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Robot ensembles for grafting herbaceous crops

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Legislation and regulation is increasingly limiting the use of pesticides or chemical fumigants to counteract soil-borne pathogens. Therefore the use of disease resistant grafted plants is increasing. However, the grafting of herbaceous crops is a labour-intensive technique, with consequent costs. These aspects have encouraged the development of automated machines able to increase productivity and rooting success rate while reducing costs. This paper presents an innovative solution for automatic grafting of vegetable crops, suitable for small to medium sized farms. The concept is to use a group of cooperative robots, adaptable in number, to meet workload specifications. The machine consists of one or more grafting units, able to cut and join scions and rootstocks, and a supplying and sorting system based on an ensemble of single-axis, identical and independent robotic modules, displacing on a unique rail, which coordinates the movement and the selection of scions, rootstocks and grafted plants. Overall productivity is given by the number of grafting units, the number of robotic modules implemented in the supply system, and the efficiency of the control and task allocation strategy. Together with the description of the innovative aspects of the machine mechanics, designed to face intrinsic variability in vegetable objects, the objective of this paper was to present the ensemble synthesis of the control policies, based on heuristic scheduling priorities, to allocate and coordinate the team of robots to a set of spatially distributed tasks.

1. Introduction

Grafting of vegetable seedlings is a horticultural practice that was developed in East Asia in the early 19th century, in order to counteract huge crop losses due to infection of soil-borne diseases in intensive cultivation. The grafting process consists in attaching scions of the crop to be reared onto more vigorous rootstocks, which absorb soil nutrients making them available for scion's growth. Since the adoption of this technique in Europe, which began in the 1990s, the number of grafted seedlings used in commercial vegetable production is constantly increasing, thanks to the many derived benefits. Indeed, the adoption of robust rootstocks enhances seedlings tolerance to abiotic stress, like thermal, humidity and water stress in harsh environments (Schwarz, Rouphael, Colla, & Venema, 2010), as well as the resistance to soil-borne diseases and nematodes (Louws, Rivard, & Kubota, 2010). The

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Nomenclature

WS	Working Station
WS-A	Seedling loading area
WS-B	Vision and classification system
WS-C	Scions feeding zone to the grafting unit
WS-D	Zone devoted to feeding the grafting unit with rootstocks and to releasing the grafted shoots
WS-E	Unloading area for grafted plants
G	Sliders guide
g_i	$i-th$ equal length guide segment
N_G	Number of equal length segments g_i, constituting the guide G
l_S	One slot width
p_i	$i-th$ independent slider
P	Set of independent sliders
N_P	Number of independent sliders
s_i	$i-th$ slot housed on a slider
S	Set of slots housed on sliders p_i, with $i = 1,\ldots,N_P$
N_S	Number of slots housed on each slider p_i
N_H	Number of slots housed on all the sliders $p_i \in P$
t_k	$k-th$ time instant
$\Vert\cdot\Vert_\infty$	ℓ_∞ norm
$\Vert\cdot\Vert_1$	ℓ_1 norm
$M_{pi}(t_k)$	Set of N_S adjacent guide segments occupied by the slider p_i at time t_k
$V(t_k)$	Vector state of the system at time t_k
$v_i(t_k)$	Discrete position of slot s_i on the rail at time t_k
$\tilde{V}_j(t_{k+1})$	$j-th$ new sliders configuration obtained with one-segment long movements of the set of sliders S, at time t_{k+1}
$\mathbb{V}(t_{k+1})$	Set of all possible movement combinations $\tilde{V}_j$, at time t_{k+1}
$\mathbb{V}_F(t_{k+1})$	Set of all feasible movement combinations
V^*	Chosen new sliders configuration
$H(V(t),I(t))$	Cost function of the heuristic search
h_i	$i-th$ heuristic, with $i = \{1,2,3\}$, constituting H
$I(t)$	Binary vector collecting the *immediate requests* of the system
T_m	$m-th$ task that the supply system can performs (*immediate request*)
$\mathbb{T}$	Set of all the *immediate requests*
N_T	Cardinality of $\mathbb{T}$
$r_i(t_k)$	State of $i-th$ *immediate request* at time t_k
q_{T_m}	Position on the guide of the T_m task (one of the WSs)
Q	Set of all the WSs positions
$w(s_i,T_m)$	Weighing function of the heuristic h_1 and h_2
S_{T_m}	Set of slots suitable for the task T_m
W	Queue of vector state V^*
n_r	Number of pixels rows of the image acquired by vision system
n_c	Number of pixels columns of the image acquired by vision system
(x_0,y_0)	Coordinates of the stem bottom end
(x_c,y_c)	Coordinates of the midpoints of the stem in correspondence to the cotyledons node
α	Average tilt angle of the stem

improved adaptive capabilities to unfavourable soil and environmental conditions increase crop yield, from both quantitative and qualitative points of view, reducing at the same time the amount of needed chemical treatments during the growth cycle (Edelstein et al. 1999). This last aspect complies with recent European Community directives, which are increasingly limiting the use of pesticides or chemical fumigants, such as methyl bromide, to counteract soil-borne pathogens. It also is in accordance with current policies for developing organic, more sustainable practices, and environmentally friendly agriculture.

The adoption of disease resistant grafted plants (e.g. tomatoes or peppers) is a promising technique although it is labour consuming and involves tedious repetitive actions, such as the selection of compatible shoots, cutting and applying the best graft. These aspects have encouraged the development of automated machines, in order to increase the productivity and the rooting success rate while reducing costs, allowing grafting to be more economically sustainable.

The first semi-autonomous prototypes for grafting were developed in the 1990s (Honami, Taira, Murase, Nishiura, & Yasukuri, 1992; Kubota, McClure, Kokalis-Burelle, Bausher, & Rosskopf, 2008; Lee et al., 2010; Oda, 1995) and were only able to perform a limited number of the operations required to obtain a complete grafted seedling and they usually required the supervision of at least three expert workers to feed the machine and to check the quality of the products produced (e.g. Helper Robotech, 2015; Iseki, 2015; Iso Groep, 2015; Kang, Han, Noh, & Choi, 2005). The selection of scion and rootstock couples, which need to be compatible in terms of their diameters, is typically performed by trained operators but, in this paper, an artificial vision-based sorting system is proposed, in order to automatise all the processing phases.

Recently, a new generation of fully automated grafting robots has been developed in Europe. These machines reach higher performances, producing even more than one thousand However, these machines are rather complex, are designed for large-scale production and require heavy investment from farmers. These factors make them unsuitable for typical Mediterranean nurseries. For these reasons, in this context, this operation is still carried out manually in almost all cases.

To tackle this lack of technology, a national research project in Italy (PRIN, 2013) was financed to conceive and develop an innovative machine specifically designed for small and medium Mediterranean farms (Belforte, Deboli, Gay, Piccarolo, & Ricauda Aimonino, 2006). The design objectives of the machine were simplicity, reliability, ease of maintenance and cleaning, and cost-effectiveness, relying on automation and control for the fulfilment of performance specifications.

This paper presents the innovative aspects of the mechanics and of the discrete-events controls of the machine, designed to handle the intrinsic variability of vegetal objects, maintaining the lowest possible level of complexity. The proposed solution is based on an ensemble of cooperative robots, constituted by single-axis independent sliders moving on a passive rail, which supply and sort plants to the grafting units, which are constituted by two independent pneumatic manipulators, a couple of blade cutters and a clip feeder system. The number of independent sliders can be varied and can be determined (by simulation) for optimal operation under a given expected workload.

The challenge is to obtain high performance from the ensemble by synthesising the control policies to allocate and coordinate the team of robots to a collection of spatially distributed tasks.

This paper is structured as follows. Section 2 describes the design solutions adopted for the different robotic components of the machine (supplying, sorting and grafting subsystems) and the overall layout. Optimisation and control algorithms are presented in Section 3, while the artificial vision system and algorithms for seedlings classification are reported in Section 4. Simulated and experimental results are presented in Section 5 and discussed in Section 6. Some animations reporting the results of the machine processes simulations are also available on the journal website as additional material. Finally, conclusions and future developments are discussed in Section 7.

2. Design

2.1. General description

The fragmentation of the Mediterranean area horticulture market prevents the diffusion of the already existing grafting machine, suitable for the medium-large nurseries of the northern Europe. The following design objectives and specifications were detected and necessary to develop an automatic grafting machine suitable for small and medium size nurseries:

- simplicity: the machine should operate in greenhouses, using standard trays and facilities;
- reliability, robustness and ease of use, maintenance, and cleaning: insensitive to dirt, soil and water, the operators should have access to every part of the machine without requiring disassembly, with the possibility of quickly replacing damaged components;
- productivity and costs: scalable and compatible with small and medium size nurseries, it should work without involving operators for supervision and general supplying;
- modular structure: a machine layout able to adapt to the required workload of different-sized nurseries.

Developed on the base of these specification, the prototype (Fig. 1) can be described in three main parts: (1) a supply system, (2) a vision-based sorting system and (3) one or more grafting units.

Unlike other machines (see e.g. Chiu, Chen, & Chang, 2010; Iseki, 2015 and Kobayashi, Suzuki, & Sasaya, 1999) which typically use two independent supply routes or sub-systems (one for scions and one for rootstocks) and another for the grafted seedling, this solution, is characterised by a single supply system which handles at the same time scions, rootstocks and the complete seedlings. The developed system is based on a number of independent single-axis robotic modules, hereafter also referred to as *sliders*, which move on a single rail. Each slider is equipped with a stand with several holding cavities (*slots*), allowing to simultaneously host several shoots during the slider deployment along the guide (Fig. 2). During the machine operations, each slot can indiscriminately host a scion, a rootstock or a grafted plant. Since the effectiveness of the grafting operation is enhanced by processing seedlings with isometric diameters, a vision system was developed in order to classify incoming shoots in two (or more) stem diameter classes. The supply systems must therefore be able to provide two fitting stems belonging to the same class to the grafting units. Each grafting unit consisted of two independent pneumatic manipulators that pick the seedlings from sliders, cut and join scions and rootstocks together, and release the grafted plants onto a slider with one free slot (Belforte & Eula, 2012). The guide areas devoted to loading/unloading shoots to/from sliders have been denominate working station (WS).

In detail, the following WS were designed (Fig. 1):

- seedling loading area (WS-A),
- vision and classification system (WS-B),
- scions feeding zone to the first grafting unit (WS-C_1),
- zone devoted to feeding the first grafting unit with rootstocks and to releasing the grafted shoots (WS-D_1),
- scions feeding zone to the N-th grafting unit (WS-C_N),
- zone devoted to feeding the N-th grafting unit with rootstocks and to releasing the grafted shoots (WS-D_N),
- the unloading area for grafted plants (WS-E).

The prototype is fed by two seedlings trays, one for scion and one for rootstock. The loading procedure is performed by a handling system devoted to pick seedlings by needle-pliers from the trays and place them onto a slider at the receiving position on the rail (WS-A). The choice between requesting a scion or a rootstock, to be picked from the incoming trays, is performed with the objective of maintaining the ratio of rootstocks hosted on the sliders over the 20% compared to the total amount of hosted seedlings.

In the overall process, seedlings, once loaded on the sliders, are moved to WS-B to be classified by the vision system and then, if a couple of seedlings (one for scion and one for rootstock) are detected and if the grafting unit is ready, the supply system will deliver them to WS-C and WS-D respectively. Once a slider has been unloaded of a shoot, it is free to move again and, when both scion and rootstock are loaded, the grafting unit starts the processing cycle. After the grafting procedure, the grafting unit obtains the grafted shoot available in WS-D and then a slider delivers it to the last station WS-E for the unloading procedure. In WS-E, the solution adopted for unloading grafted shoots is the same as the one adopted in WS-A, where pick & place operations can performed using the clips nowadays used in high-performance transplanting machines (e.g. Hu et al., 2014; Urbinati, 2015).

In the case where it becomes impossible to find a class match between roots and scions already carried, the supply system also act as a buffer. This property is achieved by predisposing each slider to host several seedlings. In this way, by adequately coordinating the sliders, it is possible to reach size matching between scions and rootstock, even if the respective incoming shoots present different diameters. In the (very) unlikely case that all the slots are hosting shoots classified as incompatible, a procedure is provided to bring

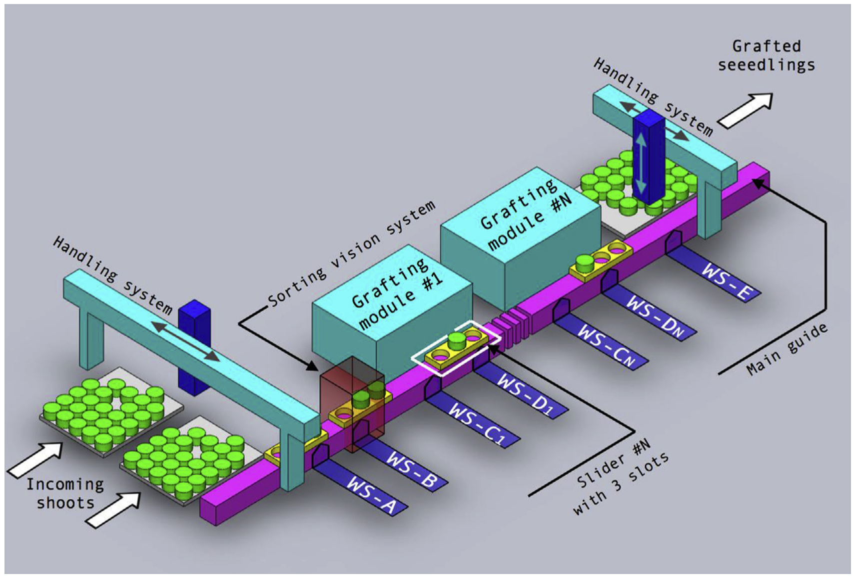

Fig. 1 — Scheme of the whole grafting machine, constituted by three main subsistems: the (1) supply system (comprising the main guide and two handling systems for incoming seedlings and leaving grafted shoots), the (2) vision-based sorting system and (3) grafting core-units. Guide areas where different tasks take place are denominated Working Stations (WS): seedlings loading area (WS-A); classification system (WS-B); scions feeding zone (WS-C); rootstock feeding zone and grafted shoots releasing area (WS-D); unloading area for grafted plants (WS-E).

back a shoot and to free up a slot that can be used in the loading area, thereby avoiding a machine stall condition.

The single rail solution, designed to pursue the structure's simplicity, forces sliders not to change their relative order so that, in the undesired case that the first slider is required in the last station WS-E, all the other sliders must be moved passing it. The essential objective of the control policy is to assign tasks to the sliders avoiding (or at least strongly limiting) this unwanted, time-consuming eventuality.

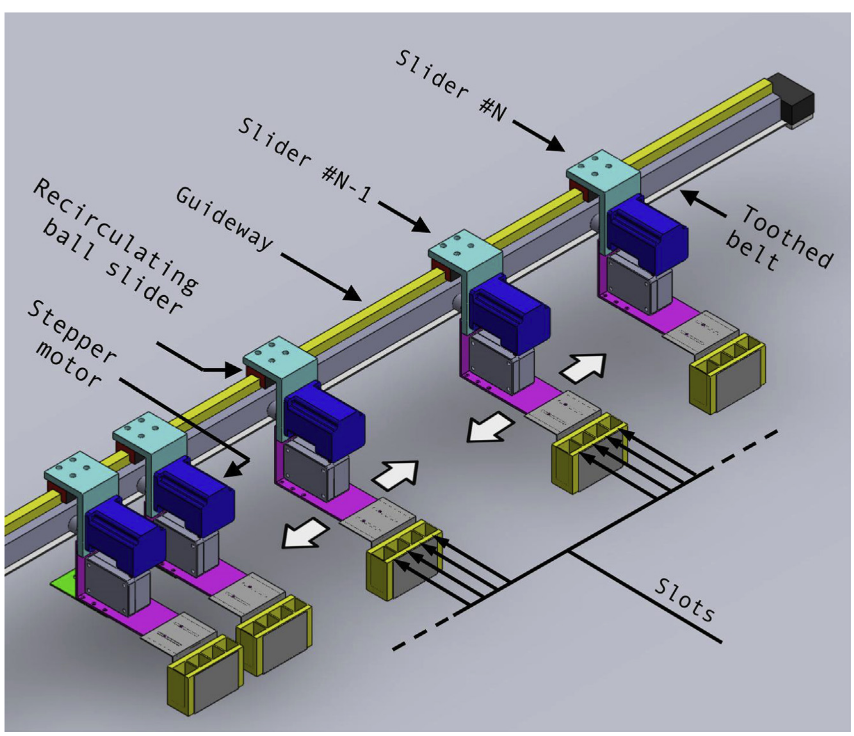

Fig. 2 — Detailed 3D design of the supply system. Each module (*slider*) is linked to the linear guideway (yellow) by a recirculating ball slider (red). A stepper motor (blue) provides the slider driving force to a pinion engaged to a fixed toothed belt (white) parallel to the guideway. A polystyrene stand with four slots (yellow) is held at the lower edge of a steel bracket (purple and grey).

2.2. The supply and sorting system

A structure of bars sustains a linear steel guideway on which several sliders shift horizontally. The driving force to the sliders is provided by an on-board stepper motor coupled with a single fixed belt, shared by all the sliders. Each driver is equipped with an encoder which controls slider position and an external proximity sensor which performs additional motion safety verifications. At the lower edge of a steel bracket, a polystyrene stand is positioned to hold seedlings. Determination of the optimal number of slots on each independent slider, and their total quantity was the object of the design optimisation process described in Sections 4 and 6. Details of the design and implementation of the single slider can be seen in Fig. 2.

Slider displacement along the guide is coordinated by a central unit, according to the request of the grafting unit and of the other machine subsystems, which manages the interaction with the handling system for incoming trays, the vision system, one or more grafting units and the outflow handling system for grafted seedlings. Target positions of each slider are assigned to the stepper motor drivers by an RS-485 serial bus, also used to read out the instantaneous position provided by the on-board encoders. An ArduinoMega 2560 (Smart Project srl, Scarmagno, Italy) microcontroller was adopted to manage the digital inputs and outputs of the handshaking signals with the grafting units, as with the two handling systems. The vision system is directly linked to the control software by using the USB communication standard, as shown in Fig. 3.

3. Supply system: control and task assignment algorithms

The overall performance of the machine depends on how efficiently and timely the sliders carry the seedlings through the working stations A-E. The upper performance boundary is obtained when the grafting units operate continuously, without any delay in supplying. This is pursued if the supply system is able to manage seedlings diameter variability (finding proper scion-rootstock couplings) while managing logistics. In fact, at any instant a WS can signal an *immediate request* (Psaraftis, 1980) to be served by a slider for loading/unloading or classification, which forces a timely rescheduling of the current slider movements. The online arrival of requests by the WS, with the need to redirect moving sliders to new destinations nearby and the consequent request for real-time knowledge of sliders position, transforms the original problem of static routing of the sliders to a dynamic problem, which is somewhat similar to the dynamic vehicle routing problem (Pillanc, Gendreau, Guéret, & Medaglia, 2013) or the taxi-dispatcher problem (Zion et al., 2014). Dynamic routing problems require making decisions very quickly, imposing a balance between reactiveness and quality of the decision. This task can be performed periodically by solving a static problem corresponding to the current state of the machine, either at fixed time intervals or whenever a new WS immediate request arises. A FIFO queue has been used to process possible concurrent received requests. During rescheduling, a slider sent to a given destination may be re-routed to another destination on the base of the new priority set of incoming request.

More generally, the problem of control and optimal coordination of multi-robot systems, composed by a group of identical robots, operating on shared or neighbouring workspaces with real-time requests, has been considered in different contexts (Durrant-Whyte, Roy, & Abbeel, 2012). Bozma and Kalalıoglu (2012) and Comba, Belforte, and Gay (2013) presented novel approaches for pick-and-place tasks performed by a team of identical robots operating on a conveyor band. In these cases, the goal was to plan and assign tasks to each robot to pick (and place in a secondary package) as many of the products moving in the workspace, as soon as they are identified and classified by an artificial vision system (Bozma & Yalcin, 2002). Zion et al. (2014) proposed a method for planning the harvesting order and the task assignment for a multi-arm robotic melon harvester. Here, a number of

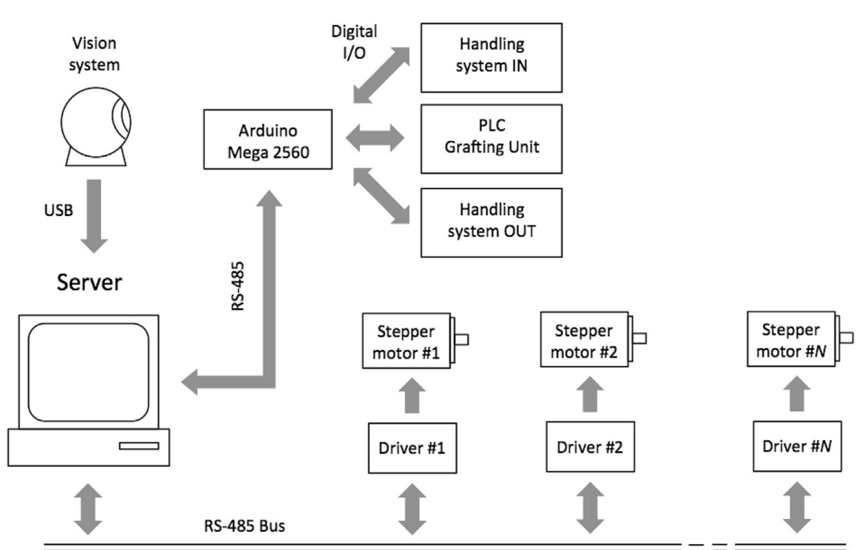

Fig. 3 – Scheme of the control hardware and communication.

Cartesian manipulators were mounted in parallel on a rectangular frame that traverses laterally across the crop bed, even if, as in this case, they do not share the same workspace. The objective was to develop a method for planning the assignment of melons to be harvested by each of a number of arms, in a collaborative way, to maximise the amount of collected fruit.

3.1. Problem formulation and optimisation

The supply system can be modelled as a discrete-event system, where the state vector is constituted by the position of the slots on the rail. Firstly, considering the guide G virtually discretised in $N_G \in Z^+$ equal length segments $g_i \in G$, $i = 1,\ldots,N_G$, each one corresponding to one slot width l_S. A set of independent sliders $P = \{p_1, \ldots, p_{N_P}\}$, $N_P \in Z^+$, are mounted on the rail. Since the same quantity $N_S \in Z^+$ of slots is housed on each slider $p_i \in P$, the holding capacity of the supply system turns out to be provided by the set of slots $S = \{s_1, \ldots, s_{N_H}\}$, with $N_H = N_P \cdot N_S$. At any time instant t_k a slider $p_i \in P$ occupies a set of N_S adjacent segments $M_{p_i}(t_k) = \{g_j, \ldots, g_{j+N_S-1}\} \subset G$, with $j \in \{1, 2, \ldots, N_G - N_S + 1\}$. With this assumption, the vector state of the system can be formally expressed as:

$$V(t_k) = [v_1(t_k), \ldots, v_{N_H}(t_k)]^T, \tag{1}$$

where $v_i(t_k) \in G$ is the (discrete) position of the slot s_i on the rail.

The method proposed here to determine the best assignment of sliders displacement on the rail is based on a greedy-type optimisation algorithm, which pursues the optimal solution of the problem through a sequence of steps. In this case, the planning of slider movement is divided in one-segment l_S long movements, making the choice that looks best at that moment.

More in detail, at each step (time t_{k+1}), all possible movement combinations $\mathbb{V}(t_{k+1})$ are generated and then the most performing one is discerned among all these feasible solutions $\mathbb{V}_F \subset \mathbb{V}$ of the problem. Starting from an initial configuration $V(t_k)$ of the sliders on the rail, the adopted strategy consists in computing a set

$$\mathbb{V}(t_{k+1}) = \left\{ \tilde{V}_j : \left\| \tilde{V}_j(t_{k+1}) - V(t_k) \right\|_\infty \le 1,\ j = 1, \ldots, n \right\} \tag{2}$$

of all possible candidate new configurations

$$\tilde{V}_j(t_{k+1}) = \left[v_{j,1}(t_{k+1}), \ldots, v_{j,N_H}(t_{k+1}) \right]^T \tag{3}$$

obtained with one-segment long movements of the set of sliders S.

This set of solutions is thinned out by considering only feasible configurations, verifying the fulfilment of all physical constraints of the system, e.g. the impossibility of sliders to be located in the same place or to swap each other on the rail. The chosen sliders displacement $V^* \in \mathbb{V}_F$ is determined using a heuristic search by minimizing a cost function $H(V(t), I(t))$, which evaluates the goodness of the configuration $V(t)$ of each slider on the basis of the particular state of the *immediate requests* (e.g. move a slider with a free slot to WS-A to receive a new seedling from the incoming tray, etc.), collected in the binary vector

$$I(t) = [r_1(t), \ldots, r_{N_T}(t)]^T \tag{4}$$

with $N_T = card(\mathbb{T})$ and $\mathbb{T}$ the set of all the tasks that the supply system can performs.

Henceforth, for simplicity, a supply system serving a sole grafting unit is considered, but the discussion can be extended to the case of multiple grafting units by adapting the set of tasks $\mathbb{T}$ that can be requested accordingly.

The computation of $H(V(t), I(t))$ mainly depends on the distances between the sliders and their temporary target positions, the five working stations A-E (positioned along the guide in $Q = \{q_1,\ldots,q_5\}$, $q_i \in G$), but also on the priority assigned to the several tasks. In detail, the cost function is composed by the linear combination of three chosen heuristics h_1, h_2, and h_3, which depend on the particular set of temporary requested tasks $I(t)$. Weighing the terms of $H(V(t), I(t))$ it is possible to take into account the priorities assigned to the various tasks $\mathbb{T}$ which, in the case of a single grafting unit, follows this heuristically determined priority list (in descending order of priority):

- displacement of a slider with a free slot in WS-D to receive a grafted seedling if the grafting module has completed a cycle;
- provide a scion to WS-C or a rootstock to WS-D if the grafting module is idle and it is also waiting for seedlings;
- if the grafting module is working, get a slider close to WS-D in order to make it ready to receive a grafted seedling at the end of the grafting procedure;
- move the slider with a grafted shoot to WS-E for unloading procedure;
- if a couple of compatible scions and rootstocks are present on the sliders, start to move them near to WS-C and WS-D respectively in order to prearrange the next grafting cycle loading phase;
- move the sliders hosting unclassified scions and/or rootstocks to WS-B in order to assign it/them to a stem diameter class;
- in case of all the slots saturation with incompatible shoots (buffering capacity saturation), move a slider to WS-A to free up a slot with the unloading procedure;
- push a slider with a free slot to WS-A to receive a new seedling from the incoming tray (scion or rootstock).

Each task $T_m \in \mathbb{T}$ is associated with a WS, positioned in $q_{T_m} \in Q$, but, obviously, several different tasks can take place in the same WS.

A proper weighing function $w(s_i,T_m)$ has also been defined to privilege some sliders s_i for a specific task T_m. For example, this is the case of WS-A that should preferably be served by the first sliders (see on the left in Fig. 2) while, with the same approach, the last WSs by sliders p_i with greater index i. Indeed, if the grafted shoot to be picked up in WS-D and delivered in WS-E was being performed by the slider p_i, the movements of all the subsequent sliders p_j, $j > i$, would be limited during this operation. Similarly, in WS-A the first sliders are favoured to receive a scion, while the last ones a rootstock, in order to obtain sliders that host seedlings correctly prearranged for the following feeding phase of the grafting module in WS-C and WS-D.

These considerations are formalised in the following three heuristics:

$$h_1\left(\widetilde{V}_j(t_{k+1}), T_m\right) = \sum_{i \in S_{T_m}} |v_{j,i}(t_{k+1}) - q_{T_m}| \cdot w(s_i, T_m) \tag{5}$$

which accounts for the sum of the distances of all the slots S_{T_m}, suitable for the task T_m, from the working station placed in $q_{T_m} \in Q$;

$$h_2\left(\widetilde{V}_j(t_{k+1}), T_m\right) = \min_{i \in S_T}(|v_{j,i}(t_{k+1}) - q_{T_m}| \cdot w(s_i, T_m)) \tag{6}$$

which identify the closest (suitable) slot for the task T_m, and then

$$h_3\left(\widetilde{V}_j(t_{k+1}), V(t_k)\right) = \frac{\|\tilde{V}_j(t_{k+1}) - V(t_k)\|_1}{N_H}. \tag{7}$$

expressed to privilege the slider configuration $\tilde{V}_j \in \mathbb{V}_F$ which requires fewer sliders movements.

Path planning of the sliders is periodically repeated whenever the sliders have almost completed a segment-long movement and/or (asynchronously) whenever the state $I(t)$ of the system is updated, as in the case of a WS new request. In order to assure the required fluency to the sliders movements, the control unit must send the new target position to the slider drivers with sufficient time advance, by allowing the blending procedure between the old and the new velocity trajectories before the current target has been reached. To speed up this task, a short queue of vector state $W = \{V^*(t_{k+1}), V^*(t_{k+2})\}$ was introduced with the aim of planning the slider's movements two steps (of length l_S) ahead compared with its current position $V(t_k)$. Each target state vector $V^*(t_j)$ is determined by the optimisation procedure on the base, as starting system status, of the previous configuration $V^*(t_{j-1})$. As described in the flowchart in Fig. 4, the control unit, in the case of the 1-step movement almost completed at time t_k, sends the motion targets collected in $V^*(t_{k+1})$ to the motor drivers and then updates the queue W by removing the employed vector state $V^*(t_{k+1})$ and inserting $V^*(t_{k+3})$. In the eventuality of new requests $I(t)$, the entire queue W should be rescheduled.

4. Vision-based sorting system

For successful grafting, seedlings need to be classified in terms of their stem diameter. However, there are also other morphological parameters, in particular the position of cotyledons node and the stems inclination that should be assessed to ensure proper operation of the machine as a whole. The grafting unit, in fact, takes seedlings in fixed positions in

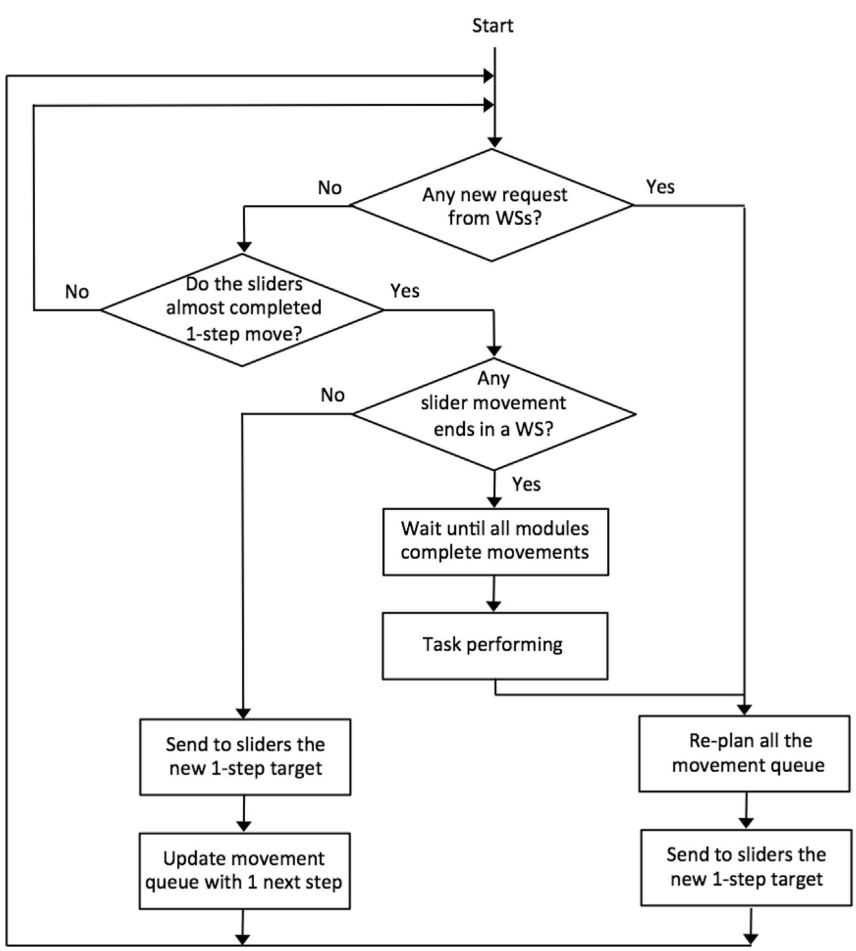

Fig. 4 – Flowchart of the control and tasks assignment algorithm.

respect to the slider slots by using its auto centring grippers which have a maximum opening of 10 mm. Seedlings too tilted may not to be gripped and scions with cotyledons which are too low would not be correctly processed. Less critical is the forward or backward seedling inclination, since a small centring device leads the stems into a proper position during gripping.

4.1. *Computer vision system*

The implemented image acquisition system consisted of a HP webcam HD 2300 digital camera (Hewlett-Packard Development Company, L.P., Houston, Texas, U.S.), with 1280 × 720 pixels resolution, coupled with a 120 × 120 × 30 mm backlighting panel (equipped with a 12 × 6 matrix of cold white LEDs), positioned at a distance of 80 mm and 40 mm from the centre of the sliders slots, respectively (Fig. 5). Backlighting produces a greater contrast between the seedling and the background than other lighting systems, with a consequent greater accuracy in stem diameter measurement (Ashraf, Kondo, & Shiigi, 2011). Furthermore, seedlings sorting is carried out only on the basis of their morphological features, hence no colour information, which would be lost with backlighting, is needed. The whole system was installed along the guide and covered, allowing sliders movement, with a plastic panel to shield external light. Acquired images were stored in TIFF format and directly processed as a task of the implemented control system.

4.2. *Image processing*

The developed algorithm consists of three main steps: (1) image pre-processing and segmentation, (2) cotyledons node detection, and (3) morphological parameters assessment (cotyledons node height, stem tilt angle and diameter).

In the first step, the acquired image was converted to grey scale format and cropped to eliminate the stems of the seedlings placed in the neighbouring slots, adopting a cropping window whose width corresponds to that of a single slot (about 35 mm). A fixed threshold was then applied to the segmentation; as steady lighting conditions allow excluding an automatic thresholding. The result is a binary image in which the value ‘0’ is assigned to the background (white pixels) whereas the seedling elements (black pixels) have value ‘1’ (Fig. 6.a). This image can be treated as a matrix, with n_r rows and n_c columns, with a direct correspondence between pixels and matrix elements.

The identification of the lowest part of the stem is the first phase of cotyledons node detection. Considering the binary image, most pixels close the bottom edge have value ‘1’ (black pixels), because they represent the slider border and/or a portion of the transplanting plug (Fig. 6.a). The initial part of the stem was found by counting the number of black pixels along the rows from the bottom edge of the image. The stem began in correspondence with row y_0 where the number of black pixels fell in a range of 30–50 pixels. This row was the starting point for stem identification, which was carried out by the iterative process described in Fig. 7. At each iteration, the left and right edges of the stem, on the i-th row, are detected from the stem midpoint of the row $i-1$ obtained at the previous step. The column indexes (x coordinates) of the stem edges and midpoint are then progressively stored in an array ($n_c \times 3$). In Fig. 6.b, the result obtained at the end of the iterative process is shown. As can be observed, the algorithm identifies the stem profile, whereas cotyledons and most leaves were not detected. Only a portion of the true leaves was still visible in the top-side of the figure, but the region around the cotyledons node was well defined. The position of the cotyledons node was determined by going along the midline of the stem from bottom up. The stem midline is practically continuous up to the cotyledons node where, owing to stem lengthening, an evident discontinuity can be observed (Fig. 6.b).

After the localisation of the cotyledons node, the required morphological features were assessed as follows. The average tilt angle α of the stem, with respect to the vertical axis, was calculated as

$$\alpha = \tan^{-1}\frac{x_c - x_0}{y_c - y_0}. \tag{8}$$

where (x_c,y_c) and (x_0,y_0) are the coordinates of the midpoints of the stem in correspondence to the cotyledons node and the stem bottom end, respectively (Fig. 6.c).

The height of the cotyledons node with respect to the plug is given by the difference of the vertical coordinates $(y_c - y_0)$ of the same points, while a procedure similar to that proposed in Ashraf et al. (2011) was adopted to determine the diameter of the stem, considering five equidistant points below the cotyledons node (Fig. 6.c).

The algorithm was tested both by preliminary trials and during the experimentation of the whole system. All seedlings were correctly sorted in terms of stem diameter and tilt angle; only in few cases (less than 4%) the position of the cotyledons node was erroneously detected. In particular, this error was due to the partial overlapping of cotyledons of a neighbouring seedling with the stem of the analysed one.

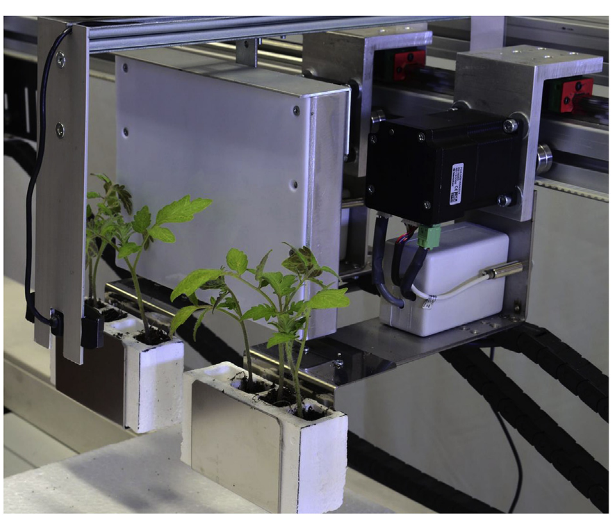

Fig. 5 – Detail of the developed vision sorting system (without the cover to shield external light): the slots that host the plants pass between the camera (on left) and the backlighting system (on right).

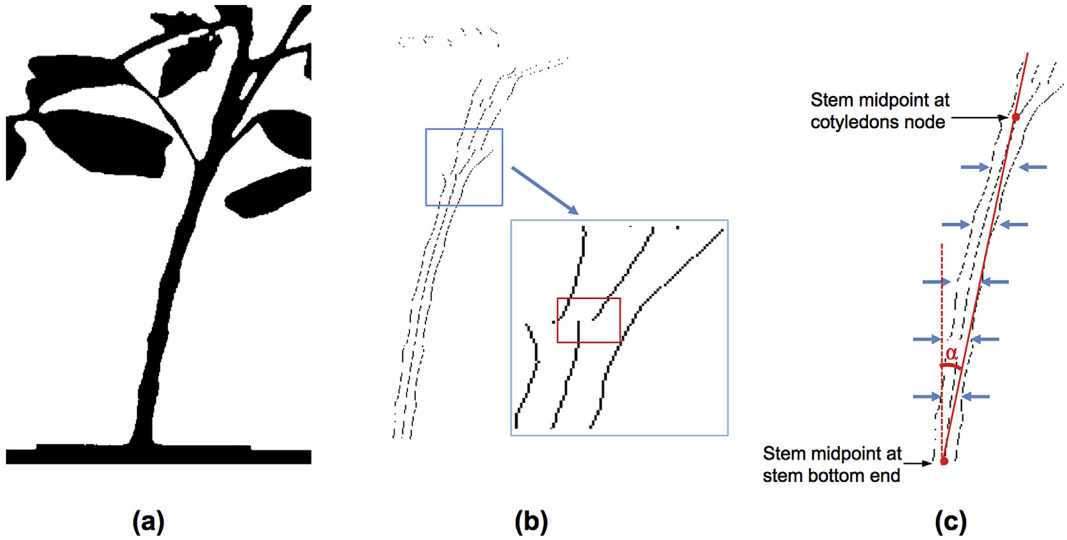

Fig. 6 – Binary image (a) obtained after segmentation; the result of stem detection algorithm (b): the discontinuity of the stem midline is evident in correspondence of the cotyledons node; determination of the morphological parameters (c): the blue arrows indicate the five points adopted for average stem diameter calculation.

5. Optimal system design

The supply system solution with a single passive rail requires to properly tune a set of supply system and control strategy parameters in order to maximise the overall machine performance, in terms of grafting and success rates, respecting movement constraints of the modules ensemble which are unable to swap each other along the rail. Moreover, the choose of the proper number N_P of sliders and the optimal quantity N_S of slots on each slider is crucial to enhance process productivity without compromising mechanical simplicity, limiting the overall rail length and the final machine cost.

The design of the supply and sorting system was achieved with the aid of a simulation framework, which allows for the performance evaluation of a broad spectrum of supply system configurations during long working sessions. Also, the effectiveness of different control strategies was investigated with the simulation tool, helping with the development of an algorithm that properly manages sliders movements.

Each component of the grafting machine was modelled separately, timing the working cycles and operations. The mean time required by the grafting unit to join a scion and a rootstock was experimentally determined timing 100 grafting cycles, which took an average time of 8.1 s to complete. The scions and rootstocks loading procedure to the grafting module (in WS-C and WS-D), constituted by the grip arm elongation, the nipper closing to hold the seedling stem and the elevation to extract the plug from the slot, was performed in 0.8 s. The same time was required to release a complete grafted plant into an empty slot in WS-D, at the end of the grafting procedure. Concerning the loading and unloading systems, 3.7 s was the time taken for a pick & place cycle for picking up a seedling from the incoming trays and then

```
0.  array[nr,3] ←0  ( nr x 3 array to store stem edges and midpoint at each iteration)

1.  find the left stem edge (x_l,0) and the right stem edge (x_r,0)
    moving along row y_0
2.  calculate stem midpoint x_0←(x_r,0-x_l,0)/2
3.  array[0]← [x_l,0, x_0, x_r,0]

4.  for i=y_0 to n_r
5.      find the left stem edge (x_l,i) moving to left from x_i-1
6.      find the right stem edge (x_r,i) moving to right from x_i-1
7.      calculate stem midpoint x_i←(x_r,i-x_l,i)/2
8.      array[i] ← [x_l,i, x_i, x_r,i]
9.  end for
```

Fig. 7 – Algorithm adopted for the stem detection; the first three steps (1,2, and 3) are referred to the search of the edges and the midpoint in the stem bottom end.

placing it onto a supply system slider (in WS-A) and finally delivering a grafted plant to the outgoing tray (from WS-E).

A first prototype with $N_P = 3$ and $N_S = 1$ was developed to investigate the dynamic behaviour of the mechanical components adopted in building the supply system. According to the discrete-event approach, the average travelling time taken by a slider to cover one l_S length segment (referred also as *step*) is required to simulate the sliders translation along the guide. Since a segment long move could be part of a longer slider total movement to reach the target position, a step could be a complete movement or the first, middle or last part of the total movement. For this task, four different cases were considered:

1. slider starts the step with a null starting velocity and stops after it has covered the l_S length segment (acceleration and deceleration);
2. slider enters the guide segment with a starting velocity and stops at the end of the step (deceleration);
3. slider shifts with constant velocity, keeps moving after the step (constant velocity);
4. slider starts the step with a null starting velocity and keeps moving after the l_S length segment (acceleration).

To determine the travelling times in these four cases, a set of experimental trials has been conducted using the pilot prototype. Each trial consisted in randomly moving the sliders along the guide for a 20-min long session, during which more than 10,000 timings where collected. This test was repeated with several maximum velocity settings, in order to also investigate the upper limit performance of the overall mechanical system, in terms of servo response and measured sliders velocity. The effect of the communication delay between the control unit and each motor driver was also decisive to this limit. In Fig. 8, it can be seen how the best velocity, during slider movement, was obtained with the maximum switching frequency of the stepper motor set to 1250 *Hz*, where sliders cover one l_S length segment in an average time of 0.061 s, which corresponds to a linear velocity of 0.41 ms^{-1}. Dynamic performances are conditioned to total allowed cost of the system. In this case, as will be discussed in the next section, a reduced cost solution was prioritised, obtaining these reference features.

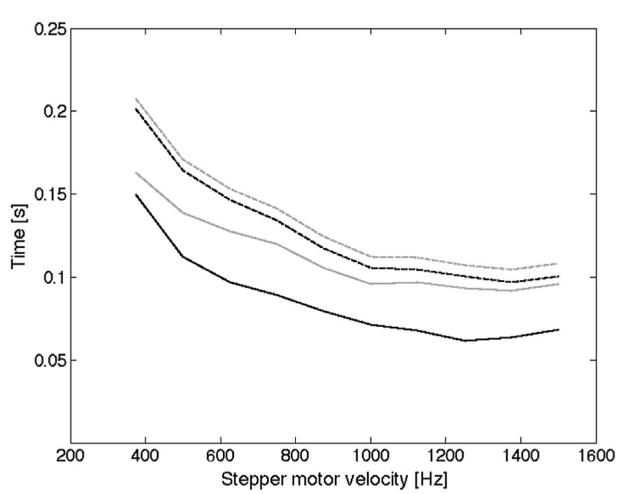

Fig. 8 – Average travelling time taken by a slider to cover one l_S length segment of the guideway, in 4 dynamic conditions: acceleration and deceleration (grey dashed), only acceleration (black dashed), only deceleration (grey solid) and constant velocity (black solid).

In this work, design optimisation was conducted for the case of a supply system serving a single grafting unit. Simulations have been performed with all the possible configurations generated by the combination of different numbers of sliders N_P (1–6) and slots N_S (1–7). The shoots on the incoming trays, both for scions and rootstock, were randomly generated using different stem diameters, and the same trays were processed by all the simulated machine configurations. All the other parameters (e.g. positions of WS A to E on the guide, control strategy, heuristic weight and parameters, etc.) were also fixed in all the simulations, ensuring that the results were comparable. Every supply system configuration has been tested with 10 repetitions of 60-min-long simulations, in order to obtain more reliable results, since the simulated process was affected by the distribution of the stem diameters of the incoming seedlings. In particular, the simulations were carried out classifying stem diameters, generated with a uniform distribution probability, in two size classes (A and B).

The developed modelling framework, including both the supply system model and the control algorithms, was implemented in Matlab® (The MathWorks™, Natick, Massachusetts, U.S.) and simulations were carried out on a 3.2 GHz Quad-Core Intel Xeon server with 8 GB of RAM memory (1066 MHz DDR3 ECC).

6. Results

Machine performance was evaluated by defining the *grafting rate*, expressed as the number of grafted shoots processed per minute. While maximising the grafting rate, the machine design should also minimise the *"unmatching" rate*, which is the number of shoots that must be returned to the incoming trays (or discarded) in the eventuality that all the sliders slots are hosting scions and rootstocks with incompatible stem sizes. An illustrative example of this procedure can be seen in the animation M1.avi, available as additional material in the online version of the paper, at time 26′:05″ and 26′:15" [min:s]. The notation adopted in the animation is explained in Fig. 9 where an annotated frame from the movie is shown. Values reported in Table 1 represent the average grafting rate of a set of 10 simulations performed with the same machine configuration and different incoming trays of seedlings. The best grafting rate was obtained with a supply system with an ensemble of $N_P = 5$ sliders, with $N_S = 4$ holding slots each. In this configuration, the grafting machine processes, on average, 5.08 shoots min^{-1} and, considering a complete grafting time of 9.7 s (including loading and unloading times in WS-C and WS-D), the supply system assures a workload of 82.12% to the grafting unit. Important role has been played by the skill of the planning system to anticipate the request of WSs, making sliders available, in the proper position, in

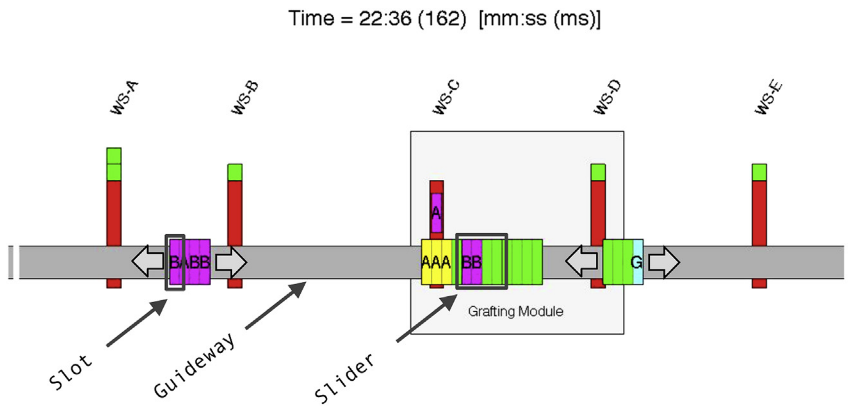

Fig. 9 – Movie frame of a simulation with the supply system made by 5 sliders and 4 slots each. The state of each slider is represented by its colour: green = free, magenta = holding a scion, yellow = holding a rootstock, cyan = holding a grafted seedling. The letter "A" or "B" represent the class diameter of the scion/rootstock held by the slider; the class diameter is assigned after the slider has passed through the vision system. Red rectangles represent the five Working Stations from A to E. A green mark on the top of the station indicates the request to be served by a slider.

advance. Examples of this feature can be seen in the movie M2.avi at times 23′:35″, 23′:45″ and 23′:55″. The presence of a performance maximum, resulting from the *grafting rate* deterioration in the case of supply systems with a (too) high a number of sliders and slots, can be pinpointed to the negative interaction phenomenon occurring between sliders that, with their increasing quantity and dimensions, interferes with each other during movements. This aspect can also be confirmed by observing the influence of the buffer size during the working sessions: in Table 1, it can be seen how better performance was obtained with a total hosting capacity N_H of the supply system ranging from 16 to 20 slots. In these configurations, the buffer turns out to be properly dimensioned since the average quantity of seedlings simultaneously hosted on the sliders was near to 50% of all available slots N_H, as reported in Table 2. Considering a constructive slot width l_S equal to 25 mm, the amount of space taken up by all five sliders was 500 mm, which is about 19% of the overall guide length, a dimension comparable with the distance between two working stations. When this threshold is exceeded, the probability of undesired interaction between sliders serving two different tasks can negatively affect the overall performance of the machine. An example of this phenomenon can be observed in the animation M3.avi at times 26′:07″ or 26′:18''. A buffer with a reduced capacity can be used more intensively, but usage greater than 60% can lead to the possible occurrence of undesired lack of stem matching between all the seedlings carried on the supply system (Table 3), a phenomenon that must be avoided.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.biosystemseng.2016.02.012.

A final prototype of supply system was implemented according to the optimal configuration found by serving a single grafting unit (Fig. 10). The geometrical dimensions of the parts of the machine lead to a 2.6-m-long guideway, with the position of the working stations, from A to E, positioned at Q = {0.5, 0.8, 1.3, 1.7, 2.1} m from the beginning of the rectilinear guide. The first rail portion of 0.5 m was dimensioned to allow hosting all the robotic sliders if needed. Since with $N_S = 4$ each slider width was 100 mm, the last slot s_{20} could also be positioned in WS-A. Similarly, at the other end of the rail, a guide section of 0.5 m was been provided after the last working station, allowing slot s_1 to reach WS-E and bringing the total rail length to 2.6 m.

To validate the results obtained by the simulator, the final prototype processed the same set of (virtual) seedlings trays

Table 1 – Average grafting rate of each group of ten simulations, expressed in grafted shoot per minute. Best performing result, obtained with 5 sliders with 4 slots each, is highlighted in grey.

		# sliders					
		1	2	3	4	5	6
# slots	1	–	1.92	1.95	3.17	3.38	4.25
	2	1.95	2.55	3.43	4.03	4.32	4.77
	3	2.40	2.63	3.82	4.42	5.05	4.62
	4	2.57	2.77	4.20	4.80	5.08	5.02
	5	2.65	2.82	4.80	5.07	4.73	4.98
	6	2.72	2.83	4.82	4.93	4.57	4.63
	7	2.75	2.87	4.60	4.65	4.58	4.55

Table 2 – Average buffer usage during the grafting process, expressed in percentage of hosted seedling with respect the overall amount of slots.

		# sliders					
		1	2	3	4	5	6
# slots	1	–	60%	74%	75%	79%	71%
	2	47%	65%	64%	67%	67%	64%
	3	57%	57%	65%	64%	56%	49%
	4	66%	58%	64%	55%	43%	34%
	5	71%	55%	57%	43%	32%	27%
	6	51%	50%	50%	33%	26%	23%
	7	52%	45%	44%	28%	24%	22%

Table 3 – Average “unmatching” rate.

		# sliders					
		1	2	3	4	5	6
# slots	1	–	1.70	1.85	0.75	0.45	0.40
	2	1.80	0.50	0.30	0.30	0.20	0.10
	3	0.85	0.25	0.20	0.10	0	0
	4	0.50	0.15	0.10	0	0	0
	5	0.35	0.05	0	0	0	0
	6	0.25	0	0	0	0	0
	7	0.20	0	0	0	0	0

used during the simulations. In particular, 10 working-sessions (one hour-long each) were carried out. Performances, together their standard deviations, are reported in Fig. 11. As can be seen, the experimental results were very close to those obtained by simulation, validating this tool for design purposes.

Concerning the vision-based sorting, the proposed system showed a high reliability in seedling classification both during preliminary tests and after its integration with the grafting machine. In spite of the complexity of the scenario, due to the presence of more seedlings on the same slider at short distances (less than 20 mm), the algorithm was not very sensitive to the presence of parts of the neighbouring plants within the camera field of view, as well as to the irregular arrangement of leaves or cotyledons. Excluding the case in which leaves were completely overlapped to the stem, the proposed method for cotyledons node detection appears to be more robust than the one adopted by Ashraf et al. (2011). The identification of the stem considering its midline was, in fact, less affected by the presence of disturbance elements with respect to counting the number of pixel with value ‘1’ within a horizontal axis.

The achieved performance in terms of image processing time, about one second for each image (acquisition and processing), was compatible with the timing of the whole process. On the whole the developed sorting system is cost-effective, simple and reliable.

Fig. 10 – Implemented grafting machine prototype in which the supply and sorting system (on left) is coupled with a single grafting unit (on right).

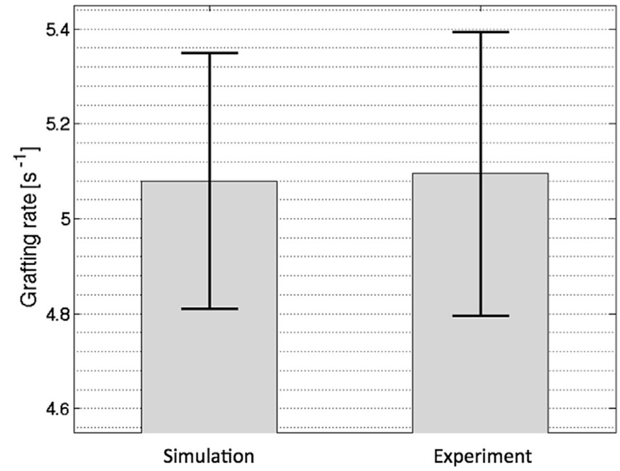

Fig. 11 – Mean grafting rate obtained by 10 simulations and by 10 experimental tests of the supply and sorting system with 5 sliders and 4 slots each (error bars indicate standard deviation).

7. Conclusions

A new and innovative concept of prototype for vegetable grafting is presented in this paper. The goal was to simplify mechanics by using an ensemble of rather simple robotic modules, ensuring performances by means of an efficient path planning control algorithm based on greedy-type optimisation. The adopted solution is modular and robust and can be adapted to different system productivity targets. Indeed, the number of grafting units have to be suitably chosen to meet the productivity level of the nursery, consequently adapting the length of the single guide supply system. In the case of multiple grafting units, the heuristic, and task, priorities could be redefined and tuned with an approach similar to the one proposed in the paper, hence the case of grafting single unit was discussed. This operation, however, does not imply expensive hardware intervention. The developed simulation framework can be profitably adopted designing the supply system also in the case of different machine configuration, e.g. in the case of multiple grafting unit, aiding the appropriate settlement of construction parameters.

The design of many parameters, as e.g. the number of robotic modules and the size of buffers, was obtained by optimisation, with the aid of a discrete-events simulator. These parameters, as others discussed in the paper concerning the structure and the complexity of the system, were determined by using extensive simulations to obtain target performances. The machine handled natural variability of the shoots diameters classifying them by an artificial vision system and then coupling them in the supplying phase.

This paper demonstrates how, under some circumstances, mechanical complexity can be reduced without compromising performances by adopting advanced control algorithms. Future developments will concern the improvement of the speed of the sliders, adopting more performing driving motors, being aware that higher velocity leads to faster movements, but also reduces the duration of the time available to elaborate planning strategies. Shorter computing time can be achieved using a real-time embedded system and directly implementing heavy computational part of the control algorithm, such as the image processing code, in a field programmable gate array (FGPA) shield.

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