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Simulation modelling of mechanical systems for intra-row weeding in a precision farming approach

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Abstract

Aim of study: To test new approaches to perform mechanical weeding inside the row in horticulture and tree fruit fields. The idea is to weed the row by skipping the crop by means of a rotating system instead of a traditional crosswise one.

Area of study: North of Italy.

Material and methods: Numerical models have been developed to simulate mechanical weeding over time by generating numerical maps to quantify the different kind of worked areas.

Main results: Considering the efficiency of weed control on the row, the rotating plant-skipping system with vertical axis (RPSS-VA model) with two working tools gives the best performance index (*1.1.RWA%* = 95.9%). A similar performance can be obtained by the crosswise displacement plant-skipping system, but with very high crosswise translation velocity (with v_a/v_r ratio = 1/5, *1.1.RWA%* = 94.5%). With regard to the outwards worked area the RPSS-VA models give the best performances (*2.2.%OWAR* index from 127.2% up to 282.3%). To reduce the worked area outside the row, the FBTS models give lower index (*2.1.OWAR%*), while the RPSS-HA works only on the row, but with the lower *1.1.RWA%* index among all tested models (55.8%).

Research highlights: Rotating systems resulted more efficient than traditional ones, and provide considerations on the use of electric drive power instead of hydraulic one. This study highlights also the need of new approaches in designing lighter working tools. Lastly, the proposed classification of the worked areas could be used as reference standard.

Additional key words: designing; organic farming; lighter working tools; precision control weeding.

Abbreviations used: CDSS (crosswise displacement plant-skipping system); FBTS (forward-backward tilting plant-skipping system); FBTS-CR (return in the row at constant angular speed); FBTS-VR (return in the row at controlled (variable) angular speed); MWAR (maximum workable area); RB (rotating body -holding 2, 3 or 4 THFs-); RPSS-HA (rotary motion plant-skipping system, horizontal rotation axis); RPSS-VA (rotary motion plant-skipping system, vertical rotation axis); RZ (respect zone; a circular area centred on the crop plant to be skipped by mechanical weeding); THF (tool holder frame); WT (working tool supported by the THF; *e.g.* a vertical rotary spike-tooth harrow). **Symbols:** DS (distance of THF from the plant detection sensor, m); $D_{t\,min}$ (minimum distance between plants in the row required to avoid plant damaging, m); n_{wt} (number of working tools, each mounted on a THF); r_r (radius of the RZ, m); r_t (radius of the working tool, m); v_a (advancing velocity, m s^{-1}); v_r (crosswise translation of the THF in CDSS model, m s^{-1}); XR (entering distance in CDSS model, m); α_{min} (THF angular position to calculate the minimum distance between two plants in the row, RPSS-HA model, rad); α_{THF} (angle between two adjacent THFs, rad); ω_R (return angular velocity in the row, FBTS models, rad s^{-1}); ω_{rot} (minimum angular velocity of the THF to skip the plant, rad s^{-1}).

Authors' contributions: Both authors conceived the work, designed the experiment, analysed the data and wrote the paper. Models development: PL.

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Supplementary material (Annexes A, B and C) accompanies the paper on SJAR's website

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Introduction

The cultivation of fruit trees and vegetable crops in open fields is becoming more and more important nowadays. In the last few years, three important events have encouraged the development of alternative technologies to chemical weed control. First of all, the ascertained toxicity of products such as glyphosate, so already eliminated from some uses and limited to others; in Europe, some Commissions implementing Regulations restrict its use that is monitored by the Committee on the Food Chain and Animal Health. Secondly, the high number of weeds in commercial crops have developed resistance to active principles such as the glyphosate (Perez-Jones *et al.*, 2005; Gaines *et al.*, 2010; Salas *et al.*, 2012); finally, the focus on a type of sustainable agriculture is causing many farmers to shift to organic farming. In Italy, the 6th General Census of Agriculture has allowed us to collect information on the structure of organic farms. In particular in our Country there are 44,455 organic farms (2.7% of the total) (ISTAT, 2013).

Organic farms are particularly important both because they contribute to the spread of forms of land and farm management in a compatible way with the protection of the environmental, soil and genetic diversity, and because it would foster the best quality of products. In this perspective it is evident how the use of mechanical or physical control systems (as an alternative to the normal practice of chemical weed control) becomes essential.

Additional attention required by this approach will be recouped in the form of fewer time for weeding during the cultivation of the crop. Anyway, despite several years trying to work on the competitiveness of crops versus weeds (Davies *et al.*, 2004; Hoad *et al.*, 2008), their control still represents a very critical aspect, and not only for Italian agriculture.

To these preventive techniques need to be matched, during cultivation, to weed control practices, especially for the control of weeds which develop intra-row, and are not affected by inter-row cultivation, such as hoeing (Granatstein, 2018). Intra-row weeds, if insufficiently controlled, cause major problems for organic intra-row crops, such as vegetables and maize (*Zea mays* L.). Manual intra-row weeding is expensive, time consuming and difficult to plan.

The control of weeding using a mechanical tool, *e.g.* with hoe and rotary tiller, is by far the most used technique during the first years of the plant. There is a wide variety of tools in the market, which can be more or less expensive and more or less effective to implement this operation along the row without damaging the young plants of the crop at different automation level (Fennimore *et al.*, 2016). The choice is guided by a prevention approach by applying better practices of fertilization and irrigation, although the direct intervention on weeds through mechanical, physical or biological methods is far more important.

Especially in the field of mechanical systems, for many years weeding approach follows the same functional methods, although using different types of tools and variously articulated plant-skipping systems, dating back to the principles developed several decades ago, in the early ‘70s (Rastgordani *et al.*, 2013). Same considerations are showed in integrated and organic floor management for orchard and biomass crops (Tahir *et al.*, 2015; Assirelli*et al.*, 2016).

Simplified mechanical weeders (for example, cultivators) are mainly used in low-density crops (Van der Weide *et al.*, 2008; Peruzzi *et al.*, 2017), while in high-density crops spring harrows are used. Instead, Flame systems are suitable for all crops independently from seeding density (Martelloni *et al.*, 2016). Among the simplified systems we can count spring-tine harrows and cultivators, and, among new techniques, finger-weeders and torsion-weeders (Kunz *et al.*, 2018, Granatstein, 2018). An interesting low-cost approach to weed a maize field is proposed by controlling the tine angle of a harrow (Rueda-Ayala *et al.*, 2015).

In literature there are several innovative systems to skip the crop plants. For example, Pérez-Ruíz *et al.* (2014) used two hoes in the close position to work intra-row, and opening them laterally like a scissor to skip the crop plants. A similar approach is used in the *Sarl Radis* model, as described in Van der Weide *et al.* (2008). Wisserodt *et al.* (1999) developed a system to intra-row weeding made by a rotating body bringing eight rotating tines; these can skip the crop plants by individual rotation when signalled by an optical sensor. The above-mentioned weeding system has been also tested by using a GPS-based system instead of the optical sensor (Nørremark *et al.*, 2008). Rasmussen *et al.* (2012) designed a rotor tine cultivator to skip the crop plant. A similar approach was used by Li *et al.* (2015) designing a controlled rotating blade (sickle-shaped).

Among these we can mention, for example, the high-pressure water system (Ishida *et al.*, 2005; Losavio, 2016) and the well-known systems using free or guided flame by liquid propane. But there are also more sustainable recent systems, characterised by commercial success (Jabran & Chauhan, 2018), such as that using wooden pellets for combustion, integrated or not with perimetrical jets of boiling water or steam to increase the herbicide effect, and, in the same time, to reduce the risk of fire in summer usage (Li Gotti *et al.*, 2018). Other hot foam systems are being tested at Italian research institutions (Jebu Mia *et al.*, 2020a, and 2020b). All these systems, even though they do not use moving parts, cannot be turned off during their usage to save the crop plant (and turned on when needing to remove weeds), and cannot be turned off too rapidly, and therefore they need a mechanical crop plant-skipping system like those here presented.

Dimensions, shape and weight of the tools related to specific operating modes strongly characterize the different types of machines with respect to their working methods in field operation. From this point of view, the present work is intended to provide useful indications to combine the type of tool and working mode of the machine, its intra/inter-row working modality, and indication on the possible development phase.

From this point of view, the present study relates the functional and dimensional aspects of mechanical weed control systems in orchards with the binding kinematics and the treated and safety areas, in order to increase the efficiency and the performance of the system and avoiding to damage the stems of the plants. This work aims to provide a guidance on implementation and on functional modalities, as well as on mechanisms, to apply to weed control, with the main purpose to limiting the environmental impact of technology, and in full respect of the concepts of a sustainable and precision agriculture. Further model implementations, including aspects related to soil typology, could allow for a more accurate assessment of the suitability of tools of different shapes, configurations, functional working principles in relation to the actual cultivation conditions (*e.g.* level of growing, etc.), and also of different pedoclimatic conditions. Such considerations would play a very important role in reducing soil organic matter content, often attributed to a strong impact of mechanical actions (*e.g.* considerable working depth), or to wrong weeding practices with respect to crop growth.

Material and methods

The simulated models differ in how to skip the plant during the working of the row. The classic model skips the obstacle exiting the row by a crosswise displacement of the working tool (here called the Crosswise displacement plant-skipping system, CDSS). All the other proposed models, instead, use the rotation of the tool holder frame (THF) as plant-skipping system; moreover, a tilting motion approach has been taken into consideration.

Finally, to make the simulation realistic, a vertical axis rotary harrow, of radius r_t, was used as exemplary working tool (WT). In fact, the WT may also be of another type, even lighter if possible, also newly designed, in order to meet the spirit of the present work, that is to create a lighter and simplified weeding system.

A rather important aspect concerns the dimensional aspects of the working tools and of the plants localization, in particular their distance in the row and the interactions tool-plant, to allow a suitable entry and exit procedure of the working elements in/from the row itself.

For all the proposed schemes numeric simulation models were developed, including the classical ones with the aim of evaluating in a comparative way the main processing indexes as a function of some operating parameters (operating speed, angular velocity of THF rotation, THF radius of rotation, etc.).

Although the models provide analytical solutions, some aspects of the simulation have been solved by means of a numerical approach, which was necessary to identify more easily the different kind of worked areas (Table 1 and Fig. 1). The developed code implements a numerical map of the worked area by tracking the working tool (by simulating its rotation and translation over time). The code does not present any particular problem, so we decided to develop it in Visual Basic for Application inside the Excel application (Microsoft), also to facilitate the animation of the simulation and the subsequent data processing.

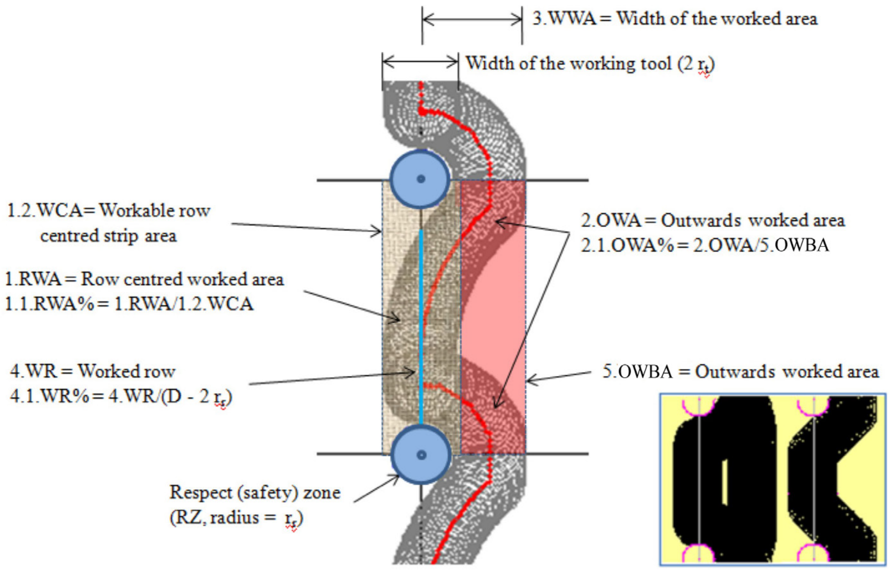

Figure 1. Operating indexes considered for the comparison among the simulated models. The gray track represents the worked area; circular areas represent the safety zones around the plants (RZ). In the picture box on the right the numerical mapping results from the RPSS-VA model with 2 THFs (left), and the CDSS model (right). CDSS: crosswise displacement plant-skipping system.

The analytical solution was used to determine the necessary operating parameters for the correct operation of each machine (THF rotation and translation speed), trying to define the most salient aspects of each application solution.

For all the simulated models, a safety zone (respect zone, RZ) was established in order to allow a comparison of the characteristics of the worked areas, represented by a circular surface, of radius r_r, centred on the plant. The safety zone is defined only in ordinary conditions, without considering other aspects. Particular conditions (presence of stones, hardness of the soil, or height of the weeds) could lead to an increase in the safety zone. This area is not related to dimensional aspects of the working element, and should be stated by the operator on a case-by-case basis. The operational processing parameters are calculated to work, as far as possible, the whole row excluding the safety zone (*1.2.WCA index*).

Simulated models

Crosswise displacement plant-skipping system (CDSS)

As already told, CDSS is the traditional model mainly used in small and medium-sized inter-row hoeing machines with horizontal displacement and working tools from 40 to 100 cm. The system is technically very simple and suitable for processes that involve good aggression on weeds and also a certain depth of work. The main limitation concerns the poor maintenance of the surface profile due to the transverse exit and re-entry movements of the working organ. Although its mode of operation is well known, its simulation was necessary to allow comparison with the other proposed models. The plant is skipped by a crosswise movement of the THF, with a motion perpendicular to the direction of the path.

Taking into account the RZ with radius r_r surrounding the plant, the point where the THF has to begin its exit from the row (X_R point in Fig. 2), in order to avoid trespassing the RZ, is calculated using the following formula:

$$X_R = X_F + r_t \tag{1}$$

where:

$$X_F = -\frac{a_F}{b} \tag{2}$$

$$a_F = \frac{r_r + r_t}{\cos(\alpha)} \tag{3}$$

$$\alpha = atn(b) \tag{4}$$

where b is:

$$b = \frac{v_r}{v_a} \tag{5}$$

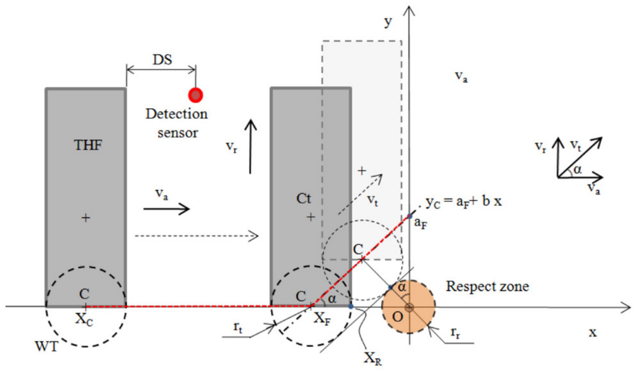

Figure 2. Sketch of the crosswise displacement plant-skipping system (CDSS). The plant detection sensor is situated ahead the THF to detect in advance the plant to be skipped.

Considering that the plant detection sensor is positioned further ahead with respect to THF by DS (Fig. 2), starting of translation of THF must be delayed by an interval time given by: $(DS - X_R) / v_a$.

The exit of the THF will continue until the lower point of the WT is out of the respect zone; considering the trajectory of the centre C of the WT described by the equation $y_C = a_F + b\,x$, this condition is verified when $y_C = r_t + r_r$. So the exit will end when $X_C = (r_t + r_r - a_F)/ b$. The row re-entering will follow a symmetrical direction.

Rotating tool holder frame - Vertical rotation axis (VA)

Although little used by agricultural machinery manufacturers, even, if properly sized, especially with regard to the rotating frame radius, it allows precise respect of the safety zones around the plants with a simple and free continuous rotary movement. Especially with vertical axis tools it would allow to maintain a good surface profile and an adequate aggressiveness on not too developed weeds.

Rotary motion plant-skipping system. Vertical rotation axis (RPSS-VA)

In this model there are two, three or four THFs radially arranged around the rotating body RB (Fig. 3); each THF is equipped with a WT. When a THF is working in the row, it is perpendicular to the row itself and fixed (not rotating). When the plant is signalled by a suitable sensor system (its positioning is depicted in Fig. 3, at a distance of r_r from the THF), the RB start a rotation at a proper velocity (ω_{rot}) in the opposite direction compared to the running one; this allows the THF to exit from the row to preserve the RZ. The rotation will end after an angle of π/n_{wt} rad (n_{wt} = number of working tools); at this point, the THF closer to the one that just left the row will be perpendicular to the row itself with its WT ready to work.

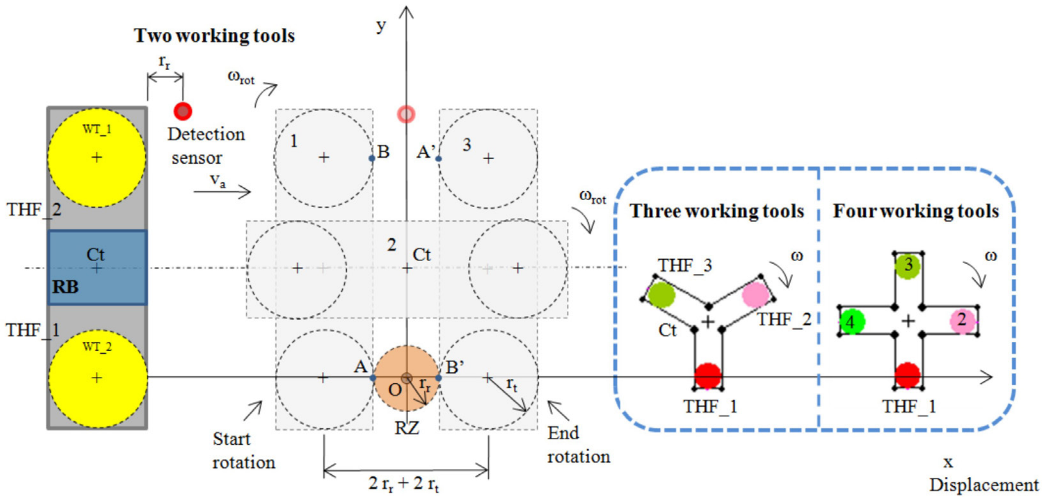

Figure 3. Sketch of the RPSS models with two THFs. This sketch is valid both for vertical and horizontal models (RPSS-VA, RPSS-HA). For the RPSS-VA model, the sketch represents the top view (the XY plane is parallel to the ground), while for the RPSS-HA model, the sketch is to be seen as a side view (the XY plane is perpendicular to the ground). In both models the x-axis represents the planted row. The framed figure on the right shows a simplification of the configurations with three and four THFs.

Calculation of the angular velocity (ω_{rot}) to skip the plant

With reference to Fig. 3 it is possible to establish that the THF inside the row should begin its rotation just when its point A is against the RZ (at the distance of r_r from the plant). The rotation will end after an angle of π rad, when point B "touches" the RZ on the other side of the plant. In this context the travelled distance by the centre C_t of the rotating body (RB) during its rotation will be $2 \cdot (r_r + r_t)$, with a rotation time of $t_r = 2 \cdot (r_r + r_t)/v_a$. In general, considering n_{wt} as working tools (with n_{wt}= 2, 3 and 4, Fig. 3) the rotation angle of the THF needing to skip the plant is $\alpha_{THF} = 2\pi / n_{wt}$ (rad); consequently, the correct angular velocity ω_{rot} of the THF is given by the following equation:

$$\omega_{rot} = \frac{\alpha_{THF}}{t_r} = \frac{\pi \cdot v_a}{n_{WT} \cdot (r_r + r_t)} \quad (6)$$

In this way the plant will be skipped without undergoing any damage and without invading the RZ. Higher n_{wt}, lower will be ω_{rot}.

If we do not want to work outside the planted row (that is to work only in the intra-row) with the RPSS-VA model, it is possible to tilt the rotating axis of the RB towards the worked row by a suitable angle (Fig. 4). In this way only the WT on the row will be active, while the other one will be out of the ground.

Forward-backward tilting plant skipping system (FBTS)

These systems are widely used in recent decades with good results by manufacturers for intra-row rotary mowers, especially in the variable return version (VR), with a working element ranging between 40 and 60 cm of diameter. The constants return version (CR) could be very interesting as maintaining the same safety zone of the VR version, furthermore allowing, in the same time, a greater weeds controlled area. These models are suitable with vertical axis cutting elements that perfectly follow the soil profile without interfering with it. In this model the RB has only one THF, and the rotation motion is not just in one direction, but it has a tilting rotation motion: in one direction of rotation the THF enters the row (at the angular speed of ω_R), in the opposite direction it exits the row (at the angular speed of ω_o, Fig. 5). As in the previous model, during its operation the THF is perpendicular to the row. The plant-skipping procedure follows three phases (Fig. 5):

1. Rotation of the THF in the sense of advancing of an angle of α_{max} at the given rotation speed of ω_o; rotation starts in C_{SX} and continues until the action area of the WT (with the action radius of r_t) is out of the RZ,

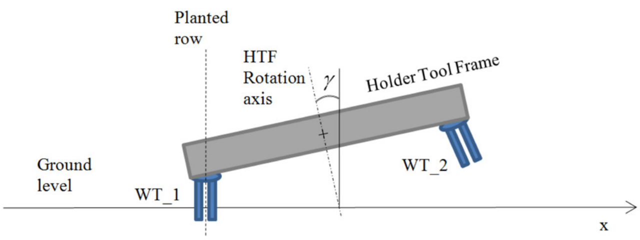

Figure 4. Side view of the RPSS-VA model with tilted rotation axis to enable to work only the WT in the row (WT_1), while WT_2 is away from the ground.

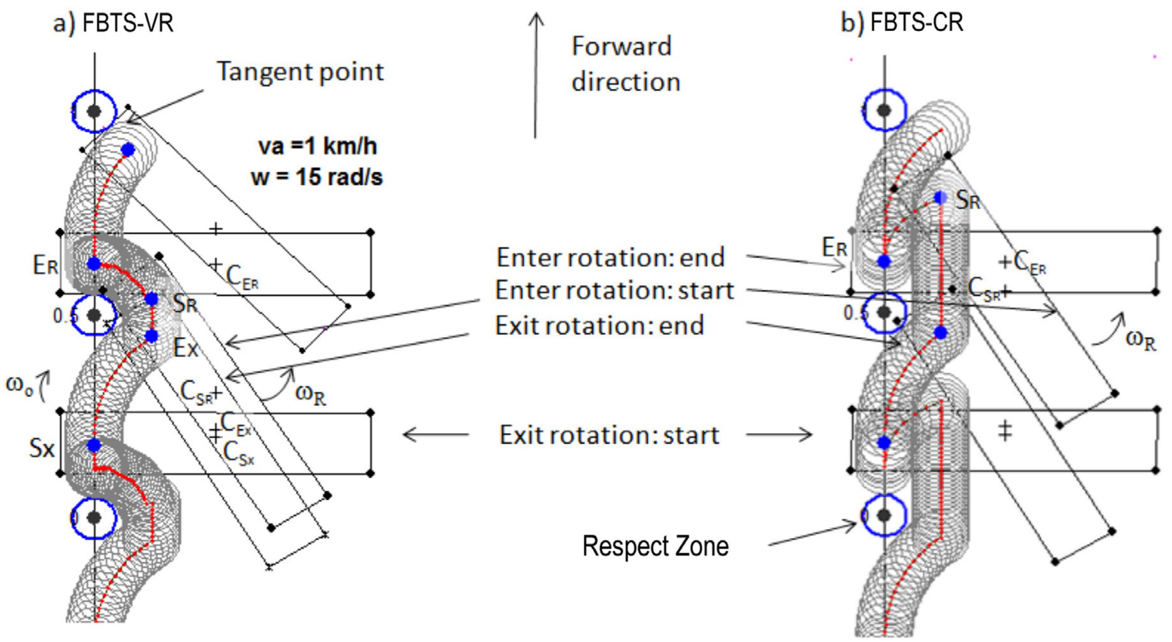

Figure 5. Model simulation of the forward-backward tilting system (FBTS): a) at variable return angular speed (FBTS-VR); b) at constant return angular speed (FBTS-CR). *Sx* = start exit rotation, Ex = end exit rotation; S_R = start return rotation, ER end return; C = centre of rotation of the THF. Red line = trajectory of the WT centre.

that is in C_{EX} position (Fig. 5 and Fig. A1 in Annex A [suppl]); at this point the centre of WT is in the E_x point (Fig. 5);

2. The THF, fixed in the angular position reached at the previous step, by translation at the advancing speed v_a, skips the plant (in this phase the final point SR, reached by the centre of WT, is distinct for the FBTS-CR and the FBTS-VR models);
3. The THF enters again the row thanks to a rotation of an angle of α_{max} in the opposite direction of the phase 1. The starting point of rotation to enter the row begins at C_{SR} point, and the angular speed (ω_R) depends on the modality of the rotation, which can be constant (in the FBTS-CR model) or variable (in the FBTS-VR model, with controlled variable ω_R).

Annex A [suppl] shows a detailed calculation of C_{SX}, C_{EX}, and α_{max}; these parameters are the same for both FBTS-VR and the FBTS-CR models.

a) Return in the row at constant ω_R (FBTS-CR model)

In this case the translation (without rotation, with the THF fixed at α_{max}) of phase 2 of the plant-skipping procedure will continue up to the centre of rotation of the THF will pass the RZ in C_{SR} position with $C_{SR}= + r_r$ as in Fig. 5b. At this point the return rotation at ω_R angular speed begins. Considering that the rotation of α_{max} will require the same time necessary to run the distance r_t to be completed, we can calculate ω_R as follows:

$$\omega_R = \frac{v_a \cdot \alpha_{max}}{r_t} \tag{7}$$

b) Returning the row at controlled speed rotation ω_R (FBTS-VR model)

In this configuration the speed of rotation is controlled with the aim to follow as close as possible the RZ edge. Annex B [suppl] presents the calculation of the starting point of rotation to return in the row (C_{SR}) for the FBTS-VR model. The speed rotation of the THF is regulated by the following simple loop algorithm at each time step dt; before starting we set $\alpha = \alpha_{max}$:

$$\alpha = \alpha - dt \cdot \omega_R;$$

If distance (centre of the WT, plant position) $\geq (r_r + r_t)$
then $\omega = \omega_R$
else $\omega = 0$; //no rotation, only translation

In this way the rotation of the THF during the entering of the row, proceeds in an irregular way until $\alpha = 0$, that is until the rotating body reach the vertical position (Fig. 5a, and Fig. A1 [suppl].

The angular speed ω_R used is calculated considering that in the meantime that THF moves from C_{SR} to C_{ER} (just in the position outside the RZ), the THF performs the α_{max} rotation. Therefore, ω_R will be:

$$\omega_R = \frac{v_a \cdot \alpha_{max}}{(C_{SR} + C_{ER})} \tag{8}$$

It is not possible to return in the row with a continuous rotation at ω_R since, if the final position remains the same of the controlled approach, the WT will invade the RZ.

The plant-skipping procedure could be done also by reversing the direction of the rotation to entering/exiting the row as described so far.

Rotary motion plant skipping system. Horizontal rotation axis (RPSS-HA model)

This solution is similar to the RPSS-VA, but the rotation axis of the THF is horizontal and perpendicular to the row. So, the plant-skipping system is just similar to a wheel with two, three or four "spokes" (obviously, without the rim), each one is provided with a WT (Fig. 6). The angular speed of rotation of the "wheel" (ω_{rot}) is the same as in the *RPSS-VA* (Eqn. 6).

While rotating over the ground to skip the plant, in order to prevent the THF from hitting the plant itself during its movement, a suitable distance between two plants in the row must be ensured. As a reference, the same scheme of Fig. 3 (used for the *RPSS-HA* model) can be used, but, in this case it has to be considered as a side view, differently from the *RPSS-HA* model, used as top view.

In general, for each given v_a and ω_{rot}, a minimum distance between the plants must be, depending also on the THF dimension (the radius of rotation R, and the width of the THF, that is 2 r_t). Referring to Fig. 7, it is possible to calculate the minimum distance between the plants in the row (D_{tmin}), which is necessary to avoid damaging the plant during the rotation of the THF:

$$D_{t\ \min} = \left| x_{A\ \min} \right| + r_t + 2r_r \tag{9}$$

If ω_{rot} is calculated using Eqn. 6, $D_{t\ min}$ can be considered as an invariant with respect to v_a, on equal terms, because the angular position of the THF (α_{min}) inside the row (Fig. 7) is always the same.

In general $x_{A\ min}$ depend on v_a / ω_{rot} ratio, on R, and on r_t. Annex C [suppl] contains a detailed calculation of $x_{A\ min}$ and α_{min}.

For this model the working indexes can be analytically calculated as follows:

$$\left.\begin{aligned} &1.RWA = [D_t - 2\ (r_r + r_t)]\ 2\ r_t + \pi\ r_t^2 \\ &4.WR = D_t - 2\ r_t \\ &4.1.WR = 100\% \end{aligned}\right\} \tag{10}$$

This model can be used, as a first approximation, with plants no higher than the THF radius R (Fig. 7), or better with the overall dimensions of the THF interacting with the crossing plant, as highlighted in Fig. 6 (the red edges of the THFs). In general it can be used for all herbaceous and tree crops in the early stages of development, when weed control is most problematic.

Results

In order to make a suitable comparison among the different models proposed in the present paper, all the simulations were performed using the following settings:

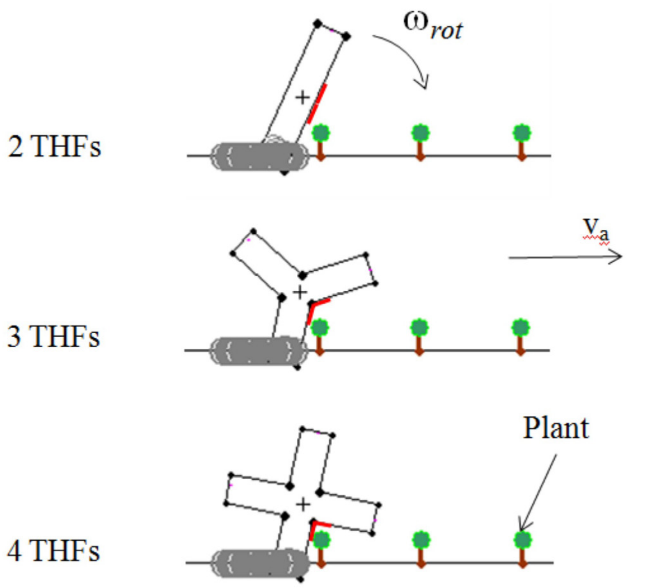

Figure 6. Side view of the rotary motion plant-skipping system with horizontal rotation axis(*RPSS-HA*); solution with two, three, and four THFs (that is with two, three, and four WTs). The zone of the THFs body highlighted with a red line can interact with the crossing plant.

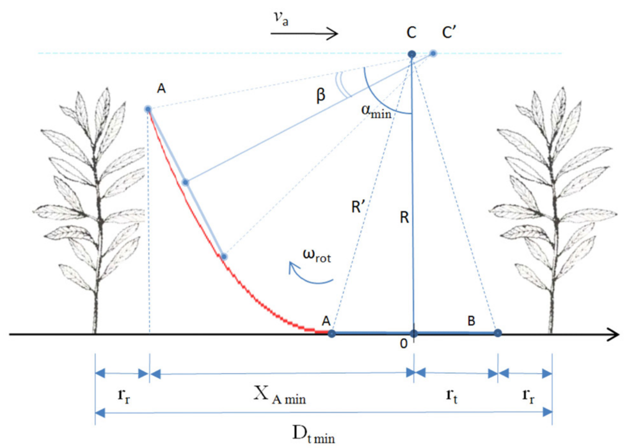

Figure 7. Sketch used to calculate the minimum distance between two plants in the row ($D_{t\ min}$), required distance to avoid damaging of the plants with the *RPSS-HA* model. The AB segment represents the diameter of the WT, while R is the radius of the THF. C-C' = THF advancement during α_{min} rotation.

- Radius of the working tool: r_t = 0.075 m.
- Radius of the Respect zone (RZ): r_r = 0.05 m.
- Radius of the THF: R = 0.35 m. In the *RPSS* models, the radius depends on the number of THFs used (2, 3, or 4 tools); the selected radius is the one that allows for the maximum worked area around the RZ.
- Row spacing: D_t = 0.5 m (slightly greater than that required by the *RPSS-HA* model:
- $D_{t\,min}$ = 0.41 m, as calculated by Eqn. 9.
- *MWAR* = 0.067 m^2: the maximum workable area (*MWAR*) along the row is given by $MWAR = D_t\, 2r^t - \pi\, r_r^2$.
- Advancing velocity: v_a = 0.28, 0.56, and 0.83 m s^{-1} (respectively 1.0, 2.0, and 3.0 km h^{-1}). The selected velocities are those normally used with the most common mechanical weeding operating machines (both hydraulically- or mechanically-driven with rotating working tools with both vertical and horizontal axle).

Table 2 shows the results for the CDSS, RPSS-VA and RPSS-HA models. The RPSS models have been tested for all possible combinations for the selected values for v_a and the number of THF ($3v_a$ × 3 #WTs). For the RPSS-HA the working indexes are drawn by analytical calculations, and not by simulation. In this model all the calculates indexes for the characterization of the worked area give the same values for all the testing conditions because ω_{rot} used for simulations is calculated by Eqn. 6; this makes that the position of the THF on the row does not depend on v_a or on the number of THF to the progression of the simulation time.

For the CDSS model, in addition to the indices shown in Table 1, we report the X_R values (the point where the THF starts to exit from the row to avoid the RZ (Fig. 2)). The used v_r/v_a ratios have been chosen to highlight the CDSS model under the most relevant operating conditions. So, the CDSS models have been tested for four advancing/crossing velocity ratios (v_r/v_a = 1/1; 2/1, 3/1, 5/1, and 5/3).

Table 3 shows the results for the FBTS-CR and FBTS-VR models. The return angular speed ω_R has been calculated by Eqn. 7 and Eqn. 8, respectively for the *FBTS-CR model* and the *FBTS-VR* model; ω_R depend on v_a, the size of the model, and the RZ, but it does not depend on the outward angular velocity. The FBTS models have been tested for all possible combinations for the selected values for v_a and the number of THF ($3v_a \times 3\omega_o$, the outward angular velocity).

Figure 8 shows the entering distance (X_R) and its derivative with respect to v_r/v_a ratio for the CDSS model, while the patterns of the WT is shown in Fig. 9 for three different v_a/v_r ratios.

Figure 10 presents the patterns of the working tools of three configurations of the RPSS-VA model (with 2, 3 and 4 THFs).

Each simulated model is intended to work the row just one time (it is not considered the second run on the same row on the other side).

Discussion

In general weeding efficiency depends on the percentage of the intra-row worked area linked to the ability of the WT to uprooting and/or burying weeds during its passage (Kurstjens & Kropff, 2001); efficiency also depend on several other aspects at the moment of weeding (e.g soil moisture, soil cone index, etc.; Kurstjens & Kropff, 2001; Home, 2003). As a first approximation, in this research paper, we can say that the greater the worked area, the greater the weed control efficiency.

Nørremark *et al.* (2012), to evaluate the percentage of the intra-row worked area by an eight sigmoid-shaped tines rotor (cycloid hoe), have set the width of the worked area to 0.080 m (in the present simulations is set to 2 r_t = 0.15 m), and the RZ radius to only r_r = 0.01 m *vs* 0.05 m

Table 1. Calculated indexes by means of the simulation models for the characterization of the worked area (see Fig. 1).

Indexes	Definition
1.RWA	Row centred worked area (m^2)
1.1.RWA%	Percentage of *1.RWA* in terms of *1.2.WCA* (%)
1.2.WCA	Workable row centred strip area (m^2); the strip of soil as wide as the working tool (2 r_t) between two contiguous plants, and centred in the row
2.OWA	Outwards worked area (m^2); worked area outside RWA
2.1.OWA%	Percentage of *2.OWA* in terms of *5.OWBA* (%)
2.2.OWAR%	Outwards worked area *2.OWA* in terms of *1.RWA* (%)
3.WWA	Width of the worked area (m) considered from the row towards the enter/exit side of the THF
4.WR	Worked row (excluded the respect zone) (m)
4.1.WR%	Percentage of the worked row *4.WR* in terms of *6.WBR* (%)
5. OWBA	Outwards workable area (m^2); its width depends on the selected model
6.WBR	Workable row (plant spacing excluded the respect zone, r_r) = D - 2 r_t

in our work. Anyway, although the system they used is not comparable to those proposed here, except for the fact that it is an intra-row weed control system, we can only highlight that the intra-row tilled area in percent of total intra-row area is *1.1.RWA%* = 69% at v_a =0.31 m s^{-1}, in the better performance; in our work the worst case, reached by the CDSS model, shows anyway a higher value: *1.1.RWA%* = 85% (Table 2, Test#1, v_r/v_a= 1/1). Considering both intra- and inter-row area, their solution can reach, theoretically, up to the 92% of worked area.

Pattern of the path of the working tools on the soil

In the CDSS model, with v_r/v_a > 1.5, there was no significant reduction in the distance X_R (the starting point to enter the row), as its derivative with respect to v_r/v_a tends to zero (Fig. 8). The patterns of the WT shown in Fig. 9 for three different v_a/v_r ratios, highlight as the smaller the ratio, the greater the worked area. Table 2 explains how X_R decreases from 0.102 m (Test# 1), with v_a/v_r = 1/1, to 0.065 m (Test# 2), with v_a/v_r = ½, but by passing to v_a/v_r = 1/3, X_R the reduction is only 0.008 m (Test# 3).

Considering the patterns of the working tools in the RPSS-VA model, if ω_{rot} is calculated using Eqn. 6, the patterns will be always the same for any v_a setting, as shown in Fig. 10 for three configurations (with 2, 3 and 4 WTs). We can highlight that the width of the worked area (*3.WWA* index) obtained is greater in the vertical axis version of the RPSS model, but not directly proportional to the number of working tools: passing from 2 to 4 tools

Table 2. Results for the crosswise displacement plant-skipping system (CDSS) and the rotary motion plant-skipping system (RPSS) models.

Test #	Plant-skipping system	# Working tools	Advancing velocity (v_a, km/h)	Crossing velocity (v_r, km/h)	Body length (m)	1.RWA - Row centered strip worked area (m^2)	1.1.RWA% - Row centered worked area (%)	2.1. OWA% Worked area outside row strip (%)	2.2. OWAR% Outwards worked area in term of 1.RWA (%)	3.WWA - Width of the worked area (m)	4.1.WR% Worked row (%)	X_R (m)
1	Cross displacemet system (CDSS)	1	1.0	1.0	0.50	0.057	85.0	59.3	67.5	0.21	89.6	0.102
2		1	1.0	2.0	0.50	0.062	92.4	62.6	63.1	0.20	97.0	0.065
3		1	1.0	3.0	0.50	0.063	93.4	65.5	67.9	0.21	98.6	0.057
4		1	1.0	5.0	0.50	0.063	94.5	69.8	68.7	0.20	99.5	0.052
5		1	3.0	5.0	0.50	0.062	92.4	59.4	59.8	0.20	95.8	0.071
				Angular velocity, ω_{rot} (rad/s)	Radius of the rotating body (m)							
6	Rotary motion system Vertical axis (RPSS- VA) (*)	2	1.0	3.5	0.16	0.064	95.9	96.4	127.2	0.25	100.0	
7		3	1.0	2.3	0.20	0.063	93.9	89.9	178.3	0.33	100.0	
8		4	1.0	1.7	0.25	0.061	91.0	98.6	282.3	0.43	100.0	
9		2	2.0	7.0	0.16	0.064	95.9	96.2	127.0	0.25	100.0	
10		3	2.0	4.7	0.20	0.063	93.9	89.8	178.0	0.33	100.0	
11		4	2.0	3.5	0.25	0.061	91.1	98.6	282.0	0.43	100.0	
12		2	3.0	10.5	0.16	0.064	95.4	96.1	127.6	0.25	100.0	
13		3	3.0	7.0	0.20	0.063	93.6	88.9	177.0	0.33	100.0	
14		4	3.0	5.2	0.25	0.061	90.7	97.9	281.2	0.43	100.0	
15	Rotary motion system Horizontal axis (RPSS-HA) (*)	2-4	1.0 - 3.0	3.5 - 1.7	0.35	0.038	55.8	0.0	0.0	0.15	100.0	

(*) ω_{rot} calculated by Eqn. 6. Testing conditions: Row spacing, D_t = 0.50 m. Diameter of the working tool, 2 r_t = 0.15 m; Diameter of the respect zone, 2 r_r = 0.10 m. *1.RWA* = Row centred worked area (m^2); *1.1.RWA%* = Percentage of row centred worked area; *2.1.OWA%* = Percentage of outwards worked area in terms of outwards workable area; *2.2.OWAR%* = Percentage of outwards worked area in terms of *1.RWA; 3.WWA* = Width of the worked area (m); *4.1.WR* = Percentage of the worked row; X_R = Entering distance in CDSS model (m).

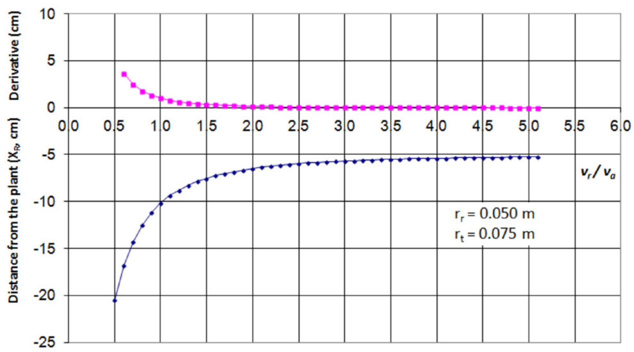

Figure 8. Entering distance (X_R) and its derivative with respect to v_r/v_a for the CDSS model.

the increase is 72% (from 0.25 to 0.43 m, respectively). Anyway, being the worked area subject to multiple passages, a more aggressive intervention on weeds is performed.

In the FBTSs and CDSS, the path pattern on the soil is determined by the single THF entering/exiting the row to avoid the RZ, as depicted in Fig. 5 and Fig. 9. In this context there is not multiple passages of the WT on the soil. In general, for the above mentioned models, the width of the worked area (*3.WWA* index) is about 0.20 m for all the operating settings, that is the radius of RZ (0.05 m) plus the diameter of the WT (2 r_t = 0.15 m).

Working indexes comparisons

— Percentage of row centred strip worked area (*1.1.RWA%* index) and workable row (*4.1.WR%* index). This parameter can be considered the one directly related to the efficiency of weed control.

Considering the maximum workable area (*MWAR*) along the row, we can make comparisons among the models by taking into account the percentage of the worked area (*1.1.RWA%*). This index, for the CDSS model, ranges from 85% up to 94.5% with a v_r/v_a ratio of 1/1 and 5/1, respectively. The same trend occurs for the worked row index (4.1WR%).

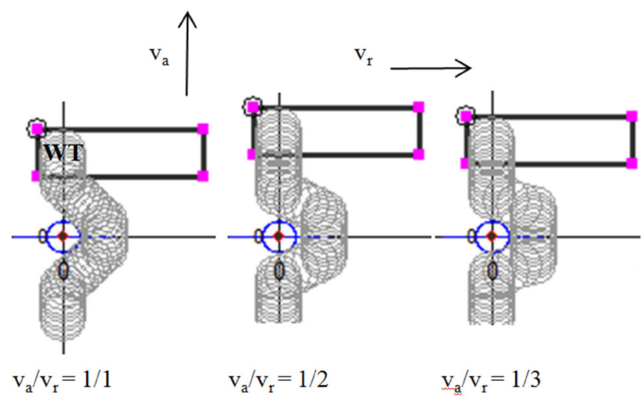

Figure 9. CDSS model: WT patterns with different v_a/v_r ratios (1/1, 1/2, and 1/3, respectively).

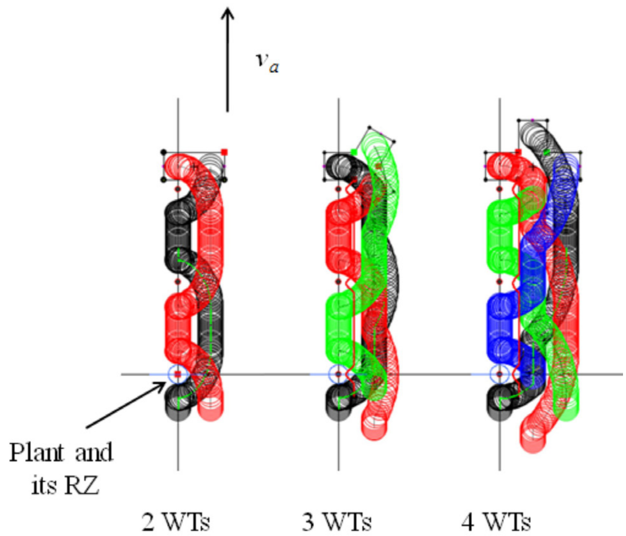

Figure 10. RPSS-VA models (top view): WT paths with different number of THFs (WTs).

The RPSS-VA with two THFs (that is two WTs) shows the best performance with *1.1.RWA%* = 95.9 % (Test# 6, #9, and #12).This is due to the fact that the lower the number of WTs, the higher ω_{rot} will be, allowing to working the row up to the last one before starting the exit procedure from the line (we recall here that ω_{rot} is inversely proportional to the number of WTs). In Fig. 10 is evident as the RZ perimeter is better followed in the case of two WTs.

The absolute worst performance comes from the FBTS-CR model, with va = 0.83 m s^{-1} (3 km h^{-1}) and ω_{rot}= 10 rad s^{-1} (*1.1.RWA%* = 82.1%, Test# 27). The FBTS-VR shows a similar behaviour. In general, the higher the v_R/v_a ratio, the higher the *1.1.RWA%* index. Kumar *et al.* (2020) present a model similar for the pattern of the WT path to the FBTS-VR one, but with constant angular speed rotation, both to exit and to enter the row. In their work, they do not calculate which is the worked area, although they take into account several conditions (plant spacing, velocity, depth of operation, cone index). They only consider the number of weeds before and after the passage of the weeding system, and damages on the crop plants. Further considering the work of Kumar *et al.* (2020), the angular speed rotation to exit/enter the row they found ranges from 16.2 rad s^{-1} to 20.0 rad s^{-1} (from 154 rpm to 191 rpm, as in their paper), with the advancing velocity passing from 0.96 km h^{-1} to 2.58 km h^{-1} respectively, as calculated by a fuzzy logic algorithm. Applying the higher values of the operating parameters to the FBTS-VR model, we obtain performance indexes in agreement with those obtained as in Test#33 (v_a = 3 km h^{-1}

and ω_{rot} = 15 rad s^{-1}): the index *1.1.RWA%* is 84.2% and 85.0%, while *4.1.WR%* is 96.3% and 97.5%, respectively for the FBTS-VR and the Kumar *et al.* (2020) models. Anyway, in our work we have a constant rotation speed to exit the row, and the model calculates the position on the row where start the exit/enter procedure of the THF.

The rotative models (RPSS and FBTS) show the best performance with respect to the worked row (excluding the RZ area, the maximum workable row is given by 4.WR =$D_t - 2\ r_r$ = 0.40 m). In particular the RPSS model gives the maximum worked row allowed (*4.1.WR%* = 100%, Tests# 6-15) for all the tested operative conditions, while in the FBTS models *4.1.WR%* ranges from 96.3% (Test# 16, 17, etc.) up to 98.8% (Test# 26).

The FBTS models (CR and VR) with operative parameters set at v_a= 0.83 m s^{-1} and ω_{rot}= 5 rad s^{-1} are not able to sufficiently and conveniently exit the row, so the WT invades the RZ (*4.1.WR%* > 100%, Tests#18 and #27).

The performance of the CDSS model can be extremely good at low v_a/v_r ratio. With v_a/v_r = 1/3 the worked row is *4.1.WR%* = 98.6% (Test#3).

— Outwards worked area in term of row strip worked area (%) (*2.2.%OWAR* index). The worked area outside the row by the CDSS model is at maximum 67.9%, with v_a= 0.83 m s^{-1} , and v_r= 0.28 m s^{-1} (1 km h^{-1}) (Table 2, Test#3), while the RPSS-VA models ranges from 127.2% to 282.3%, passing from two WTs to four WTs (Tests# 6-8 for v_a= 0.28 m s^{-1}; same results with any v_a, because ω_{rot} is calculated with Eqn. 6. Paying particular attention to the types of operations that can be performed with working tool with horizontal axle using rigid blades or plastic flails compared to the vertical ones, generally only rigid or elastic metal (Granatstein, 2018).

Should be interesting to evaluate the energy and agronomic aspects on the soil profile, although in the present work we only address the functional aspects of the worked area.

The FBTS-CR model ranges from 92% to 112.1%, while the FBTS-VR model shows values comparable with the CDSS model, with a percentage of worked area going from 57.5% (Table 3, Test# 27, the absolute minimum) to 71.3% (Test# 33).

In relation to the need to work or not out of the row strip (*2.1.OWA* and *2.2.%OWAR* indexes), or how much to work, these model simulations represent a help to choose the best solution in relation to specific aspects of the context in which the control weeds takes place. So, for example, if we do not want to work out of the row, the best solution is represented by the RPSS-HA models (*2.2.%OWAR* = 0.0%); alternatively, among the models with vertical rotation axis (RPSS-VA), the minimum external worked area is obtained with two WTs (a higher number of WTs gives a higher *2.2.%OWAR* index). Also the RPSS-VA model with the tilted RB axis, as shown in Fig. 4, could be an innovative solution if one need to work only in the row.

Among the different tilting systems (FBTS typology) the FBTS-VR model gives the lowest *2.1.%OWAR* index, ranging from 57.5% (Test# 27) up to 71.3% (Test# 33). This behaviour is due to the fact that the WT exit the row only to avoid the crop plant, while FBTS-CR model once out of the row remains longer there before re-entering (Fig. 5).

The main cause of soil irregularity during working (formation of depressions and dunes) is due to the displacement of the WT. So, to limit this problem, we can opt for the RPSS-VA model with three or four WTs, since, at equal working speed, a higher number of WTs allows for a reduction in relative displacement, and, consequently, slighter soil profile modifications, with adequate consideration in term of energy input.

The total width of the worked area is another important aspect to ensure a better weed control. To reduce the non-worked area, we need to increase the number of WTs using three or four WTs with the RPSS-VA model. In this case we have a *3.WWA* index of 0.43 m with four WTs, while with only two WTs we have just 0.25 m, rather tight for effective weed control over time. This system in the VR version is adopted in the more recent machine for weeds control with water pressure (Losavio, 2016), allowing the respect of the safety zone, without the need to interrupt the water flow, that should be a hard task at so high pressure.

Working machines for intra-row weed control can differ according to their constructional and functional typology, as well as according to the function of the different working depths. The availability of a simulation model to evaluate in advance their performances can help the machine manufacturer to design and develop new solutions, also by taking into account a given planting layout. The construction typology directly influences also the kinematic chain and the overall complexity of the identified working system. Different types of driving power can provide for different solutions, going from the mechanical to the hydraulic power, to the electric power, mainly depending on the required power level. Most modern tractors show enough potential in all these modalities. Even the electric drive would not require significant integrations in most of the available electrical systems.

Application notes

In all the proposed models it is possible to use a stepping motor to better control the rotation (in RPSS models) or the partial clockwise and counter clockwise rotation (in FBTS models).

Table 3. Results for the forward-backward tilting plant-skipping system (FBTS-CR, return in the row at constant angular speed) and the FBTS-VR (Return in the row at controlled (variable) angular speed) models.

Test #	Plant-skipping system	Advancing velocity (v_a, km/h)	Outward angular velocity, ω_O (rad/s)	Return angular velocity, ω_R (rad/s)	*1.RWA* - Row centered strip worked area (m²)	*1.1.RWA%* - Row centered worked area (%)	*2.1. OWA%* Worked area outside row strip (%)	*2.2.OWAR%* Outwards worked area in term of *1.RWA* (%)	*3.WWA* - Width of the worked area (m)	*4.1.WR%* Worked row (%)
						Constant				
16	Forward-backward balancing system ω_{return} = constant (FBTS-CR)	1.0	5.00	3.68	0.056	81.6	97.0	108.4	0.20	96.3
17		2.0	5.00	7.36	0.055	80.6	95.4	107.4	0.20	96.3
18		3.0	5.00	11.04	0.060	79.8	88.8	92.0	0.20	110.0
19		1.0	10.00	3.68	0.057	84.2	97.1	107.3	0.20	96.3
20		2.0	10.00	7.36	0.056	83.6	97.1	108.1	0.20	97.5
21		3.0	10.00	11.04	0.055	82.1	96.5	109.4	0.20	95.0
22		1.0	15.00	3.68	0.057	84.5	96.5	110.5	0.21	97.5
23		2.0	15.00	7.36	0.057	84.6	96.1	110.0	0.21	97.5
24		3.0	15.00	11.04	0.056	82.9	96.0	112.1	0.21	96.3
						Variable (controlled)				
25	Forward-backward balancing system ω_{return} = variable (FBTS-VR)	1.0	5.00	0.89	0.056	84.0	64.3	71.2	0.20	96.3
26		2.0	5.00	1.80	0.057	82.5	62.5	68.8	0.20	98.8
27		3.0	5.00	2.77	0.060	79.1	55.1	57.5	0.20	107.5
28		1.0	10.00	0.88	0.057	85.4	63.3	69.0	0.20	97.5
29		2.0	10.00	1.81	0.056	84.0	63.8	70.7	0.20	96.3
30		3.0	10.00	2.76	0.056	83.8	63.2	70.2	0.20	96.3
31		1.0	15.00	0.89	0.057	85.6	61.6	69.6	0.21	97.5
32		2.0	15.00	1.81	0.057	84.8	61.7	70.5	0.21	96.3
33		3.0	15.00	2.80	0.057	84.2	62.0	71.3	0.21	96.3

Testing conditions: Row spacing, D_t = 0.50 m. Diameter of the working tool, 2 r_t = 0.15 m. Diameter of the respect zone, 2 r_r = 0.10 m. *1.RWA* = Row centred worked area (m²); *1.1.RWA%* = Percentage of row centred worked area; *2.1.OWA%* = Percentage of outwards worked area in terms of outwards workable area; *2.2.OWAR%* = Percentage of outwards worked area in terms of *1.RWA; 3.WWA* = Width of the worked area (m); *4.1.WR* = Percentage of the worked row.

Configurations without control unit

RPSSs do not need a control unit to be operative in a weeding machine. In order for it to correctly work as described above, it must be equipped with a sensor (*e.g.* Assirelli *et al.*, 2015) to detect in advance the plant at a distance r_r from the point A of the THF (Fig. 3), to give the command to start the rotation of the THF itself. In order to skip the plant without damaging it, ω_{rot} must be set by considering Eqn. 6. If we consider to operate the THF by means of a free wheel with a radius R_{FW}, and an angular velocity ω_{FW} ($\omega_{FW} = v_a / R_{FW}$), the transmission ratio TR can be calculated as follows:

$$TR = \frac{\omega_{rot}}{\omega_{FW}} = \frac{R_{FW} \cdot \pi}{n_{WT} \cdot (r_r + r_t)} \quad (11)$$

If the used detection sensor has a non-negligible response time, this configuration needs for a control unit to manage the delayed response of the sensor. Within certain margins, if the response time is fixed and not excessive, to take into account this delay might be enough to increase accordingly the distance of the sensor from the THF (Fig. 3).

Configurations using a control unit

While a control unit is not always necessary in RPSSs, it is essential in FBTSs, in order to guide the partial rotations to enter and exit the row. The control unit becomes absolutely necessary with the FBTS-VR to continuously regulate the angular speed during the entering rotation, with regard to the advancing speed va. In this case a stepping motor should be used in order to operate the THF and enable an accurate adjustment of the rotation.

In this case the non-negligible response time of the sensor can be managed by the same control unit used to regulate the angular speed of the THF itself.

Conclusions

The present theoretical study has shown new systems to perform the mechanical weed control within the planted row. The main idea focuses on the use of a rotating system (rotating, RPSS, or partially rotating, *i.e.* tilting, FBTS) to skip the plant of the crop to be left, in opposition to the traditional crosswise translation one (CDSS).

The different configurations experimented by means of simulation models have produced different results: the RPSS-HA allows to work only in the row (intra-stool space), while all the other models present also a worked area outside the row.

In the proposed models, in perspective, it is also possible to adopt a stepping motor in order to continuously adjust the speed of rotation as a function of the working speed. In particular, for the FBTS-VR model, due to the continuous control of the rotation during row entering, such motor becomes key. On the contrary, a free wheel with a suitable transmission ratio could be sufficient to power the RPSS models.

As far as the presence of irrigation systems is concerned, all the solutions that include operated systems require the lifting of the line; only exception for fixed systems oscillating on one side, able to operate a few centimetres below the surface, so that even a line remaining on the ground would not gives problems.

All the evaluated models can work regardless of the type of the used detection sensor; physical direct sensor can immediately drive the working element. Other plant detection system (*e.g.* image analysis) must take into account the response time if not negligible.

All the proposed models may have use limitations with respect to the plant intra-row distance (D_i). In general, the smaller the diameters of WT and RZ, the smaller the distance between plants can be. Rotation speed (ω_{rot}) can also be limiting but, by increasing it, smaller intra-row plant distances will be possible.

Finally, another aspect that can be drawn from the present work, and that does not concern directly weed control, is the possibility to eliminate the surface crust with positive effects on water management and gaseous soil exchanges, especially in the nursery and in those areas directly affected by the roots of young plants. In this case the RPSS-VA approach allows to obtain the highest worked area outside the row (in the inter-row space).

The machines currently available in the market mainly use CDSS inter-row hoeing machines. The FBTS–VR model with flail mowers, grass cutters and crust breakers, in future perspectives, could take into consideration the results of this work for the containment of the overlapping worked areas; the organ drive systems should be activated only in the presence of weeds, and automation systems can vary working depth and rotor speed of the working tool according to the species/type and to the level of development of the weed.

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