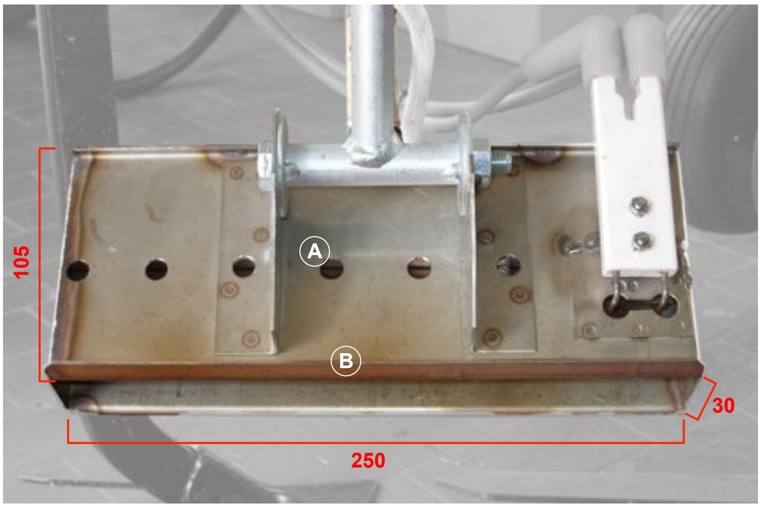

Figure 7.15. Burner: A) holes for secondary air intake; B) reinforcing wing (dimensions are expressed in mm).

7.4 The ignition system

The ignition system is almost instantaneous. As a matter of fact the flame is active and able to control weeds 0.39 s after the activation of the relays by the PLC. The ignition system is composed by one transformer (Cofi® TRL 24-30C) for each burner, converting the voltage value of 24V-DC to 12kV-AC, and one bipolar electrode with a ceramic voltage insulator body, placed on the burner. The transformer is wired to the electrode with special high voltage wires coated in silicone rubber in order to resist to high temperatures. The power of the transformer (80 W) allows to obtain a continuous electric arc between the two poles of the electrode, which ignites the LPG/air mixture even at the higher values of working pressure (Fig. 7.16). All transformers and electro-valves are wired to relays managed by the PLC. When weeds are detected during treatment, the PLC activates the appropriate relays in order to open the proper electro-valve and simultaneously provide the power supply for the ignition transformers. The time lapse between the activation of the relays by the PLC and the presence of a complete flame was estimated using frames from a video. An operator simulated the function of the PLC using a manual controller (Fig. 7.17) to switch on the electro-valve and the ignition transformers at the same time. Using QuickTime™ 7.6.4, the frames involved in the complete ignition process were isolated from the entire video (Fig. 7.18). The identification numbers of the video frames and the events associated are reported in table 7.1. The entire ignition process covers six frames. The total number of frames (552) and the length of the video (36 s) give the number of frames per second (15.33 frames s^{-1}). The duration of six frames was therefore 0.39 s. However, this may be an overestimation of the ignition delay of the burners. As a matter of fact, as shown in figure 7.18, in frame 56, after only 0.13 s, there is the presence of the main part of the flame probably already able to perform thermal weeding.

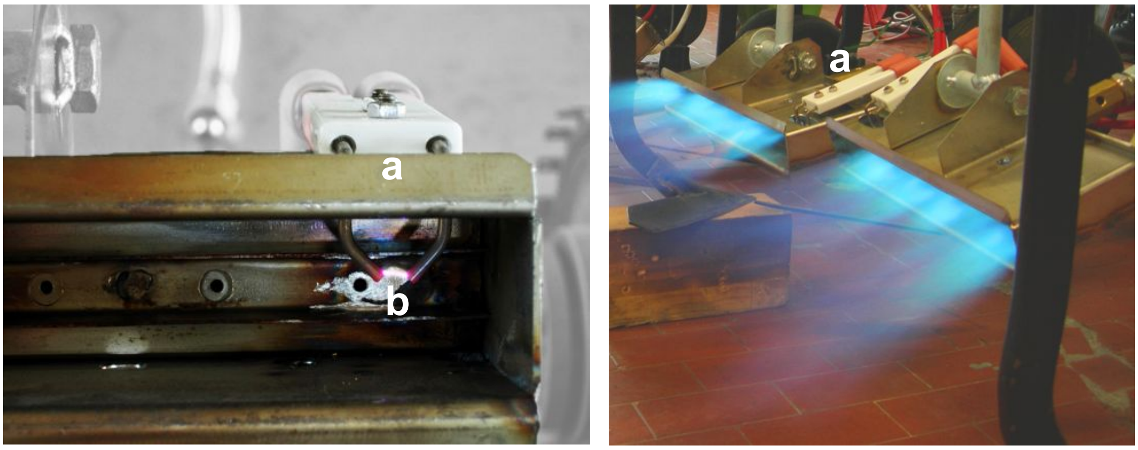

Figure 7.16. Burners with ignition system: a) electrode; b) electric arc between the two poles of the electrode.

Figure 7.17. Manual controller of electro-valves and ignition transformers.

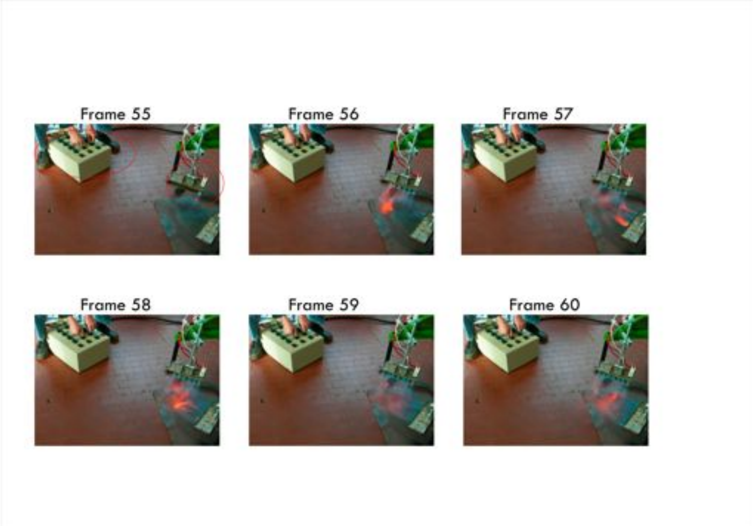

Figure 7.18. Six video frames involved in the complete ignition process.

Table 7.1. List of the identification numbers of the video frames involved in the ignition and related events.

Frame number	Event
55	Switches turned on and first strip of flame
56	Flame almost complete
57	Flame almost complete
58	Flame almost complete
59	Flame almost complete
60	Flame complete

Most of the market flaming machines equipped with burners use a pilot flame as ignition system. These machines need a manual ignition of the pilot flame before starting a flaming treatment. A LPG low pressure is used and the pilot flame is maintained always "on" also during turning and transfer phases. The use of instantaneous ignition system, instead of a pilot flame, is very important in order to obtain a lower LPG consumption and reduce the risk of burners switching off.

7.5 Hydraulic system

The machine is equipped with a folding system in order to make easy the transfer and the transport. The main frame is divided into three parts: one central and two lateral foldable parts. Two cylinders powered by the hydraulic circuit of the GMU drive the folding system (see Chapter 6.5) (Fig. 7.19). The width of the implement when it is closed is 2.48 m wide. The folding system is equipped with two couples of inductive sensors in order to detect both the closed and the open configuration (Fig. 7.20).

Figure 7.19. Machine folded for transfer and transport.

Figure 7.20. Inductive sensor installed on the machine.

In order to follow the direction given by guidance system of the GMU (see Chapter 6.3.1), and avoid to damage the crop (Fig. 7.21), the machine is equipped with an automatic steering system driven by a central double-rod hydraulic cylinder that enables little change in direction of two metal directional wheels that allow small lateral movement along the maize rows (Fig. 7.23a). Machine lateral displacement is measured by a linear sensory system (potentiometer and encoder). The positioning system measures the relative displacement of the implement with respect to the GMU in a direction perpendicular to its longitudinal axis. The system is based on a telescopic arm joining the GMU and the implement. An end of the arm is fixed to the GMU through a rotary passive joint, with the rotation axis perpendicular to the sensor arm. The other was fixed to a carriage though a ball joint. The carriage can slide over a linear guide. A linear potentiometer measures the distance between the carriage and a fixed point (Fig. 7.22; Fig. 7.23b).

Figure 7.21. Machine coupled with GMU following correctly maize rows.

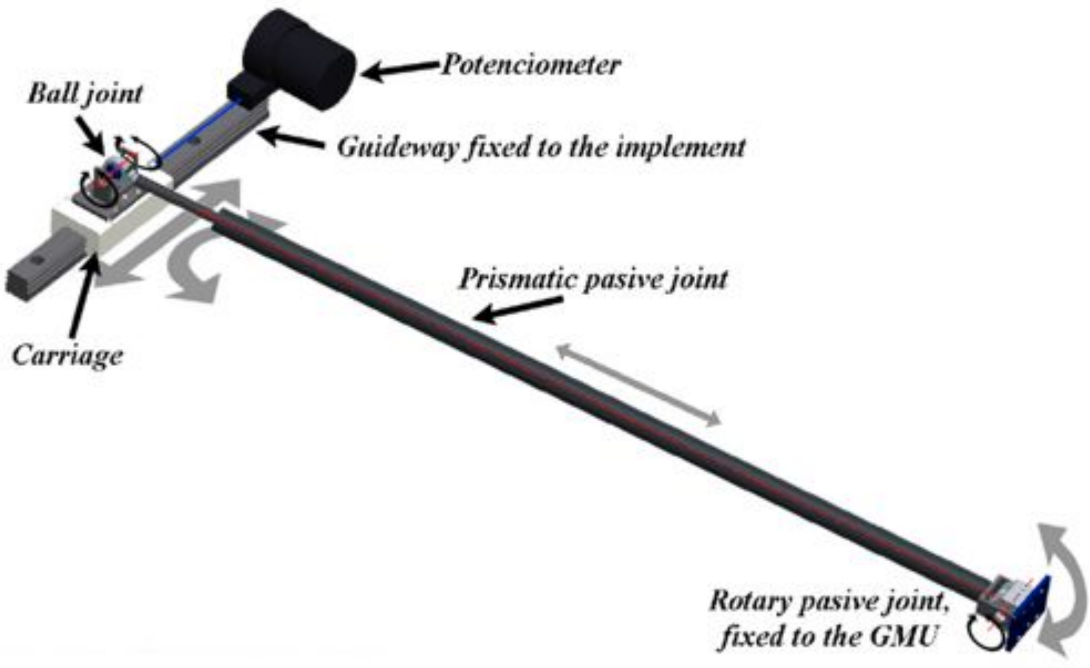

Figure 7.22. Basic scheme of the sensory system.

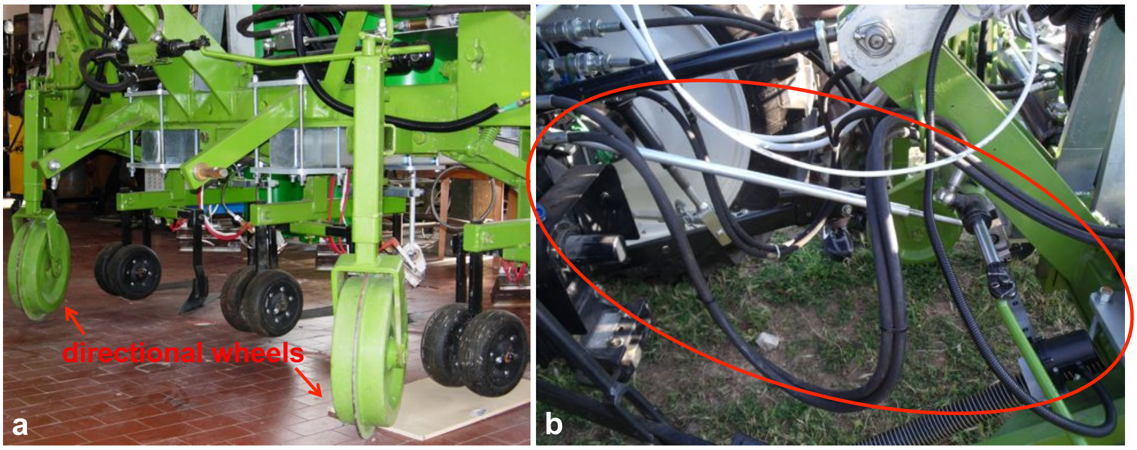

Figure 7.23. Automatic steering system. a) directional metal wheels; b) sensory system placed between the Ground Mobile Unit and the implement.

7.6 Electric system

The main components of the electric system of the machine are: (1) an emergency circuit for safety connected with an external button in order to manually interrupt the electric current, (2) fuses installed to protect the system and all the devices from an over amperage (3) relays for both manual and PLC controls (Fig. 7.24). The PLC is installed into the box and is connected with relays that allow the automatic opening of electro-valves and ignition transformers according to the information received by the weed detection system. Each electro-valves and ignition transformers have their own fuse.

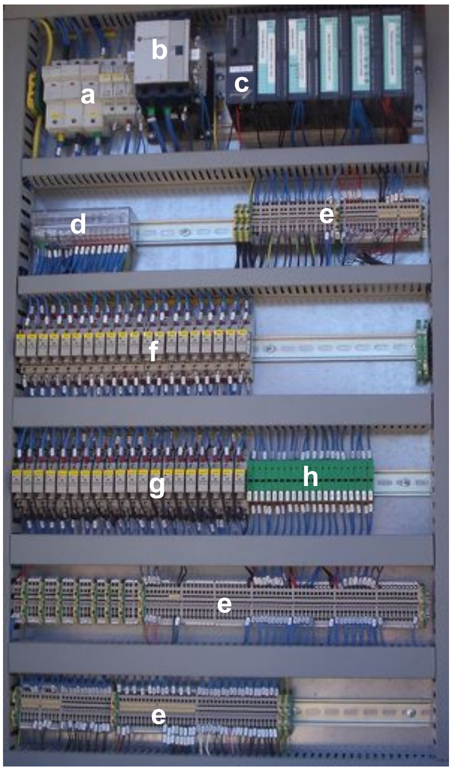

Figure 7.24. Inside of the electric box. a) fuses; b) emergency circuit; c) PLC; d) current divider; e) connectors; f) relays of the manual controller; g) relays of the PLC; h) fuses of the electro-valves and ignition transformers.

7.7 Simulation of LPG consumption

The effectiveness of flaming on weeds is strictly related to the LPG dose per unit surface (Ascard, 1994). This parameter is influenced by the working speed of the machine, the LPG pressure and the typology of the used burners (Galbiati, 2005). In order to calculate the LPG consumption per hour of the 25 cm wide rode burners a test bench was used. The LPG feeding system of the test bench was equipped with a manual pressure regulator with a pressure gauge, a manual valve to open/close the LPG flux, an external mixer with a 1.1 cm diameter nozzle, a 15 kg LPG tank, and a heat exchanger. The composition of the mixture contained in LPG bottle used in this test is reported in table 7.2. The consumption of LPG was calculated as the difference in the weight of the LPG tank before and after one hour of burning at various working pressure. The trial was replicated three times. The mean values of LPG hourly consumption are reported in table 7.3.

The LPG consumption per unit surface and the effective biological dose supplied to the weeds were then estimated assuming a continuous treatment carried out at the constant working speeds of 3 and 6 km h^{-1}. In the case of cross flaming the LPG consumption and the LPG effective biological dose should be taken into account. LPG consumption is the amount of LPG per unit surface consumed, considering the entire working width of the machine (3 m). The LPG effective biological dose is the amount of LPG per unit surface that is distributed in the 0.25 strips with the crop rows in the middle. Both consumption and effective biological dose were calculated with the following equation:

$$Ga = \frac{Ch \cdot n}{\left(\frac{v \cdot l}{10}\right)}$$

Where *Ga* is the LPG amount per unit surface (kg ha^{-1}); *Ch* is the hourly LPG consumption of one burner (kg h^{-1}); *n* is the number of burners; *v* is the working speed adopted for the treatment (km h^{-1}); *l* is the working width (m).

In table 7.4 are shown the values, at various working pressures, of LPG consumption and effective biological dose, assuming two working speeds (3 and 6 km h^{-1}).

Table 7.2. Composition of the mixture used to determine LPG gas consumption.

Component	Composition (%)
propane	50
n-butane	25
i-butane	25

Table 7.3. LPG consumption of a single burner at different levels of working pressure.

Working pressure (MPa)	LPG consumption (kg h^{-1})
0.10	1.96
0.15	2.45
0.20	2.93
0.25	3.42
0.30	3.91
0.35	4.40
0.40	4.88
0.45	5.37
0.50	5.86

Table 7.4. Estimated values of LPG consumption (continuous treatment) and LPG effective biological dose (EBD) assuming two constant working speeds of 3 and 6 km h^{-1}.

	LPG consumption (kg ha^{-1})		LPG EBD (kg ha^{-1})	
Working pressure (MPa)	3 km h^{-1}	6 km h^{-1}	3 km h^{-1}	6 km h^{-1}
0.10	17.4	8.7	52.2	26.1
0.15	21.8	10.9	65.2	32.6
0.20	26.0	13.0	78.2	39.1
0.25	30.4	15.2	91.2	45.6
0.30	34.8	17.4	104.2	52.1
0.35	39.0	19.5	117.2	58.6
0.40	43.4	21.7	130.2	65.1
0.45	47.8	23.9	143.2	71.6
0.50	52.0	26.0	156.2	78.1

In order to evaluate the LPG consumption for a site-specific flaming treatment, a 16 row maize field infested with weeds was simulated. The crop rows were divided into 0.25 m wide and 0.5 m long cells. Then three ranges of weed cover were associated to three LPG doses: (1) 0≤weed cover<5% no treatment; (2) 5≤weed cover<25% treatment using 52 kg ha^{-1}; (3) weed cover≥25% treatment using 65 kg ha^{-1}. In this case the working pressures were adjusted to 0.1 and 0.15 MPa when the working speed was 3 km h^{-1} and to 0.3 and 0.4 MPa when the working speed was 6 km h^{-1}.

One hundred digital photographs were collected in a surface 0.25 m wide and 0.5 m long along the crop rows in a real maize field in order to generate a weed distribution map. The experimental maize field (FAO class 500) was located in San Piero a Grado (Pisa, Central Italy) 43° 41' 07.34'' N, 10° 20' 35.06'' E. Before sowing 400 kg ha^{-1} of an inorganic NPK ternary fertilizer (8-24-24) and 100 kg ha^{-1} of urea were distributed and incorporated into the soil. Photographs were taken 30 days after sowing when the maize plants were at the phenological stage of 5 leaves with collar (V5). In order to determine weed cover the digital files were analysed with an imaging crop response analyser (Rasmussen *et al.*, 2007). The frequencies of the weed cover values according to the three ranges are reported in table 7.5.

Table 7.5. Frequencies of the weed cover values observed in the rows of a real maize field divided according to the three ranges.

Weed cover ranges (%)	Observed frequency
0≤weed cover<5%	0.51
5≤weed cover<25%	0.32
weed cover≥25%	0.17

A weed distribution map was drawn up, associating a random number from 1 to 100 with each cell, assuming that the probability of having a cell with weed cover within one of the determined ranges was equal to the frequencies observed. If a random number associated with a cell was between 1 and 51, was assumed a weed cover for that cell within the first range (0≤weed cover<5%). If the random number associated with a cell was between 52 and 83, was assumed a weed cover for that cell within the second range (5≤weed cover<25%). If the random number associated to a cell was between 84 and 100, was assumed a weed cover for that cell within the third range (weed cover≥25%). In figure 7.25 is shown the in-row weed distribution map obtained with this simulation. The LPG consumption per ha calculated according to this map and the three levels of treatment corresponding to the three LPG effective biological doses (52 and 65 kg ha^{-1}) was about 10 kg ha^{-1}. This value is quite low if compared with the LPG consumption of continuous flaming treatment carried out with 52 and 65 kg ha^{-1} LPG effective biological doses (respectively about 17 and 22 kg ha^{-1}). This expected result has to be verified and confirmed by real field tests.

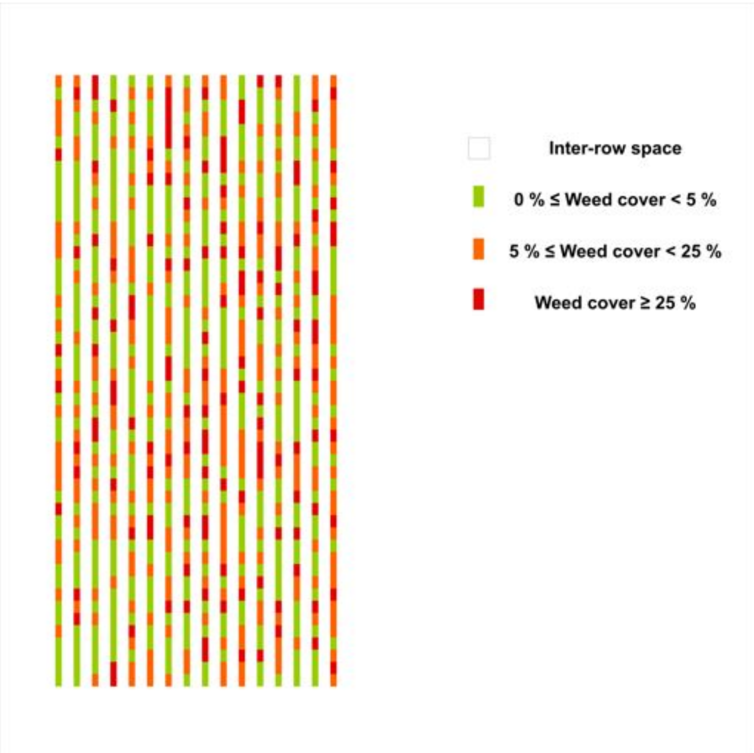

Figure 7.25. In-row weed map distribution obtained with a simulation based on weed cover frequencies of a real maize field.

CHAPTER 8. INTRA-ROW CROSS FLAMING TREATMENTS APPLIED TO MAIZE IN ORDER TO TEST CROP TOLERANCE AND WEED CONTROL

8.1 Introduction

Weeds are responsible for significant crop yield reduction (Datta & Knezevic, 2013; Fontanelli *et al*., 2013; Peruzzi *et al*., 2007). Flaming is the most common thermal weed control method used in agriculture in both organic and conventional systems (Ascard, 1995) as one of the main alternatives to herbicides distribution (Datta & Knezevic, 2013; Fontanelli *et al*., 2013; Peruzzi *et al*., 2007). LPG (propane and butane mixture) is commonly used to feed burners and generate flame at an average temperature of about 1500 °C, that heats the exposed leaves very rapidly, thus devitalizing the weeds without burning them (Ascard, 1995). Heat exposure denaturizes plant proteins, which results in loss of cell function, causes intracellular water expansion, ruptures cell membranes, and finally desiccates the weeds, normally within two to three days (Mojžiš, 2002). The growth stage at the time of flaming determines weed sensitivity to heat. As a matter of fact, flaming is most effective on weeds at an early growth stage (Ascard, 1995; Mojžiš, 2002).

There are three fundamental types of burners on the market: open flame with cover (T max=1900 °C), open flame without cover (T max=1500 °C) and infrared weeder (T max=500°C). (Ascard, 1995; Knezevic *et al*., 2013; Raffaelli *et al*., 2013; Rask *et al*., 2012).

The main advantages of flame weeding are the lack of chemical residues in the crop, soil and water, the lack of herbicide carry-over the next season, the very wide spectrum of weeds controlled and the absence of resistance to flaming (Ascard, 1995; Mojžiš, 2002; Fontanelli *et al*., 2013). Flame weeding could be used in pre-sowing, pre-emergence or pre-transplanting in order to devitalize weeds that emerged prior to the crop (Hatcher & Melander, 2003; Peruzzi *et al*., 2007). Post-emergence flaming can be used in heat-tolerant crops (i.e. maize, soybean, sunflower, onion, garlic, etc.) (Knezevic, 2009; Peruzzi & Raffaelli, 2000; Ulloa *et al*., 2011a).

The aim of this research was to test the tolerance of maize (*Zea mays* L.) to cross flaming treatments and the effectiveness in control weeds as influenced by LPG dose and crop growth stage at the time of treatment. Thus, this research represents a preliminary field application for the future adoption of the innovative automatic machine designed and realized to perform site-specific flame weeding in maize within the RHEA Project at the University of Pisa.

8.2 Materials and Methods

Experiment set up

A field experiment was carried out in 2013 at CiRAA "E. Avanzi", experimental farm of the University of Pisa (+43.7°N +10.3°E) located in San Piero a Grado, close to Pisa, in Central Italy. The trials were repeated in two sites of 5 ha each during the growing season resulting in a total of two studies in one year. The soil type was loam in both sites (52% sand, 38% silt, 17% clay, 1.8% organic matter, pH of 8.2 and a CEC of 11 in site 1; and

37% sand, 46% silt, 17% clay, 2.6% organic matter, pH of 8.1 and a CEC of 7 in the site 2).

The previous crop was maize. Soil tillage included a shallow ploughing (0.25 m deep) and two passes of a rotary harrow. Fertilization consisted in the distribution of 400 kg ha^{-1} of a ternary fertilizer (8 24 24) and 200 kg ha^{-1} of urea before the second harrowing and of 200 kg ha^{-1} of urea in post-emergence. FAO 500 maize hybrid was used. Sowing was performed by mean of a four-rows planter with an inter-row distance of 0.75 m at a density of 83000 seeds ha^{-1} for both sites.

All plots where maize response to flaming was studied, untreated control included, were kept weed-free for the entire growing season performing hand hoeing.

Crop growth was dependent on precipitation, irrigation and a high water table. Water by irrigation was distributed by sprinkling. The trends of the total monthly rainfall, irrigation and temperatures (min and max) recorded during the growing season are shown in (Table 8.1).

Table 8.1. Total monthly rainfall, irrigation and temperatures recorded at San Piero a Grado (Pisa) during maize growing season (Consorzio LaAMMA, 2013).

Crop month	**2013**			
	Temperature (°C)		**Precipitation (mm)**	**Irrigation (mm)**
	Minimum	Maximum		
May	11.8	19.6	62	0
June	13.9	24.6	18	0
July	18.7	29.7	4	50
August	18.6	30.1	7	70
September	16.0	26.0	91	0

Experimental design and treatments

The experiment was carried out using a 1 way randomized blocks with three replications. The factor was LPG biological dose tested at different growth stages of maize. The plots included an untreated control, a weed free untreated control and four LPG doses witch were applied at three maize growth stages both in weed-free and real-field conditions. The stage of development of maize was assessed according to the leaf collar method (Nielsen, 2010). Flaming was performed at V2 (2-leaf stage, when the collar of the second leaf is visible), V5 (5-leaf stage, when the collar of the fifth leaf is visible) and V2plusV5 (maize treated two times, the first one at V2 stage and the second one when the maize at V5 stage was flamed).

Flaming was carried out on 28 May (V2 stage) and on 13 June (V5 and V2plusV5 stage) in both sites. Cross flaming was applied in a strip 0.25 m wide with the maize plants placed in the middle (Fig. 8.1) the intra-row space utilizing a couple of 0.25 m wide open flame burners. A mounted flaming machine, realized some years ago at the University of Pisa, equipped with four couples of burners and thus working on four maize intra-row spaces was used (Fontanelli *et al.*, 2013; Peruzzi *et al.*, 2007; Peruzzi & Raffaelli, 2000).

Four LPG doses (52, 65, 104 and 130 kg ha^{-1}) were used combining two working pressure (0.3 and 0.4 MPa) with two driving speeds (3 and 6 km h^{-1}). At the same time of flaming an inter-row hoeing was performed with a machine able to till in a single pass 5 inter-rows at a depth of 3-5 cm with a driving speed of about 2 km h^{-1}. The hoeing machine was composed by five articulated parallelograms equipped with a central goose-foot tine and two side "L" shaped sweeps (fig. 8.2).

Figure 8.1. Cross flaming treatment at V2 stage of maize.

Figure 8.2. Precision hoe performing the first mechanical treatment at V2 stage of maize.

Data collection

Crop biomass samples were collected at 7, 14 and 28 days after each treatment in order to evaluate maize tolerance to cross flaming. Plants from one linear meter of each weed-free plot were cut at ground level and dried at 105 °C to constant weight to determine plants dry weight.

Weed density was determined 7 days after each physical treatment. Samples were collected in a 0.075 m^2 area in three randomly selected sampling points of each real field conditions test plot.

Weed dry biomass at harvest was determined on weeds collected in a 3 m^2 area in each real field conditions test plot. To determine the dry biomass, weeds were cut without roots and dried at 105 °C to constant weight.
Yield was determined collecting samples in 4.5 m^2 areas placed in the middle two rows of each plot in both weed-free and real field conditions.

Statistical analysis

A combined analysis of variance and an LSD post-hoc test were performed over the two sites by Generalized Linear Model procedure using SPSS Statistics (IBM, 2011). Analysis was carried out setting blocks and LPG doses as fixed factors, the sites as casual factor and respectively maize dry biomass, maize yield, weed density and weed dry biomass at harvest as dependent variables. The results of the combined analysis showed that none LPG doses-by-site interactions were significant. Thus the data were pooled in a unique site with 6 blocks and ANOVA was performed at each maize growth stage, setting 1 way randomized blocks analysis. Maize dry biomass, maize yield, weed density and weed dry biomass at harvest were subjected to ANOVA and Fisher's Protected LSD test was used with $\alpha=0.05$ in order to describe differences between means, using CoStat (CoHort Software, 1998-2008). Weed density data were transformed using square root transformation as they follow a Poisson distribution. Statistical analyses were carried out on the transformed data.
Weed dry biomass at harvest at V5 stage in real field conditions tests were analysed using the four parameter log-logistic model (Seefeldt *et al*., 1995):

$$Y = \frac{C + (D - C)}{\{1 + \exp[B(\log X - \log E)]\}}$$

where (Y) is the response (weed dry biomass), (C) is the lower limit, (D) is the upper limit, (X) is the LPG dose, (E) is the dose giving a 50% response between the upper and the lower limit (also known as inflection point or ED_{50}) and (B) is the slope of the line at the inflection point.
Maize yield, weed density and weed dry biomass at harvest at V2 and V2plusV5 growth stage in real field conditions tests were analysed utilizing the three-parameter log-logistic model where (C) term was fixed at zero (Seefeldt *et al*., 1995):

$$Y = \frac{D}{\{1 + \exp[B(\log X - \log E)]\}}$$

Curve fitting was done by non-linear regression using the least squares method. Dose-response curves (DRC) statistical addition package (Knezevic *et al*., 2007; Ritz & Strebig, 2013) of R program (R Development Core Team, 2006) were used to perform statistical analyses and graphs. To analyse weed density the Poisson type data distribution was setting. A test of lack-of-fit at the 95% level was not significant for any of the dose-response curves (Figs. 8.3-8.7) tested indicating that the log-logistic model was correct (Knezevic *et al*., 2007).

8.3 Results

Test in weed-free conditions

None maize plant dead was observed after the flaming treatments. Generally, maize dry matter decreased, as LPG dose increased, regardless of the growth stage, at 7, 14, and 28 days after flaming (Table 8.2). In maize treated at the V2 stage dry matter resulted statistically different from that of the non-treated control also when the lowest LPG dose of 52 kg ha^{-1} was applied. A significant difference is present between the dose of 52 kg ha^{-1} and the other doses 7 days after treatment, while 14 and 28 days after treatments significant differences are present between the lowest, the highest and the middle doses. Dry matter of maize treated at the growth stage V5 resulted statistically different compared to the non-treated control only when LPG dose of 130 kg ha^{-1} was applied. Dry matter of maize treated two times (V2plusV5 stage) resulted always statistically different compared to the non-treated control independently from the applied LPG dose. Differences between the lowest and the highest dose resulted also significant. However, maize plants treated at V5 stage showed the highest tolerance to cross flaming.

No significant differences between the compared theses are present in maize yield (Table 8.3) suggesting that in weed-free conditions yield is not influenced by LPG doses and growth stage of maize.

Table 8.2. Maize dry matter resulting after 7, 14, and 28 days after flaming treatment at different LPG doses and growth stages.

	Maize dry matter (g m^{-2})								
	7 DAT			*14 DAT*			*28 DAT*		
LPG dose (kg ha^{-1})	**V2**	**V5**	**V2plusV5**	**V2**	**V5**	**V2plusV5**	**V2**	**V5**	**V2plusV5**
0	4.7 a	97.7 a	97.7 a	13.9 a	285.7 a	285.7 a	205.0 a	944.5 a	944.5 a
52	4.4 b	87.5 a	-	6.4 b	245.4 ab	-	157.9 b	799.1 ab	-
65	3.9 c	82.3 ab	-	5.8 c	232.4 ab	-	116.1 c	795.3 ab	-
104	3.7 c	63.9 ab	29.1 b	5.6 c	201.3 bc	132.1 b	113.9 c	793.4 ab	566.9 b
130	3.3 c	48.3 b	24.9 bc	4.6 d	151.2 c	121.6 b	104.3 d	644.0 b	543.0 bc
208	-	-	22.8 bc	-		100.1 bc			449.0 c
260	-	-	13.3 c	-		61.5 c			432.8 c

V2: 2-leaf growth stage; V5: 5-leaf growth stage; V2plusV5: double growth stage; 7, 14, 28 DAT: 7, 14, 28 days after the flaming treatment at V2 stage (first treatment) and after the flaming treatment at V5 and V2plusV5 stages (second treatment). In each column means followed by the same letter are not significantly different at P≤0.05 (LSD test).

Table 8.3. Maize yield influenced by different LPG doses and growth stages in weed-free conditions.

LPG dose (kg ha^{-1})	Yield (Mg ha^{-1})		
	V2	V5	V2plusV5
0	18.8 a	18.8 a	18.8 a
52	16.3 a	16.2 a	-
65	15.9 a	16.4 a	-
104	15.9 a	17.0 a	17.5 a
130	16.9 a	17.4 a	17.8 a
208	-	-	16.7 a
260	-	-	16.4 a

V2: 2-leaf growth stage; V5: 5-leaf growth stage; V2plusV5: double growth stage. In each column means followed by the same letter are not significantly different at $P \leq 0.05$ (LSD test).

Test in real field conditions

The first treatment performed at the V2 stage determined significant differences between the untreated control and all the flamed plots (Table 8.4). At this growth stage weeds were 100% dicots at the cotyledon stage (mainly represented by *Chenopodium album* L. and *Datura stramonium* L.). A reduction in weed density, increasing LPG dose, was observed 7 day after the treatment (Fig. 8.3). Regression parameters are shown in table 8.6. The percentage of reduction of weeds compared to the untreated control was 99% at the highest LPG dose. Mechanical inter-row weed control showed significant statistical differences with respect to the untreated control 7 days after the treatment. No-treated inter-row presented 163.1 plants m^{-2} whereas treated inter-row 5.3 plants m^{-2} (back transformation values).

The second flaming treatment was applied at the V5 stage and in plots already treated at the V2 stage (only those that provided the double treatment). When maize was at the V5 stage, weeds were well developed, showing 6 leaves on average. 7 days after the second treatment significant differences were present between the untreated control and all LPG doses at each growth stage (Table 8.5). Weed density decreased as LPG dose increased at each growth stage (Fig. 8.4), but at V5 stage the LPG dose needed to obtain the 50% response between the upper and the lower limit of the curve was higher (equal to 39.5 kg ha^{-1}) than those needed at V2 and V2plusV5 stages (7.6 kg ha^{-1} and 7.9 kg ha^{-1} respectively) (Table 8.6). The percentage of reduction of weeds compared to the untreated control was 79%, 94% and 99% at V5, V2 and V2plusV5 stages, respectively, at the highest LPG dose.

Inter-row hoeing determined significant differences between untreated and treated plots and between the number of treatments 7 days after the second intervention. No-treated inter-row presented 172.2 plants m^{-2}, whereas plots treated one or two times 24.3 plants m^{-2} and 5.0 plants m^{-2} respectively (back transformation values).

Table 8.4. Weed density influenced by different LPG doses 7 days after treatment at the growth stage V2.

LPG dose (kg ha^{-1})	Weed density (plants m^{-2})
0	242.2 a
52	7.3 b
65	4.8 b
104	2.2 b
130	2.2 b

Data are back transformation values. In each column means followed by the same letter are not significantly different at P≤0.05 (LSD test).

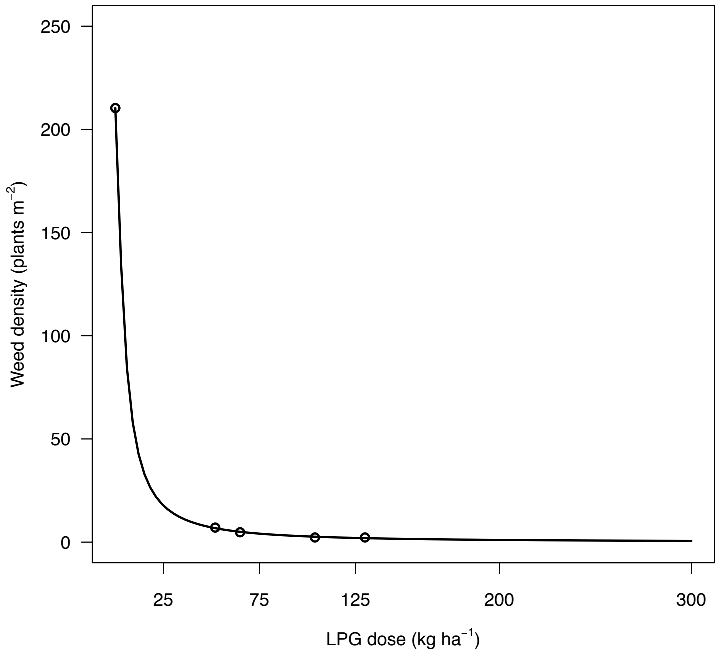

Figure 8.3. Influence of LPG flaming on weed density (7 days after the first treatment) as affected by LPG dose at the stage V2 of maize.

Table 8.5. Weed density influenced by different LPG doses 7 days after treatment at different growth stage.

LPG dose (kg ha^{-1})	Weed density (plants m^{-2})		
	V2	**V5**	**V2plusV5**
0	153.3 a	153.3 a	153.3 a
52	22.2 b	65.2 b	-
65	15.6 bc	58.5 b	-
104	11.9 bc	57.0 b	7.4 b
130	9.6 c	31.9 c	6.7 b
208	-	-	5.9 bc
260	-	-	1.5 c

Data are back transformation values. V2: 2-leaf growth stage; V5: 5-leaf growth stage; V2plusV5: double growth stage. In each column means followed by the same letter are not significantly different at P≤0.05 (LSD test).

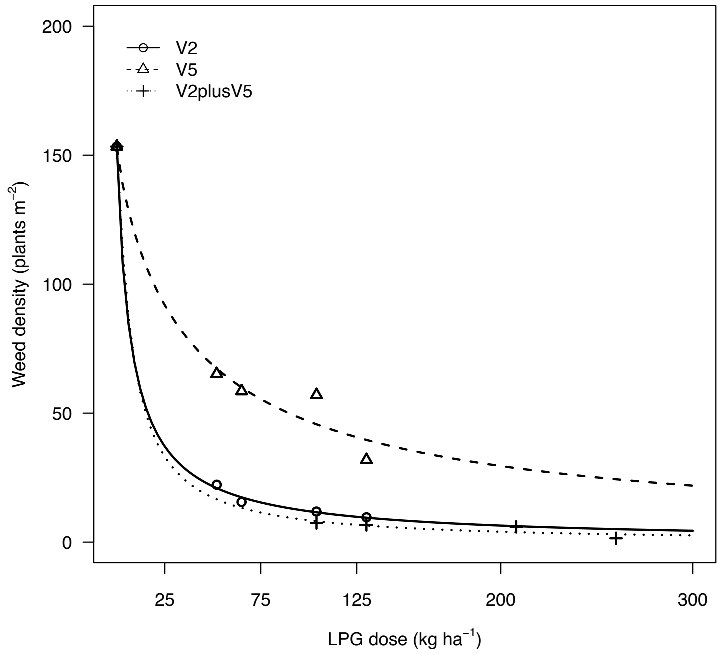

Figure 8.4. Influence of LPG flaming on weed density 7 days after the second flaming treatment as affected by LPG dose and growth stage. The growth stages tested were V5 and V2plusV5. Data were collected also in plots treated only at the stage V2.

Table 8.6. Regression parameters for weed density (plants m^{-2}) as affected by LPG dose of flaming at the stage V2 of maize 7 days after the first treatment and at three growth stages of maize 7 days after the second treatment.

Growth stage	**Regression parameters (±SE)**		
	B	**D**	**ED_{50}**
7 days after first treatment			
V2	1.4 (0.13)	210.4 (2.42)	4.5 (1.15)
7 days after second treatment			
V2	1.0 (0.10)	153.4 (2.92)	7.6 (1.79)
V5	0.9 (0.07)	153.0 (2.91)	39.5 (3.08)
V2plusV5	1.1 (0.15)	153.3 (2.92)	7.9 (3.06)

V2: 2-leaf stage; V5: 5 leaf-stage; V2plusV5: double stage; B: slope of the line at the inflection point; D: upper limit; ED_{50}: dose of LPG resulting in a 50% response between the upper and the lower limit.

Weed dry biomass at harvest resulted influenced by LPG dose and growth stage of maize at the time of treatment. At V2 and V2pusV5 stages were observed significant differences between all the LPG doses and the untreated control (Table 8.7). At V5 stage only with a higher LPG dose was possible to obtain significant differences between flaming and untreated control (Table 8.7). At all growth stages of maize at the time of flaming weed dry biomass at harvest decreased as LPG dose increased (Fig 8.5; Fig 8.6). Weed dry biomass at harvest when maize was treated at V2 and V2plusV5 stages was close to 0 when the higher LPG doses were applied. On the contrary, when maize was flamed at V5 stage, weed dry biomass at harvest was very high (533 g m^{-2}) even at highest dose (lower limit of the curve). This trend suggests that only if weeds are flamed at cotyledon stages it is possible to obtain an almost complete control in terms of weed dry biomass (table 8.8).

Table 8.7. Weed dry biomass at harvest influenced by different LPG doses and growth stage of maize.

LPG dose (kg ha^{-1})	Weed dry biomass (g m^{-2})		
	V2	**V5**	**V2plusV5**
0	1865.9 a	1865.9 a	1865.9 a
52	357.8 b	1774.2 ab	-
65	323.9 b	1515.9 abc	-
104	115.5 b	898.9 bc	210.3 b
130	54.7 b	674.7 c	68.9 b
208	-	-	51.2 b
260	-	-	32.2 b

V2: 2-leaf growth stage; V5: 5-leaf growth stage; V2plusV5: double growth stage. In each column means followed by the same letter are not significantly different at P≤0.05 (LSD test).

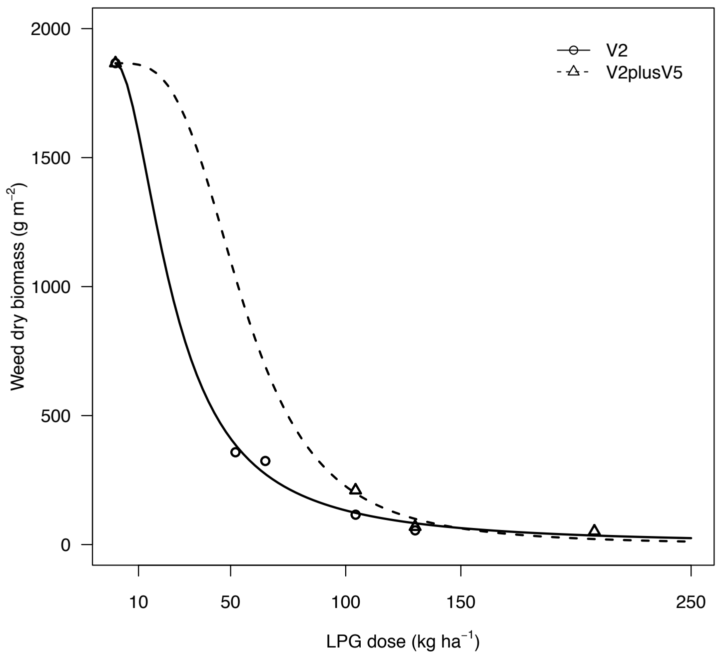

Figure 8.5. Influence of LPG flaming on weed dry biomass (at harvest) as affected by LPG dose at V2 (5-leaf) and V2plusV5 (double stage) stage of maize.

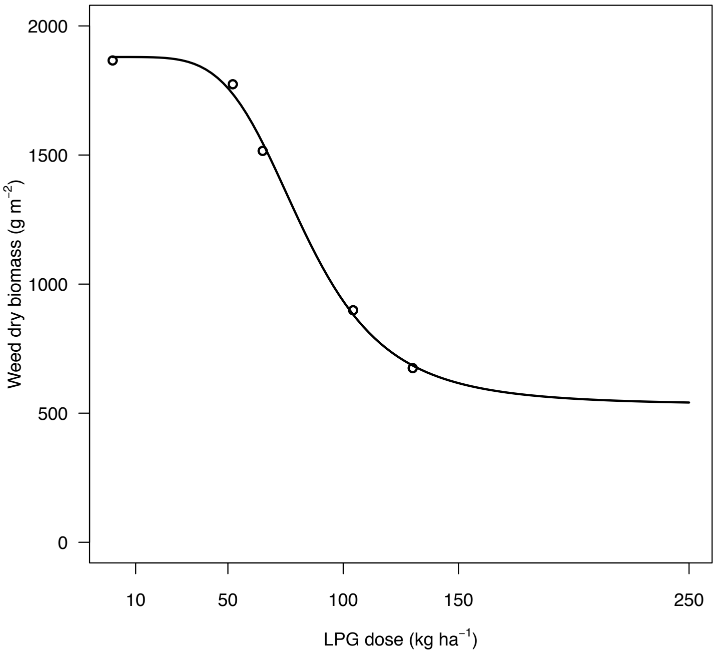

Figure 8.6. Influence of flaming on weed dry biomass at harvest as affected by LPG dose at V5 (5-leaf) stage of maize.

Table 8.8. Regression parameters for weed dry biomass at harvest (g m^{-2}) as affected by LPG dose at three growth stages of maize.

Growth stage	Regression parameters (±SE)			
	B	**C**	**D**	**ED_{50}**
V2	1.9 (1.46)	0	1865.7 (155.96)	25.6 (18.18)
V5	4.6 (6.40)	532.7 (1055.00)	1879.5 (314.65)	83.0 (47.87)
V2plusV5	3.4 (9.62)	0	1865.9 (155.94)	55.6 (108.98)

V2: 2-leaf stage; V5: 5 leaf-stage; V2plusV5: double stage; B: slope of the line at the inflection point; C: lower limit; D: upper limit; ED_{50}: dose of LPG resulting in a 50% response between the upper and the lower limit.

In real field conditions, yield resulted statistically different in respect of the untreated control at all growth stage of maize and at all LPG doses (Table 8.9). Maize yield decreased as weed dry biomass at harvest increased (Fig. 8.7). Yields were 14.9, 9.2 and 15.4 Mg ha^{-1} at V2, V5 and V2plusV5 growth stages of maize (upper limit of the curve), respectively, in correspondence of the lowest values of weed dry biomass at harvest, obtained with the maximum LPG doses used at different growth stages (533 g m^{-2} at V5 and 0 g m^{-2} at V2 and V2plusV5 stages) (Table 8.10). This trend suggests that maize yield is higher when flaming is performed twice (V2plusV5 stage).

Table 8.9. Maize yield influenced by different LPG doses and growth stage of maize in real field conditions.

LPG dose (kg ha^{-1})	Yield (Mg ha^{-1})		
	V2	**V5**	**V2plusV5**
0	2.1 b	2.1 b	2.1 b
52	12.1 a	6.9 a	-
65	13.1 a	5.1 ab	-
104	14.3 a	7.1 a	16.4 a
130	14.2 a	9.1 a	15.7 a
208	-	-	14.7 a
260	-	-	14.0 a

V2: 2-leaf growth stage; V5: 5-leaf growth stage; V2plusV5: double growth stage. In each column means followed by the same letter are not significantly different at P≤0.05 (LSD test).

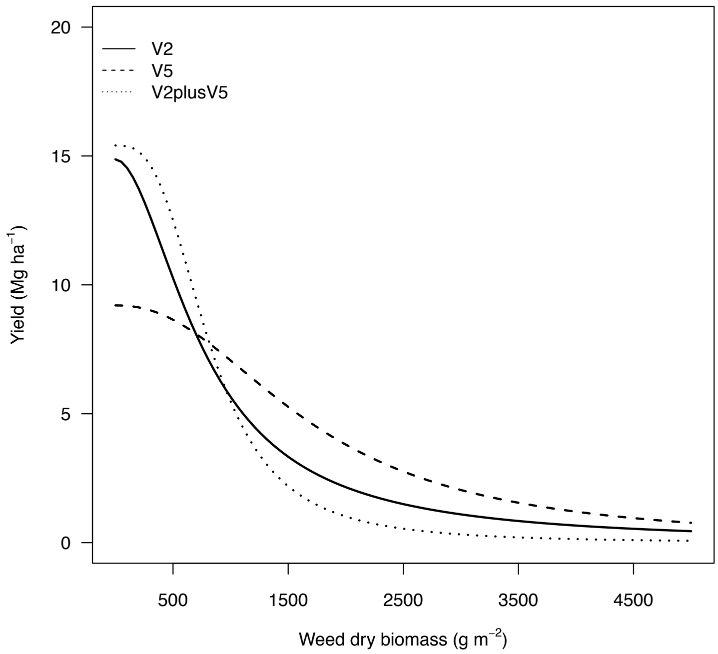

Figure 8.7. Influence of weed dry biomass at harvest on yield of maize flamed at different growth stages (V2, V5 and V2plusV5).

Table 8.10. Regression parameters for yield (Mg ha^{-1}) as affected by weed dry biomass at harvest and growth stages of maize.

Growth stage	Regression parameters (±SE)		
	B	**D**	**ED_{50}**
V2	1.9 (0.50)	14.9 (0.79)	769.1 (143.48)
V5	2.2 (1.03)	9.2 (1.43)	1710.20 (395.69)
V2plusV5	3.0 (1.22)	15.4 (0.65)	818.4 (160.90)

V2: 2-leaf stage; V5: 5 leaf-stage; V2plusV5: double stage; B: slope of the line at the inflection point; D: upper limit; ED_{50}: dose of LPG resulting in a 50% response between the upper and the lower limit.

8.4 Discussion and conclusions

In weed-free conditions the damage caused by flaming to maize measured in terms of dry matter reduction 7, 14 and 28 days after treatment indicates that plants treated at different growth stages and LPG doses resulted in different levels of growth. Plants treated at the V2 stage resulted in a reduction of growth already also when the lowest LPG dose was applied. At this stage all the applied LPG doses determined a reduction of maize growth 7, 14 and 28 days after the treatment. Plants treated at the V5 stage showed a reduced growth only if the highest LPG dose was applied, indicating that the V5 stage is less sensitive to flaming than the V2 stage. Plants treated two times (V2plusV5 stage) resulted in a growth trend similar to plants treated at the V2 stage. Ulloa and colleagues applied at V2, V5 and V7 (7-leaf) stages of maize broadcast propane flaming with "LT2 x 8 Liquid Torch" (Flame Engineering, 2007) burners in weed-free conditions and they also found that the stage V5 showed more tolerance to flaming than V2 stage 14 days after treatment. They also found that plants flamed at V2 stage with the highest propane dose resulted in the highest dry matter reduction (Ulloa *et al*., 2010c; Ulloa *et al*., 2011a).

The reduced growth observed up to 28 days after treatment as time passed tends to fade. As a matter of fact, plants that were initially smaller, 100 days after the last flaming treatment, did produce less than the untreated plants. This trend was not observed by Ulloa and colleagues that found maize yield negatively impacted by increasing dose of propane regardless of the growth stage. They also found that V2 was the most susceptible stage of maize to broadcast flaming. Ulloa and colleagues did not applied irrigation but plants precipitations ensured a mean of 100 mm $month^{-1}$ (Ulloa *et al*., 2011a). Probably this mismatch of results is due to used flaming technique revealing that maize is more tolerant to cross flaming (which acts on the base of the plants below the crop canopy) than broadcast flaming. Moreover, maize seems to be completely heat tolerant to cross flaming showing none loss of yield at harvest. Thus cross flaming should be an individual practice in order to apply non-chemical intra-row weed control in maize.

Weed density decreased as LPG doses increased at all growth stages of maize 7 days after flaming. The observed differences in weed density reduction between V5 (79%), V2 (99%), and V2plusV5 (99%) stages at the highest LPG dose confirms that flaming is less effective on well developed weed and more effective on weed seedlings, as already observed by other researchers (Ascard, 1995; Peruzzi *et al*., 1996 and 1998; Ulloa *et al*. 2010a,b,c).

The recorded values of weed dry biomass at harvest show that weeds flamed at cotyledon stage (corresponding to V2 and V2plusV5 of maize) are not able to recover. On the other hand, weeds flamed when already well developed (corresponding to V5 stage of maize) do not stop their growth resulting in a minimum dry biomass value at harvest of 533 g m^{-2} at maximum LPG doses (lower limit of the curve) (Fig. 8.6).

Taking into account that in weed-free conditions maize yield was not statistically influenced by flaming and all growth stages and that all other factors of variability were the same in both the tests, it is possible to state that differences in maize yield were determined by the effectiveness of flaming in weed control. By applying the same log-logistic model used to study the influence of LPG doses on weed dry biomass at harvest at different growth stages, maize yield was negatively influenced by weed dry biomass. The lowest value of 533 g m^{-2} of weed dry biomass at harvest observed when maize was flamed at V5 stage determines a yield value of 9.2 Mg ha^{-1} at maximum, indicating that yields results are low when weeds are flamed too late.

As a conclusion, maize flamed with cross burners proves to have a high heat tolerance even if treated with high LPG doses because, despite of the reduced growth observed during the first month after the treatment, plants successively recovered and produced as much as the untreated ones. Differences in maize yield were observed as a consequence of flaming effectiveness in controlling weeds according to their stage of development and the used LPG dose. Finally, it is possible to state that the future use in the field of the automatic machine realized within the RHEA Project, besides allowing to perform site-specific flaming, will assure to obtain satisfying levels of weed control and good results in terms of maize yield.

CHAPTER 9. CONCLUSIONS

The heterogeneous distribution of weeds in agricultural fields allows to perform their site-specific management. Automation of physical weed control in arable farming could contribute to sustainable food production at reduced costs and guarantee ecological benefits by abandoning the use of herbicides. A precise guidance and detection systems are prerequisites for successful site-specific weed management. An effective detection and identification is a primary obstacle toward commercial development and industry acceptance of robotic weed control machines. The most promising approach for weed detection is a continuous ground-based system adopting image analysis.

The new technologies for real-time sensing crop and weeds by means of image analysis, GNSS receivers, GIS mapping tools and robotics using autonomous vehicles, allow to perform precise physical weeding. The machines for site-specific physical weed control recently developed are based on vision or RTK-GNSS for guidance (or both) and on remotely map or real-time sensors (or both) for weed/crop discrimination.

Most common automatic or autonomous physical weed control machines use a vision based row detection system. As an alternative, RTK-GNSS can provide a level of lateral positioning accuracy along the row comparable to vision based guidance systems. Site-specific physical weed control machines use spectral properties, biological morphology, texture features, or the geo-referenced position of the crop plants (or a combination of these methods) in order to discriminate crop from weeds in the intra-row space.

Mechanical methods of removing weeds within the seedline are based on the use of different tools, including knives, discs, rotating hoes, etc. that are valid robotic actuators. In many case custom mechanical tools were developed to improve the precision of the weeding systems. Mechanical systems are based prevalently on crop plants recognition and avoidance. Thus, tools treat only the area between a crop plant and another along the rows. These systems do not require to vary the intensity of the treatment according to different levels of weed cover along the row because the entire intra-row, with the exception of the crop plant zone, is tilled. However, enough space between crop plants within the row for a proper insertion of mechanical tools is obviously required. A small area very close to crop stems remains untilled, giving to not-removed weeds the possibility to grow up.

Thermal methods (and particularly flaming) can be also used to devitalize weeds in the intra-row space. Flaming offers the possibility to devitalize weeds also in the area closest to plants stems in heat-tolerant crops (e.g. maize, garlic, and all the main herbaceous and vegetable crops in a late stage of development). Thus, flaming can operate on small treatment units in the row space according to the site-specific demand and varying the intensity of heat transmission according to weed cover. This way, the actuation of these thermal treatments results similar to the use of site-specific selective herbicides, but allows to avoid the disadvantages associated with their use.

According to these considerations, the RHEA project represents an innovation in the application of precision agriculture because focused on the design, development and testing of a system of robots working together by means of innovative use of innovative technologies. Integrations between systems developed by project partners were made and further integrations are planned in order to make the whole robots system fully effective

for the field final demo, which will be held in Madrid in May 2014 at the end of the RHEA project. This new generation of automated and robotized systems will be able to perform both chemical and physical effective weed management and crop protection covering a large variety of European agricultural products including narrow and wide row crops and forestry woody perennials.
The innovative machine designed and realized at the University of Pisa within the RHEA project, in order to perform site-specific flame weeding in maize, is fully realized and need only to be tested and then optimized. Preliminary tests carried out in order to verify the management of actuation devices and sensors by the PLC, the coupling with the Ground Mobile Unit and the integration with the perception system for weed and row detection (that make the machine autonomous) were satisfying, although further research activities are needed in order to optimize all the sub-systems and verify their integrated functioning. The system could enable to perform flaming only on weed patches. LPG consumption per unit surface of this machine will be lower than that of commonly used low-tech flaming implement. Obviously, this trend will be closely evaluated carrying out specific field experiments. This autonomous system for site-specific thermal weed control designed and fully realized within the RHEA Project could be applied also to other tolerant crops.
The research carried out at CiRAA "E. Avanzi" of the University of Pisa represents a preliminary field application for the future adoption of the automatic machine designed and realized within the RHEA Project. The machine was at CSIS-CAR facilities located at Arganda del Rey (Madrid, Spain) when the field tests were performed in Italy, thus two machines that performed in two times the same treatment were used. Moreover, the aim of this research was to evaluate the biological effect of the physical method and not to test the proper functioning of the automated system. As a matter of fact, proposed field trials aimed to test the tolerance of maize (*Zea mays* L.) to cross flaming treatments and the effectiveness in control weeds as influenced by LPG dose and crop growth stage. The obtained results showed that maize flamed with cross burners proves to have a high heat tolerance even if treated with high LPG doses because, despite of the reduced growth observed during the first month after the treatment, plants successively recovered and produced as much as the untreated ones. Differences in maize yield were observed as a consequence of flaming effectiveness in controlling weeds according to their stage of development and the used LPG dose. As a matter of fact, dicot weeds at seedling stage are more sensitive than well developed plants and high LPG doses resulted in a higher weeding effect. Finally, it is possible to state that the future use in the field of the automatic machine realized within the RHEA Project, besides allowing to perform site-specific flaming, will assure to obtain satisfying levels of weed control and good results in terms of maize yield.

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