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# Robot ensembles for grafting herbaceous crops

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## ABSTRACT

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.

**Keywords: Robotics, Vegetable grafting, Automation**

## 37 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 $i = 1, \dots, N_P$
$N_S$	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
$\ \cdot\ _\infty$	$\ell_\infty$ norm
$\ \cdot\ _1$	$\ell_1$ norm
$M_{p_i}(t_k)$	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 <i>immediate requests</i> of the system
$T_m$	$m$ – th task that the supply system can perform ( <i>immediate request</i> )
$\mathbb{T}$	Set of all the <i>immediate requests</i>
$N_T$	Cardinality of $\mathbb{T}$
$r_i(t_k)$	State of $i$ – th <i>immediate request</i> 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

$\alpha$	Average tilt angle of the stem
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38

39 **1. Introduction**

40

41 Grafting of vegetable seedlings is a horticultural practice that was developed in East Asia in  
 42 the early 19<sup>th</sup> century, in order to counteract huge crop losses due to infection of soil borne  
 43 diseases in intensive cultivation. The grafting process consists in attaching scions of the crop  
 44 to be reared onto more vigorous rootstocks, which absorb soil nutrients making them  
 45 available for scion's growth. Since the adoption of this technique in Europe, which began in  
 46 the 1990s, the number of grafted seedlings used in commercial vegetable production is  
 47 constantly increasing, thanks to the many derived benefits. Indeed, the adoption of robust  
 48 rootstocks enhances seedlings tolerance to abiotic stress, like thermal, humidity and water  
 49 stress in harsh environments (Schwarz et al. 2010), as well as the resistance to soil-borne  
 50 diseases and nematodes (Louws et al. 2010). The improved adaptive capabilities to  
 51 unfavourable soil and environmental conditions increase crop yield, from both quantitative  
 52 and qualitative points of view, reducing at the same time the amount of needed chemical  
 53 treatments during the growth cycle (Edelstein et.al. 1999). This last aspect complies with  
 54 recent European Community directives, which are increasingly limiting the use of pesticides  
 55 or chemical fumigants, such as methyl bromide, to counteract soil-borne pathogens. It also is  
 56 in accordance with current policies for developing organic, more sustainable practices, and  
 57 environmentally friendly agriculture.

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

64 The first semi-autonomous prototypes for grafting were developed in the 1990s (Honami,  
 65 Taira, Murase, Nishiura, & Yasukuri, 1992; Kubota, McClure, Kokalis-Burelle, Bausher, &  
 66 Roskopf, 2008; Lee et al., 2010; Oda, 1995) and were only able to perform a limited number  
 67 of the operations required to obtain a complete grafted seedling and they usually required the  
 68 supervision of at least three expert workers to feed the machine and to check the quality of  
 69 the products produced (e.g. Helper Robotech, 2015; Iseki, 2015; Kang, Han, Noh, & Choi,  
 70 2005). The selection of scion and rootstock couples, which need to be compatible in terms of

71 their diameters, is typically performed by trained operators but, in this paper, an artificial  
72 vision-based sorting system is proposed, in order to automatise all the processing phases.

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

79

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

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

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

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

104

105

## 106 2 Design

107

### 108 2.1. General description

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

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

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

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

140 slider with one free slot (Belforte & Eula, 2012). The guide areas devoted to  
 141 loading/unloading shoots to/from sliders have been denominate working station (WS).

142

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

- 144 - seedling loading area (WS-A),
- 145 - vision and classification system (WS-B),
- 146 - scions feeding zone to the first grafting unit (WS-C<sub>1</sub>),
- 147 - zone devoted to feeding the first grafting unit with rootstocks and to releasing the  
 148 grafted shoots (WS-D<sub>1</sub>),
- 149 - scions feeding zone to the  $N$ -th grafting unit (WS-C <sub>$N$</sub> ),
- 150 - zone devoted to feeding the  $N$ -th grafting unit with rootstocks and to releasing the  
 151 grafted shoots (WS-D <sub>$N$</sub> ),
- 152 - the unloading area for grafted plants (WS-E).

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

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

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



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

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

182

## 183 **2.2 The supply and sorting system**

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

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

202

## 203 **3 Supply system: control and task assignment algorithms**

204 The overall performance of the machine depends on how efficiently and timely the sliders  
205 carry the seedlings through the working stations A-E. The upper performance boundary is  
206 obtained when the grafting units operate continuously, without any delay in supplying. This  
207 is pursued if the supply system is able to manage seedlings diameter variability (finding  
208 proper scion-rootstock couplings) while managing logistics. In fact, at any instant a WS can  
209 signal an *immediate request* (Psaraftis, 1980) to be served by a slider for loading/unloading or

210 classification, which forces a timely rescheduling of the current slider movements. The online  
 211 arrival of requests by the WS, with the need to redirect moving sliders to new destinations  
 212 nearby and the consequent request for real-time knowledge of sliders position, transforms the  
 213 original problem of static routing of the sliders to a dynamic problem, which is somewhat  
 214 similar to the dynamic vehicle routing problem (Pillac et al., 2013) or the taxi-dispatcher  
 215 problem (Zion et al., 2014). Dynamic routing problems require making decisions very  
 216 quickly, imposing a balance between reactivity and quality of the decision. This task can  
 217 be performed periodically by solving a static problem corresponding to the current state of  
 218 the machine, either at fixed time intervals or whenever a new WS immediate request arises. A  
 219 FIFO queue has been used to process possible concurrent received requests. During  
 220 rescheduling, a slider sent to a given destination may be re-routed to another destination on  
 221 the base of the new priority set of incoming request.

222 More generally, the problem of control and optimal coordination of multi-robot systems,  
 223 composed by a group of identical robots, operating on shared or neighbouring workspaces  
 224 with real-time requests, has been considered in different contexts (Durrant-Whyte, Roy &  
 225 Abbeel, 2012). Comba, Belforte & Gay (2013) and Bozma & Kalaliloglu (2012) presented  
 226 novel approaches for pick-and-place tasks performed by a team of identical robots operating  
 227 on a conveyor band. In these cases, the goal was to plan and assign tasks to each robot to pick  
 228 (and place in a secondary package) as many of the products moving in the workspace, as  
 229 soon as they are identified and classified by an artificial vision system (Bozma & Yalcin,  
 230 2002). Zion et al. (2014) proposed a method for planning the harvesting order and the task  
 231 assignment for a multi-arm robotic melon harvester. Here, a number of Cartesian  
 232 manipulators were mounted in parallel on a rectangular frame that traverses laterally across  
 233 the crop bed, even if, as in this case, they do not share the same workspace. The objective  
 234 was to develop a method for planning the assignment of melons to be harvested by each of a  
 235 number of arms, in a collaborative way, to maximise the amount of collected fruit.

236  
 237

### 238 **3.1 Problem formulation and optimisation**

239 The supply system can be modelled as a discrete-event system, where the state vector is  
 240 constituted by the position of the slots on the rail. Firstly, considering the guide  $G$  virtually  
 241 discretised in  $N_G \in \mathbb{Z}^+$  equal length segments  $g_i \in G$ ,  $i = 1, \dots, N_G$ , each one corresponding  
 242 to one slot width  $l_S$ . A set of independent sliders  $P = \{p_1, \dots, p_{N_P}\}$ ,  $N_P \in \mathbb{Z}^+$ , are mounted on  
 243 the rail. Since the same quantity  $N_S \in \mathbb{Z}^+$  of slots is housed on each slider  $p_i \in P$ , the holding

244 capacity of the supply system turns out to be provided by the set of slots  $S = \{s_1, \dots, s_{N_H}\}$ ,  
 245 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  
 246 segments  $M_{p_i}(t_k) = \{g_j, \dots, g_{j+N_S-1}\} \subset G$ , with  $j \in \{1, 2, \dots, N_G - N_S + 1\}$ . With this  
 247 assumption, the vector state of the system can be formally expressed as:

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

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

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

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

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

258  
 259 of all possible candidate new configurations

$$\tilde{V}_j(t_{k+1}) = [v_{j,1}(t_{k+1}), \dots, v_{j,N_H}(t_{k+1})]^T \quad (3)$$

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

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

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

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

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

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

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

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

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

305 host seedlings correctly prearranged for the following feeding phase of the grafting module in  
 306 WS-C and WS-D.

307 These considerations are formalised in the following three heuristics:

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

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

310

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

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

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

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

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

328

## 329 **4 Vision-based sorting system**

330 For successful grafting, seedlings need to be classified in terms of their stem diameter.  
 331 However, there are also other morphological parameters, in particular the position of  
 332 cotyledons node and the stems inclination that should be assessed to ensure proper operation

333 of the machine as a whole. The grafting unit, in fact, takes seedlings in fixed positions in  
334 respect to the slider slots by using its auto centring grippers which have a maximum opening  
335 of 10 mm. Seedlings too tilted may not to be gripped and scions with cotyledons which are  
336 too low would not be correctly processed. Less critical is the forward or backward seedling  
337 inclination, since a small centring device leads the stems into a proper position during  
338 gripping.

339

#### 340 **4.1. Computer vision system**

341 The implemented image acquisition system consisted of a HP webcam HD 2300 digital  
342 camera (Hewlett-Packard Development Company, L.P., Houston, Texas, U.S.), with  
343 1280×720 pixels resolution, coupled with a 120 x 120 x 30 mm backlighting panel (equipped  
344 with a 12×6 matrix of cold white LEDs), positioned at a distance of 80 mm and 40 mm from  
345 the centre of the sliders slots, respectively (Fig.5). Backlighting produces a greater contrast  
346 between the seedling and the background than other lighting systems, with a consequent  
347 greater accuracy in stem diameter measurement (Ashraf et al., 2011). Furthermore, seedlings  
348 sorting is carried out only on the basis of their morphological features, hence no colour  
349 information, which would be lost with backlighting, is needed. The whole system was  
350 installed along the guide and covered, allowing sliders movement, with a plastic panel to  
351 shield external light. Acquired images were stored in TIFF format and directly processed as a  
352 task of the implemented control system.

353

#### 354 **4.2. Image processing**

355

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

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

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

384 After the localisation of the cotyledons node, the required morphological features were  
 385 assessed as follows. The average tilt angle  $\alpha$  of the stem, with respect to the vertical axis, was  
 386 calculated as

$$\alpha = \tan^{-1} \frac{x_c - x_0}{y_c - y_0} \quad (8)$$

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

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

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

398  
 399

## 400 **5 Optimal system design**

401

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

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

414 Each component of the grafting machine was modelled separately, timing the working cycles  
415 and operations. The mean time required by the grafting unit to join a scion and a rootstock  
416 was experimentally determined timing 100 grafting cycles, which took an average time of 8.1  
417 s to complete. The scions and rootstocks loading procedure to the grafting module (in WS-C  
418 and WS-D), constituted by the grip arm elongation, the nipper closing to hold the seedling  
419 stem and the elevation to extract the plug from the slot, was performed in 0.8 s. The same  
420 time was required to release a complete grafted plant into an empty slot in WS-D, at the end  
421 of the grafting procedure. Concerning the loading and unloading systems, 3.7 s was the time  
422 taken for a pick & place cycle for picking up a seedling from the incoming trays and then  
423 placing it onto a supply system slider (in WS-A) and finally delivering a grafted plant to the  
424 outgoing tray (from WS-E).

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

- 432 1. slider starts the step with a null starting velocity and stops after it has covered the  $l_S$   
433 length segment (acceleration and deceleration);



- 434 2. slider enters the guide segment with a starting velocity and stops at the end of the  
435 step (deceleration);
- 436 3. slider shifts with constant velocity, keeps moving after the step (constant velocity);
- 437 4. slider starts the step with a null starting velocity and keeps moving after the  $l_S$  length  
438 segment (acceleration);

439 To determine the travelling times in these four cases, a set of experimental trials has been  
440 conducted using the pilot prototype. Each trial consisted in randomly moving the sliders  
441 along the guide for a 20-min long session, during which more than 10000 timings were  
442 collected. This test was repeated with several maximum velocity settings, in order to also  
443 investigate the upper limit performance of the overall mechanical system, in terms of servo  
444 response and measured sliders velocity. The effect of the communication delay between the  
445 control unit and each motor driver was also decisive to this limit. In Fig. 8, it can be seen how  
446 the best velocity, during slider movement, was obtained with the maximum switching  
447 frequency of the stepper motor set to 1250 Hz, where sliders cover one  $l_S$  length segment in  
448 an average time of 0.061 s, which corresponds to a linear velocity of  $0.41 \text{ ms}^{-1}$ . Dynamic  
449 performances are conditioned to total allowed cost of the system. In this case, as will be  
450 discussed in the next section, a reduced cost solution was prioritised, obtaining these  
451 reference features.

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

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

468

## 469 **6 Results**

470

471 Machine performance was evaluated by defining the *grafting rate*, expressed as the number  
 472 of grafted shoots processed per minute. While maximising the grafting rate, the machine  
 473 design should also minimise the “*unmatching*” rate, which is the number of shoots that must  
 474 be returned to the incoming trays (or discarded) in the eventuality that all the sliders slots are  
 475 hosting scions and rootstocks with incompatible stem sizes. An illustrative example of this  
 476 procedure can be seen in the animation M1.avi, available as additional material in the online  
 477 version of the paper, at time 26’:05” and 26’:15” [min:s]. The notation adopted in the  
 478 animation is explained in Fig. 9 where an annotated frame from the movie is shown. Values  
 479 reported in Table 1 represent the average grafting rate of a set of 10 simulations performed  
 480 with the same machine configuration and different incoming trays of seedlings. The best  
 481 grafting rate was obtained with a supply system with an ensemble of  $N_p = 5$  sliders, with  
 482  $N_s = 4$  holding slots each. In this configuration, the grafting machine processes, on average,  
 483 5.08 shoots  $\text{min}^{-1}$  and, considering a complete grafting time of 9.7 s (including loading and  
 484 unloading times in WS-C and WS-D), the supply system assures a workload of 82.12% to the  
 485 grafting unit. Important role has been played by the skill of the planning system to anticipate  
 486 the request of WSs, making sliders available, in the proper position, in advance. Examples of  
 487 this feature can be seen in the movie M2.avi at times 23’:35”, 23’:45” and 23’:55”. The  
 488 presence of a performance maximum, resulting from the *grafting rate* deterioration in the  
 489 case of supply systems with a (too) high a number of sliders and slots, can be pinpointed to  
 490 the negative interaction phenomenon occurring between sliders that, with their increasing  
 491 quantity and dimensions, interferes with each other during movements. This aspect can also  
 492 be confirmed by observing the influence of the buffer size during the working sessions: in  
 493 Table 1, it can be seen how better performance was obtained with a total hosting capacity  $N_H$   
 494 of the supply system ranging from 16 to 20 slots. In these configurations, the buffer turns out  
 495 to be properly dimensioned since the average quantity of seedlings simultaneously hosted on  
 496 the sliders was near to 50% of all available slots  $N_H$ , as reported in Table 2. Considering a  
 497 constructive slot width  $l_s$  equal to 25 mm, the amount of space taken up by all five sliders  
 498 was 500 mm, which is about 19% of the overall guide length, a dimension comparable with  
 499 the distance between two working stations. When this threshold is exceeded, the probability  
 500 of undesired interaction between sliders serving two different tasks can negatively affect the  
 501 overall performance of the machine. An example of this phenomenon can be observed in the  
 502 animation M3.avi at times 26’:07” or 26’:18”. A buffer with a reduced capacity can be used

503 more intensively, but usage greater than 60% can lead to the possible occurrence of undesired  
504 lack of stem matching between all the seedlings carried on the supply system (Table 3), a  
505 phenomenon that must be avoided.

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

515 To validate the results obtained by the simulator, the final prototype processed the same set  
516 of (virtual) seedlings trays used during the simulations. In particular, 10 working-sessions  
517 (one hour-long each) were carried out. Performances, together their standard deviations, are  
518 reported in Fig.11. As can be seen, the experimental results were very close to those obtained  
519 by simulation, validating this tool for design purposes.

520 Concerning the vision-based sorting, the proposed system showed a high reliability in  
521 seedling classification both during preliminary tests and after its integration with the grafting  
522 machine. In spite of the complexity of the scenario, due to the presence of more seedlings on  
523 the same slider at short distances (less than 20 mm), the algorithm was not very sensitive to  
524 the presence of parts of the neighbouring plants within the camera field of view, as well as to  
525 the irregular arrangement of leaves or cotyledons. Excluding the case in which leaves were  
526 completely overlapped to the stem, the proposed method for cotyledons node detection  
527 appears to be more robust than the one adopted by Ashraf et al. (2011). The identification of  
528 the stem considering its midline was, in fact, less affected by the presence of disturbance  
529 elements with respect to counting the number of pixel with value '1' within a horizontal axis.  
530 The achieved performance in terms of image processing time, about one second for each  
531 image (acquisition and processing), was compatible with the timing of the whole process. On  
532 the whole the developed sorting system is cost-effective, simple and reliable.

533

## 534 **7 Conclusions**

535

536 A new and innovative concept of prototype for vegetable grafting is presented in this paper.  
537 The goal was to simplify mechanics by using an ensemble of rather simple robotic modules,

538 ensuring performances by means of an efficient path planning control algorithm based on  
539 greedy-type optimisation. The adopted solution is modular and robust and can be adapted to  
540 different system productivity targets. Indeed, the number of grafting units have to be suitably  
541 chosen to meet the productivity level of the nursery, consequently adapting the length of the  
542 single guide supply system. In the case of multiple grafting units, the heuristic, and task,  
543 priorities could be redefined and tuned with an approach similar to the one proposed in the  
544 paper, hence the case of grafting single unit was discussed. This operation, however, does not  
545 imply expensive hardware intervention. The developed simulation framework can be  
546 profitably adopted designing the supply system also in the case of different machine  
547 configuration, e.g. in the case of multiple grafting unit, aiding the appropriate settlement of  
548 construction parameters.

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

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

563

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565

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