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An Automatic Machine Able to Perform Variable Rate Application of Flame Weeding: Design and Assembly

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This paper describes the design and development of an automatic machine able to perform Variable Rate Application of cross flaming in maize fields. The VRA flaming machine was designed to remove weeds mechanically from the inter-row area and perform selective and targeted cross flaming along the crop rows. The mechanical treatment will be performed in a continuous way, even without weed presence. On the contrary, cross flaming on the maize rows is applied selective and automatically only if weeds are presence. Flame weeding is applied by means of prismatic burners fed by Liquefied Petroleum Gas, able to treat 25 cm wide strips of soil surface including crop rows. Flaming can be used selectively in maize, which can tolerate the heat released from the burners. Mechanism of morphological tolerance is the presence of many layers of the outer leaf tissue protecting the inner growing point. A low or a high LPG dose can be chosen automatically according to the weed cover percentage detected by a weed detection system. The ignition system of the VRA flaming machine is almost instantaneous and the complete flame in the burner is obtained in 0.4 s. The machine is provided with an automatic steering system in order to avoid damaging the maize plants with the rigid tools used for mechanical weed removal. The VRA flaming machine is a new technology for precision agriculture and was designed and built within the “Robot fleets for Highly Effective Agriculture and forestry management” (RHEA) Project, funded by EU, aimed to develop a fleet of heterogeneous autonomous robot units in order to perform site-specific treatments related to crop protection in different agricultural scenarios.
Key words: Variable Rate Application, Site-specific weed management, Real-time weed control, Mechanical weed control, Thermal weed control, Precision agriculture.

1. Introduction

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 (Gutjahr and Gerhards, 2010). Both the increasing cost of chemicals and soil pollution caused by herbicides residues inquire 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 (Fontanelli et al., 2015). The new technologies available for precision agriculture such as Global Navigation Satellite System (GNSS), remote and proximal sensors, Geographic Information System (GIS) mapping tools, and machine vision allows site-specific physical weeding to be performed (Bareth and Doluschitz, 2010).
Mechanical methods for removing weeds within the crop rows are based on the use of different tools, such as knives, discs, and rotating hoes, in order to uproot the unwanted plants. Many custom mechanical tools were developed to improve the precision of the weeding systems (Nørremark et al., 2012; Perez-Ruiz et al., 2012).
Thermal methods (and particularly cross flaming) can be also used to devitalize weeds in the intra-row space. An autonomous robot able to perform intra-row flame weed control was developed by the Frank Poulsen ApS Engineering (Poulsen, 2011). The robot is able to discriminate weeds within the rows using machine vision.
The aim of this work was to design and build an automatic operative machine able to perform site-specific VRA flaming in order to control weeds in the row of tolerant crops and remove weeds mechanically from the inter-row space. VRA flaming is a new technology for precision agriculture designed to reduce flaming costs

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and suitable to be used in connection to other advanced precision agriculture technologies. The VRA flaming machine was design and built within the “Robot fleets for Highly Effective Agriculture and forestry management” (RHEA) Project, funded by EU, aimed to develop a fleet of heterogeneous autonomous robot units in order to perform site-specific treatments related to crop protection in different agricultural scenarios (RHEA Project, 2014).

2. Machine design

This paper describes the VRA flame weeding machine that was designed and built to be coupled with a 38 kW autonomous tractor, within the RHEA Project (RHEA Project, 2014). VRA flaming means adopting the proper and required Liquefied Petroleum Gas (LPG) doses according to the level of weed infestation. Previous researches on VRA weed control are entirely associated with the application of herbicides (Grisso et al., 2011). The machine described in this paper presents the first machine able to perform a variable application of flame weeding using LPG. Thanks to the designed LPG feeding system, an operator can set two different LPG working pressures, this means three different LPG doses (no treatment, low dose and high dose flaming treatments) assuming a constant working speed of the operative machine.
The machine is equipped with a dedicated Programmable Logic Controller (PLC) and requires a weed detection system that feeds the machine with data of the weed coverage. In this sense, the implement can operate in a fully automatic mode. The weed detection system is based on machine vision and was developed by the Complutense University of Madrid within the RHEA Project (RHEA Project, 2014) in order to detect weeds in real time. The weed detection system is mounted on the roll bar of an autonomous ground mobile unit (Burgos-Artizzu et al., 2011; Guerrero et al., 2013; Montalvo et al., 2013; Romeo et al., 2013; Sainz-Costa et al., 2011). The application of a low or a high LPG dose of flame weeding is decided in real-time according to the level of weed cover detected. The Decision-Making System is in charge of processing the information for weed detection and guidance through specific procedures and algorithms (Emmi et al., 2014).

a) b)

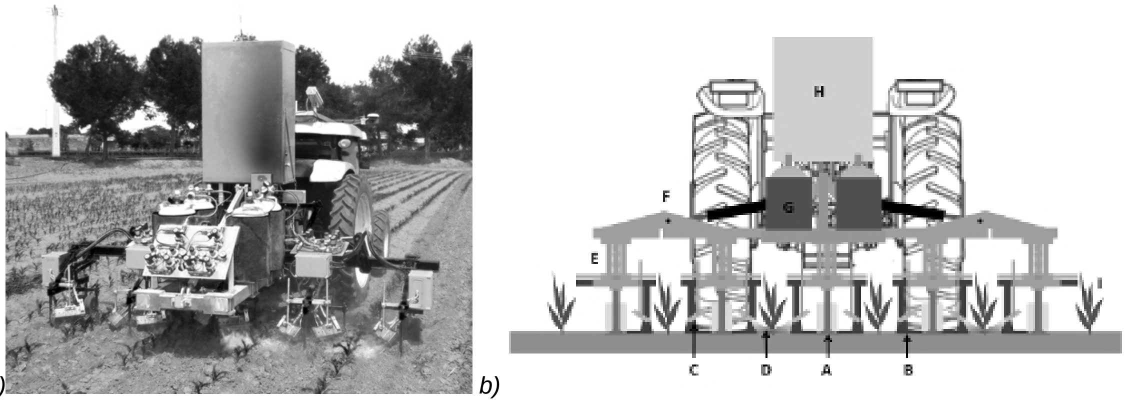


Figure 1: (a) VRA flame weeding machine developed within the RHEA Project; (b) scheme of VRA flame weeding machine: A) central sweep “V” conformed; B) adjustable rigid side sweep “L” conformed; C) 25 cm wide burner; D) VRA cross flaming on crop row; E) articulated wheeled parallelogram; F) foldable main frame; G) heat exchanger with LPG tank inside; H) electrical box; L) maize plant.

The machine is designed to perform mechanical treatments continuously even without the presence of weeds, as inter-row cultivation is very important from an agronomical point of view (Cloutier et al., 2007). In fact, the shallow tillage improves the soil conditions for the root system of the crop and increases water availability (Cloutier et al., 2007).
The machine structure was obtained integrating a row crop cultivator with a flame weeding system. A 3.46 m wide steel frame constituted the row crop cultivator, supporting 5 articulated parallelograms provided with mechanical and thermal weed removal tools. Total mass of the machine can vary from 920 kg to 940 kg, depending on the type of gas tanks (Figure 1). The weight is low compared to other pest control machines (e.g. sprayer booms) and it may be reduced in a commercial version. In addition, this machine was designed to be used under controlled traffic farming system and this further reduces the possibility of damage connected to the soil compaction. The machine was built with a shape and weights arrangement to be safely used in agricultural sloping environments.

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 tractor drive the folding system. The width of the implement when it is closed is 2.48 m. The folding system is equipped with two couples of inductive sensors in order to detect both the closed and the open configuration.

In order to follow the row without damaging the crop, there is an automatic steering system driven by a central double-rod hydraulic cylinder, powered by the hydraulic system of the mobile ground unit developed during the activities of the RHEA Project. This enables small lateral movements guided by two directional metal wheels. The machine is supplied with a real time vision-based perception system installed on the autonomous ground mobile unit (RHEA Project, 2014), which detects crop rows. The steering system consists of a hydraulic cylinder that modifies the angle of the two directional wheels. This gives the machine lateral displacement with respect to the ground mobile unit (Emmi et al., 2014), which is measured by a linear sensory system (potentiometer and encoder). The reference lateral displacement is calculated based on the current position of the mobile ground unit (Emmi et al., 2014) and the crop row detected by the perception system.

The LPG tanks are placed in cylindrical hoppers fixed to a steel frame (0.76 m x 1.46 m). Each thermal weed control unit consists in a couple of burners allowing a single crop row to be flamed. The burners are fixed on the articulated parallelogram with an adjustable connection, enabling to set: a) the distance from the soil, b) the distance from the collar of the crop plant, and c) the inclination respect to the crop row and to the soil surface. In this way, each pair of burners can be properly adjusted in order to perform cross flaming (i.e. thermal treatment on both sides of the crop row) according to the development stage of the maize plants (Figure 1). The thermal weed control units are completely independent in terms of LPG working pressure, allowing flaming treatments with different LPG doses on the different crop rows.

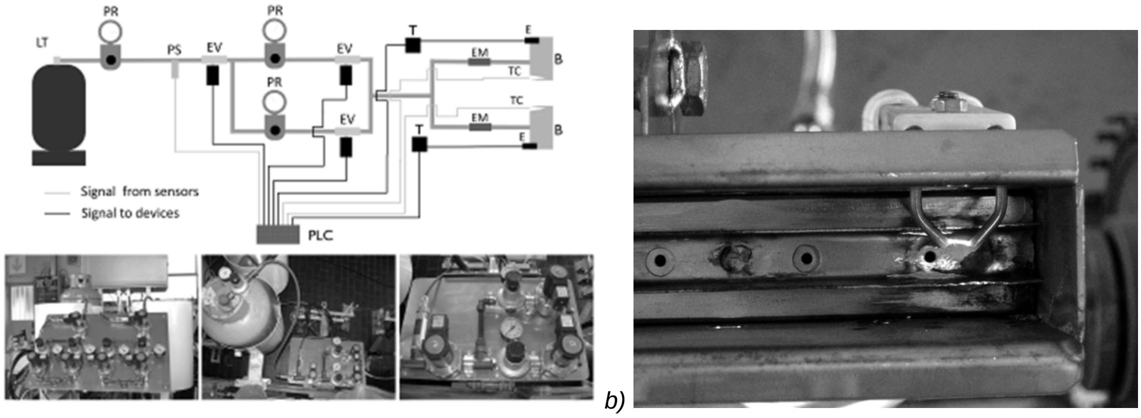
According to the 0.75 m inter-row space of maize, the machine can be adjusted in order to have a working width of 3 m and thus treat 4 crop rows and 4 inter-rows in a single pass. The three central articulated parallelograms are provided with paired burners and gangs of shanks with tools for inter-row cultivation. Paired burners, in this case, generate flames able to treat a 0.25 m wide strip of soil surface (0.125 m on each side) with the crop row in the middle, a single gang of shanks with sweeps till a 0.5 m wide strip of soil, in order to mechanically remove the weeds on the inter-row. The two external articulated parallelograms are provided with only one burner and with a gang of shanks with sweeps that tills a 0.25 m wide strip of soil, in order to reduce the overlapping of consecutives passages during the weed control treatment. Each gang of shanks are independently suspended on parallel linkages with depth-controlling wheels to provide flotation with the soil surface, in order to maintain the correct working depth of the sweep tools and the proper distance of the burners. The two external gangs of shanks are equipped with a “V” shaped sweep blade and only one “L” shaped sweep blade. On the other hand, the three central gangs of shanks are equipped with a “V” sweep and two “L” sweeps. These rigid tools control weeds in the inter row space, performing a shallow tillage (depth of 3-5 cm). “V” sweep blades are 0.24 m wide, while, “L” shaped sweep blade are 0.15 m wide.

3. The automatic LPG feeding system and burners

The VRA flaming system is composed of a LPG feeding system, 8 burners, and an ignition system. The flaming system is completely automatic and managed by the PLC utilizing the information coming from the weed detection system (Burgos-Artizzu et al., 2011; Guerrero et al., 2013; Montalvo et al., 2013; Romeo et al., 2013; Sainz-Costa et al., 2011). The machine can accommodate four LPG tanks. Each tank feeds two prismatic shape burners (Raffaelli et al., 2015) for cross flaming along the maize row. The LPG dose is variable and can be adjusted according to the level of weed infestation. VRA cross flaming is provided according to the level of weed infestation ascertained by the weed detection system in each row i.e.: no treatment if the weed cover level is near to 0%; low LPG dose if the weed cover level is lower than 25%; and high LPG dose if the weed cover level is higher than 25%.

During flame weeding treatment, the compressed LPG inside the tank needs heat to pass from the liquid to the gas phase. In operative conditions, the exchange of heat from the environment to the LPG could be not sufficient and the liquefied gas cools. When the temperature of the LPG falls the gas vaporization is not correct and the flame in the burner is uneven until extinguishing. For this reason the machine is equipped with a heat exchanger, consisting of cylindrical hoppers containing water heated by the exhausted gases that flow through a flexible hose from the endothermic engine of the tractor (Figure 2). The LPG tanks are placed inside the hopper, partially immersed in the heated water.

Gas flow in the LPG feeding line is controlled by normally closed solenoid valves managed by the PLC provided with outputs modules. 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 feeding system is provided with pressure sensors and thermocouples, connected to the inputs modules of the PLC. Following the LPG feeding line, after the tank there is a manual pressure regulator with a pressure gauge set at 0.5 MPa, one pressure sensor, and the main electrovalves. The 4 pressure sensors (Aplisen® PC29) supplied with a 12 V DC voltage, monitor the pressure status of each LPG tank and transmit an analog signal to the PLC. When the LPG in the tank is going to finish and the pressure falls below level of 0.4 MPa, the PLC closes the adjacent electro-valve (main electro-valve). After the main electro-valve, the LPG feeding line is split into two branches one for each variable LPG dose applicable. Each branch is provided upstream with a manual pressure regulator with a pressure gauge (in order to set the proper LPG working pressure) and downstream with a secondary electro-valve. The PLC sends the signal to the proper electro-valve according to level of weed cover detected.



a) *b)*

Figure 2: (a) The 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.; (b) Electric arc between the two poles of the electrode for the ignition of the burner.

After the secondary electro-valve the gas feeding line is provided with an external LPG/air mixer, which allows the intake of primary air. 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. The shield of the burners is provided with circular inlet (ø 9 mm) in order to enable the intake of the secondary air. Both primary and secondary air self-aspirating systems are based on the Venturi effect. For the external LPG/primary air mixer, depression is created by the high speed flow of the LPG via a passage through a narrow nozzle section. The secondary air is aspirated by the depression created by the flow of the flame. When the LPG/air mixture reaches an ignition electrode placed into the burner the flame is generated.

Each burner is equipped with a type K thermocouple, which monitors the presence of the flame sending a low voltage output signal to the PLC. If the flame is accidentally extinguished, PLC activates the ignition system in order to reignite the burners. If the ignition process fails after 10 s the PLC closes the main electro-valve avoiding LPG efflux. 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. Burners are made in stainless steel and are composed by an external shield and an internal prismatic diffuser. The internal diffuser is 3 cm wide and 25 cm long and has circular inlets (ø 2.5 mm) placed 3.5 cm apart.

Most of the available commercial flaming machines equipped with burners use a pilot flame as the ignition system. The pilot flame is a small flame produced at a very low gas pressure which is kept alight in order to serve as an ignition source for a more powerful flame produced at a higher working pressure for the thermal weed control. The pilot flame is maintained always on during the work period.

The ignition process of the VRA flaming machine does not require a pilot light in the burner, in fact, the electric ignition system of the VRA flaming machine consists in a transformer (Cofi® TRL 24-30C), one for each burner, converting the voltage value of 24V-DC to 12kV-AC and two electrodes separated by a ceramic insulator body placed on the burner. The transformer is wired to the electrodes with special high voltage wires coated in silicone rubber in order to resist high temperatures. The power of the transformer (80 W) enables a continuous electric arc to be obtained between the two poles of the electrode, which ignites the LPG/air mixture even at higher working pressures. Thus, when the VRA flaming machine enters the maize field, the PLC activates a relay opening the main electro-valve. During intra-row weed control, if a weed infestation is detected, the PLC activate the appropriate relays connected to the electro-valve for the low or the high LPG working pressure and simultaneously provide the power supply for the ignition transformers.

4. Estimation of the ignition delay

The ignition process of the burner is not instantaneous, the knowing of the delay time requested by this procedure is crucial for the synchronization of the overall system for automatic VRA flaming system (Emmi, 2014). In fact, other processes (i.e. Image acquisition, image processing, GPS data acquisition, inertial measurement data acquisition) are involved in the automatic VRA of flaming (Emmi, 2014). The ignition delay taken into consideration, includes the time lapse between the activation of the relays by the PLC and the presence of the flame along the complete width of the burner. In order to estimate the ignition delay, the two burners and an external manual controller wired to the relays that manage the secondary electro-valves and the transformers were videoed, using a Nikon Coolpix 7600 digital camera at 15 frames per second. An operator simulated the function of the PLC by switching-on the main electro-valve, the secondary electro-valve, and the ignition transformers at the same time. The test was replicated 10 times. Using QuickTime™ 7.6.4, the frames involved in the complete ignition process were isolated and counted from the ten videos (QuickTime File Format). Figure 3 shows an example of the isolated frames.
Each frame was associated to an event of the ignition process, from the switches turned on (beginning of the ignition process), till the complete formation of the flame along the burner width (end of the ignition process). The ignition process covered a number of frames ranging from 5 to 7 (mean value equal to 6). In this way, knowing the frame rate of the video (15 frames s^{-1}) and consequently the duration of a single frame (0.067 s), it was possible to estimate the delay related to the ignition process. The mean value of the estimated ignition delay was equal to 0.4 s with a standard error of 0.017 s (95% confidence interval 0.36 s, 0.43 s).
The estimated ignition delay was due to electro-mechanical limitation, but when the implement coupled with the autonomous ground mobile unit operate in a fully automatic mode delays related to the vision based weed detection system (image acquisition, image processing), GPS data acquisition, inertial measurement acquisition, should be taken into account. In this case the overall estimated delay of the VRA flaming system is equal to 0.7 s (Emmi et al., 2014). Knowing the overall delay of the automatic VRA flaming system it's crucial in order to perform an effective thermal treatment on the detected weed patches, in fact, according with the working speed of the implement, the Decision-Making System can adjust the coordinates where the commands for igniting the burners have to be sent (Emmi, 2014).

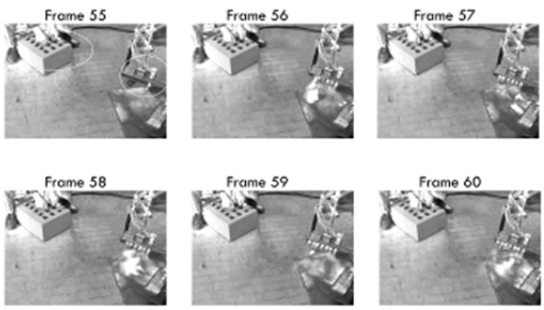


Figure 3: Example of the isolated video frames involved in ignition process of the burners.

5. Conclusions

The machine described in this paper represent the first implement able to perform a variable application of flame weeding. Thus, the VRA flame weeding machine is a new technology for precision agriculture and is suitable to be used in connection to other advanced precision agriculture technologies. This machine was realized in order to operate coupled with an autonomous ground mobile unit provided with a real time vision based weed detection system, but could be easily adapted to operate coupled with a common tractor. In this case the VRA flaming treatment would be performed according to the information of a prescription map obtained previously. Simulations and trials conducted in order to estimate the gas consumption showed that VRA cross flaming weed control enables to spare an amount of LPG that can vary from 55% (Pérez-Ruiz et al., 2015) to 65% (Emmi, 2014), respect to conventional cross flaming treatments performed in a continuous way. The variability of the values of saved gas could be explained by the fact that, in VRA flame weeding LPG consumptions are affected not only by the working speed, and the working pressure, but also by weed density,

and weeds spatial pattern, similarly to what is found in herbicide consumption with site-specific weed management (San Martín, 2015).
Moreover, the VRA flame weeding machine can be applied to perform cross flaming on other crops that can tolerate thermal treatments. In this regard a possible future development for this technology could be represented by the use of site specific broadcast flaming, allowing reducing the LPG consumption during the application of the thermal treatment in the stale seedbed technique.

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