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## Route planning for orchard operations

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# ROUTE PLANNING FOR ORCHARD OPERATIONS

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## Abstract

Orchard operations are considered a promising area for the implementation of robotic systems because of the inherent structured operational environment that arises from time-independent spatial tree configurations. In this paper, a route planning approach is developed and tested using a deterministic behaviour robot (named AMS - autonomous mechanisation system). The core of the planning method is the generation of routing plans for intra- and inter-row orchard operations, based on the adaptation of an optimal area coverage method developed for arable farming operations (B-patterns). Experiments have verified that operational efficiencies can be improved significantly compared with the conventional, non-optimised method of executing orchard operations. Specifically, the experimental results showed that the non-working time reduction ranged between 10.7% and 32.4% and that the reduction in the non-working distance ranged between 17.5% and 40.2% resulting to savings in the total travelled distance ranged between 2.2% and 6.4%.

**Keywords:** Operations management; autonomous vehicle; mission planning;

## 30 **1. INTRODUCTION**

31 Orchard operations are considered a promising area for the implementation of robotic systems  
32 because of the inherent structured operational environment that arises from time-independent  
33 spatial tree configurations. Trees have well-defined locations, and consequently, the inter- and  
34 intra-row distances are time-independent enough that route planning doesn't need to be performed  
35 every time the robot visits the block but only when its configuration changes. Based on these  
36 operational features of orchards, a number of dedicated robotic systems have been developed and  
37 prototyped. Selective examples include robots for cherry harvesting (Tanigaki et al., 2008) and  
38 apple harvesting (De-An et al., 2011). A number of navigation technologies for vehicles operating  
39 in orchards have been developed in parallel to these efforts; examples of early attempts include  
40 guidance systems based on cables (Tosaki et al., 1996), using physical contact sensors (Yekutieli  
41 and Pegna, 2002), using ultrasonic sensors combined with DGPS (Iida and Burks, 2002), and  
42 using machine vision and laser radar (Tsubota et al., 2004; Subramanian et al., 2006; Barawid Jr  
43 et al., 2007; Subramanian et al., 2009). Furthermore, navigation methods from row crop systems  
44 could be efficiently applied in orchards. These include machine vision, laser scanner, and  
45 stereovision approaches (Rovira-Mas et al., 2005; Kise et al., 2005; Hiremath et al., 2014a;  
46 Hiremath et al., 2014a). The aforementioned sensing technologies are considered an integrated  
47 part of the system combined with real time path planning modules for the case of robotic systems.  
48 These include methods that have been developed specifically for orchards (e.g., Linker and Blass,  
49 2008) or general grid-based path planning approaches from research into off-road robotics (e.g.,  
50 Ferguson and Stentz, 2006).

51 In this paper, a route planning approach for orchard operations is developed and tested using a  
52 deterministic behaviour robot. The core of the planning method is the generation of routing plans

53 for intra- and inter-row orchard operations, based on the adaptation of an optimal area coverage  
54 method developed for arable farming operations (B-patterns).

## 55 **2. MATERIALS AND METHODS**

### 56 **2.1 B-PATTERNS IN ARABLE FARMING**

57 *B-patterns* were introduced by Bochtis (2008) and are defined as “*algorithmically-computed*  
58 *sequences of field-work tracks completely covering an area and that do not follow any pre-*  
59 *determined standard motif, but in contrast, are a result of an optimization process under one or*  
60 *more selected criteria*” (Bochtis et al, 2013). The aforementioned optimisation process of finding  
61 the optimal traversal sequence of the fieldwork tracks is based on finding the shortest tour (or  
62 tours, in the case of operations constrained by material carrying capacity of the machine) in an  
63 weighted graph. In the case presented here, the optimisation criterion minimises the total non-  
64 working travelled distance by the robotic vehicle while executing an orchard operation.

65 The general optimisation problem underlying the generation of B-patterns is finding the optimal  
66 permutation (Bochtis et al, 2013):

$$67 \quad \sigma^* = \underset{\sigma}{\operatorname{argmin}} \left[ c_{0,p^{-1}(1)} + \sum_{i=1}^{|T|} c_{p^{-1}(i+1),p^{-1}(i)} + c_{p^{-1}(|T|),f} \right]$$

68 where  $T = \{1, 2, 3, \dots\}$  is the ordered set of the field-work tracks that cover a field area (or  
69 equivalently, in the presented case, the tracks required for the complete execution of an orchard  
70 operation),  $\sigma = \langle p^{-1}(1), p^{-1}(2), \dots, p^{-1}(|T|) \rangle$  is a permutation ( $\sigma^*$  the optimal one) of the inverse  
71 function of the bijection  $p(\cdot) : T \rightarrow T$ , which for any track  $i \in T$ , returns its order in the track  
72 traversal sequence in which the agricultural vehicle executes the operation,  $c_{0,p^{-1}(1)}$  is the cost for

73 the agricultural vehicle to move from the entry point (of the field or the orchard) to the first track  
 74 in the traversal sequence,  $c_{p^{-1}(|T|),f}$  is the cost for the vehicle to move from the end of the last  
 75 track in the traversal sequence to the exit point, and  $c_{p^{-1}(i+1),p^{-1}(i)}$  is the cost for moving between  
 76 tracks  $p^{-1}(i+1)$  and  $p^{-1}(i)$ . In this case, the cost corresponds to the non-working travelled  
 77 distance for moving from one track to a subsequent one.

78 It has been proven that the B-patterns generation problem can be cast as a vehicle routing  
 79 problem (VRP); consequently, any algorithmic procedure developed to solve the VRP can be  
 80 employed in the B-patterns generation problem (*cf.* Bochtis and Sørensen (2009) for an extensive  
 81 presentation of casting different types of field area operations to different instances of the VRP).

82 To generate the optimisation problem graph, the approach introduced by Bochtis et al. (2009) for  
 83 mission planning on the same robotic platform was implemented in this work. In this approach,  
 84 two nodes represent each track, one for each track ending. To implement a solver for the  
 85 corresponding VRP, the matrix containing the connection cost between any nodes of the graph  
 86 must be derived. Bochtis et al. (2009) showed that in the case of representation of a track using  
 87 two nodes, this matrix is composed of  $|T|^2$  inter-row  $2 \times 2$  matrices and is given by

$$88 \quad \mathbf{A} = \begin{bmatrix} \mathbf{O} & \mathbf{A}_{12} & \cdots & \mathbf{A}_{|T|n} \\ \mathbf{A}_{21} & \ddots & & \\ \vdots & & \ddots & \\ \mathbf{A}_{|T|1} & \cdots & \cdots & \mathbf{O} \end{bmatrix}$$

89 where  $\mathbf{O}$  is the zero  $2 \times 2$  matrix and  $\mathbf{A}_{ij}$  is the a matrix that is defined by

$$90 \quad \mathbf{A}_{ij} = \begin{bmatrix} c_{ij}^u & M \\ M & c_{ij}^l \end{bmatrix}, \quad i, j \in T$$

91 where  $M$  is a relatively (to the arc weight values in the problem) large number and is assigned as  
92 the cost for non-permitted connections and  $c_{ij}^u$ ,  $c_{ij}^l$  are the costs for the connection between  
93 tracks  $i$  and  $j$  from the upper and lower headland, respectively. The cost that is assigned to a  
94 permitted connection of a pair of nodes represents the length of the shortest headland turn  
95 between the corresponding tracks to the nodes. In general, this length (in an obstacle-free space)  
96 is a function of the starting and ending points of the turn (i.e., on the same headland ending points  
97 of the tracks that are connected), the turning radius of the vehicle, and the direction of movement  
98 on the track from where the turn is initiated:  $\Lambda(i, j) \mapsto P(x_i, y_i, x_j, y_j, r_{\min}, d)$ . This can be  
99 produced, in principle, by implementing any path-planning algorithm. In the presented case, to  
100 calculate the lengths of these headland turns, the Dubins' Theorem and the Reeds-Shepp Theorem  
101 for non-holonomic systems have been implemented to geometrically define the most common  
102 headland turns of an Ackerman-steering based agricultural vehicle, i.e., the pi-turn ( $\Pi$ -turn), the  
103 omega-turn ( $\Omega$ -turn), and the tau-turn (Tau-turn) (Bochtis and Vougioukas, 2008). In the simple  
104 case of rectangular fields, which is the case for the experimental orchards presented in this paper,  
105 the turning length is a function of the distance  $s(i, j)$  between the two connected tracks  $i, j \in T$   
106 and the relation between this distance and the minimum turning radius of the vehicle.  
107 Specifically,

$$108 \quad \Lambda(i, j) = \Lambda(s(i, j)) = \begin{cases} X(s(i, j)), & s(i, j) < 2r_{\min}, \quad X \in \{\text{Tau}, \Omega\} \\ \Pi(s(i, j)), & s(i, j) \geq 2r_{\min} \end{cases}$$

109 In the case of area coverage field operations, the distance  $s(i, j)$  is a multiple of the machine's  
110 operating width,  $w$ , e.g.,  $s(i, j) = |i - j|w$ . However, in the case of orchard operations, this does  
111 not hold true.

112 The goal of the next paragraphs is to determine how the function  $s(i, j)$  is formulated for  
113 different types of orchard operations and how, based on this function, the cost matrix  
114 corresponding to the operation VRP is created.

115 It is worth noting that, depending on the orchard spatial configuration (i.e., number and length of  
116 rows, etc.), there are cases where to visit all tracks the robot might need to drive on some tracks  
117 more than once even without working there (e.g., the mower is lifted or the sprayer is turned off).  
118 In the presented approach, due to the VRP underlying methodology, it is assumed that each track  
119 is visited exactly once (when it is worked) and all interconnections (between rows and between a  
120 row and the entry-exit points of the orchard) take place by travelling on the headland area of the  
121 orchard.

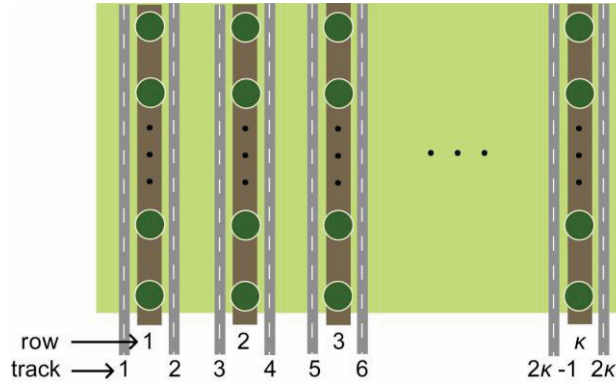
## 122 **2.2 MODELLING OF B-PATTERNS IN ORCHARD OPERATIONS**

123 In the following, the term “track” refers to the trip that the machine travels while operating that  
124 starts at one end of the orchard and terminates at its opposite end, the term “row” refers to a  
125 cluster of trees to which the machine operates parallel, and the term “*corridor*” refers to the intra-  
126 row space. Two types of operations categorise orchard operations: inter-row operations (e.g.,  
127 grass mowing in the corridors and spraying using a mist blower for pest control) and intra-row  
128 operations (e.g., mechanical weeding, spraying using nozzle sprayers).

### 129 *2.2.1 Intra-Row Operations*

130 During intra-row operations, the machine performs two trips per a row of trees (one trip for each  
131 side of the row, as shown in Figure 1). Consequently, if  $\kappa$  denotes the number of rows, the  
132 machine has to traverse a total of  $2\kappa$  tracks ( $|T| = 2\kappa$ ) to complete the operation.





133

134

**Figure 1. The derived tracks for intra-row orchard operations.**

135

One of the orchard's headlands is arbitrarily called the "upper" headland, and the other is called

136

the "lower" headland. The  $2 \times \kappa$  matrix  $\mathbf{U}_R$  is defined by the elements  $u_R(1, i)$  and  $u_R(2, i)$

137

where  $i = 1, \dots, \kappa$ . They represent the x- and y-coordinates, respectively, of the location of the last

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tree of row  $i$  on the upper headland. Similarly, a  $2 \times \kappa$  matrix  $\mathbf{L}_R$  is defined that corresponds to

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the lower headland. It should be noted that the above-mentioned matrices are inputs of the routing

140

problem with elements (coordinates of trees) derived from GPS measurements. The  $2 \times 2\kappa$

141

matrices  $\mathbf{U}_T$  and  $\mathbf{L}_T$  correspond to  $\mathbf{U}_R$  and  $\mathbf{L}_R$  and are defined with the x- and y-coordinates of the

142

locations of the tracks' ends at the upper and lower headlands, respectively. The elements of  $\mathbf{U}_T$

143

(and equivalently of the matrix  $\mathbf{L}_T$ ) can be derived using the following expression:

144

$$u_T(n, i) = u_R\left(n, \frac{i + \text{mod}(i, 2)}{2}\right) + \mu(-1)^i [\text{mod}(n, 2) \sin \theta + \text{mod}(n-1, 2) \cos \theta]$$

145

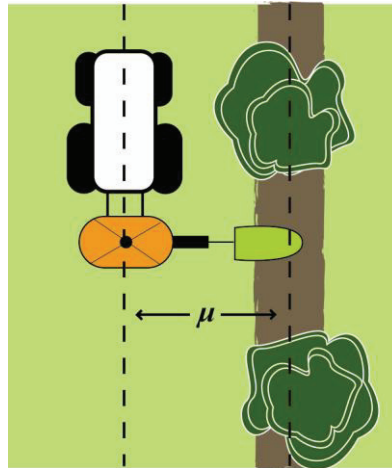
where  $i \in \{1, \dots, 2\kappa\}$ ,  $n \in \{1, 2\}$ ,  $\mu$  is the distance between the row in which the machine operates

146

and the centre line of the transverse plane to the tractor (Figure 2), and  $\theta$  is the inclination of the

147

row line.



148

149

**Figure 2. Vehicle positioning in intra-row operations**

150

151 The distance between the two tracks  $i$  and  $j$  is thus:

$$152 \quad s_u(i, j) = \left( (u_T(1, i) - u_T(1, j))^2 + (u_T(2, i) - u_T(2, j))^2 \right)^{\frac{1}{2}}$$

153 One-way oriented implements carry out intra-row operations. The specific placement of the

154 implement does not allow for transitions between specific track sequences. For example, Figure

155 3a shows that if the machine (carrying the implement on its right side) is currently working while

156 moving on track  $j$ , the next tracks on which it can move are tracks  $j-1, j+1, j+3, \dots$ , but it cannot

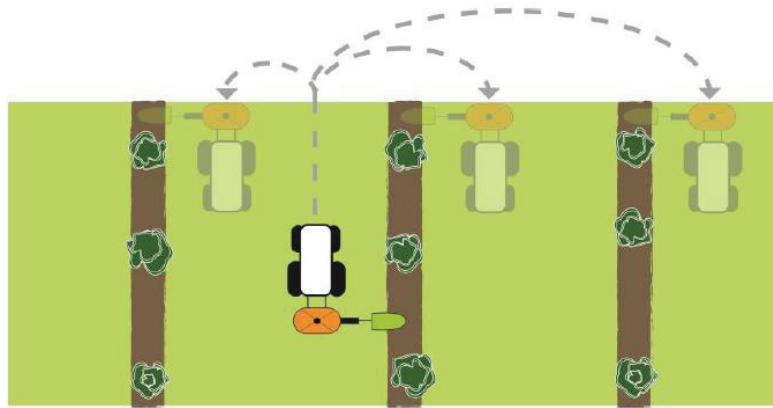
157 move on tracks  $j-2, j+2, \dots$ . In the latter case, the implement and the row to be worked would be

158 bilaterally located to the machine (Figure 3b). In general, the allowed transitions between tracks

159 are either from tracks of even parity to tracks of odd parity, or the opposite. In contrast,

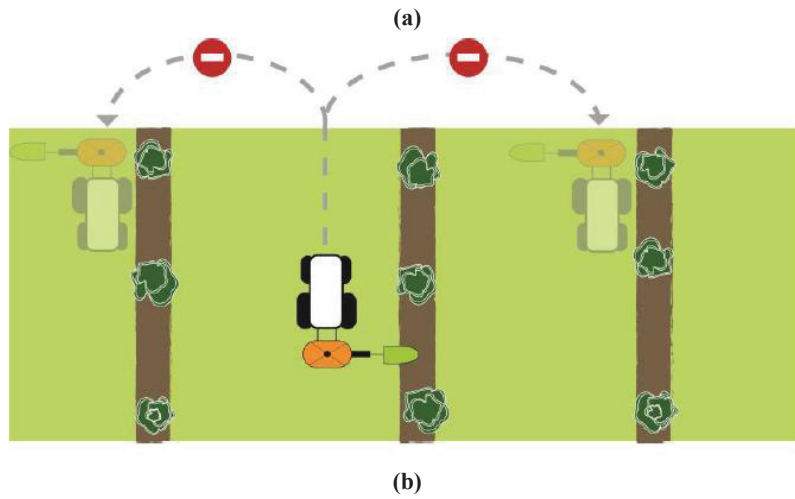
160 transitions between tracks of identical parity are not allowed. Consequently, the transition

161 between tracks  $i$  and  $j$  is allowed only if the condition  $\text{mod}(|i - j|, 2) = 1$  holds true.



162

163



164

165

166

**Figure 3 – Disallowed transitions for a robot carrying a one-way oriented implement.**

167 Based on that, the elements of the matrix  $\mathbf{A}_{ij}$  can be written as

168 
$$c_{ij}'' = \Lambda(s''(i, j)) \cdot \text{mod}(|i - j|, 2) + \text{mod}(1 + |i - j|, 2) \cdot M$$

169 When  $i$  and  $j$  are of identical parity, the term  $\text{mod}(1 + |i - j|, 2)$  equals 1, and the term

170  $\text{mod}(|i - j|, 2)$  equals 0. Consequently, the transition cost is equivalent to  $M$ , whereas in the

171 opposite case, the values of the previous terms are reversed and the matrix element corresponds

172 with the actual distance for turning between the two tracks.

173 *2.2.2 Inter-Row Orchard operations*

174 For simplicity reasons, the presentation of the method is limited to the case in which the inter-row  
 175 distances between any pair of adjacent rows are identical. Modelling inter-row operations can be  
 176 considered an extension of B-patterns implementation in numerous sub-fields (or neighbouring  
 177 fields) (Bochtis and Vougioukas, 2008). Following this approach, each corridor can be considered  
 178 a distinctive sub-area of the total area that must be covered.

179 Let  $\nu$  denote the number of field work tracks required for covering an internal corridor area. The  
 180 number of distinctive (virtual) fields is equal to  $\kappa+1$ , where  $\kappa-1$  fields correspond to corridors and  
 181 the other two boundary fields correspond to the outer parts of the first and last tree rows. Let  $T_1$   
 182 and  $T_{\kappa+1}$  denote the track sets of the boundary sub-field areas of the orchard, and let  
 183  $T_i, i = 2, \dots, \kappa$  denote the track sets of the field corresponding to the  $\kappa-1$  orchard corridors (in  
 184 which  $|T_2| = |T_3| = \dots = |T_\kappa| = \nu$ ). The union of all tracks provides the track set of the field that  
 185 corresponds to the total orchard area that must be worked:

$$186 \quad T = \Delta_1 \cup \Delta_2 \cup \dots \cup \Delta_{\kappa+1}$$

187 where

$$188 \quad \Delta_i = \left\{ \sum_{j=1}^{i-1} |T_j| + 1, \sum_{j=1}^{i-1} |T_j| + 2, \dots, \sum_{n=j}^{i-1} |T_j| + |T_j| \right\}, \quad i = 1, \dots, \kappa + 1$$

189 Considering a “virtual” tree row indexed as row “0”, a sub-field corresponds to each tree row  
 190 (e.g., the 0 row corresponds to sub-field 1). For any element  $i$  of set  $T$ , the number of the tree row  
 191  $\delta(i)$  to which track  $i$  belongs can be conversely derived using the following function:

$$192 \quad \delta(i) = \left\lfloor \frac{i-1-|T_1|}{\nu} \right\rfloor + 1$$

193 The distance  $D_{a \rightarrow b}$  between the corresponding tree rows  $a$  and  $b$  to which tracks  $i$  and  $j$  belong is  
 194 given by

$$195 \quad D_{a \rightarrow b}^u = D_{\delta(i) \rightarrow \delta(j)}^u = \begin{cases} \left( (u_R(1, \delta(i)) - u_R(1, \delta(j)))^2 + (u_R(2, \delta(i)) - u_R(2, \delta(j)))^2 \right)^{\frac{1}{2}}, & \delta(i), \delta(j) \neq 0 \\ D_{\delta(1) \rightarrow \delta(j)}^u + \mu + w(|T_1| - 1), & \delta(i) = 0, \delta(j) \neq 0 \\ 0, & \delta(i) = 0, \delta(j) = 0 \end{cases}$$

196 The relative position of track  $i$  in the specific sub-field is given by

$$197 \quad i^* = \begin{cases} i & i \leq |T_1| \\ i - [(\delta(i) - 1)v + |T_1|] & i > |T_1| \end{cases}$$

198 while the track distance relative to its associated tree row is given by

$$199 \quad v(i) = \begin{cases} -(\mu + w \cdot [|T_1| - i^*]) & i \leq |T_1| \\ \mu + w \cdot [i^* - 1] & i > |T_1| \end{cases}$$

200 To estimate the distance between the relative positions of tracks  $i$  and  $j$ , the previous distance  
 201 must be added to or subtracted from the distance of their corresponding tree rows. Consequently,  
 202 the distance between any tracks  $i, j \in T$  is given by

$$203 \quad s(i, j) = \begin{cases} D_{\delta(i) \rightarrow \delta(j)} + \frac{\delta(i) - \delta(j)}{|\delta(i) - \delta(j)|} \{v(i) - v(j)\} & , \delta(i) \neq \delta(j) \\ |v(i) - v(j)| & , \delta(i) = \delta(j) \end{cases}$$

204 The cost for transitioning the machine between these two tracks is given again by  $\Lambda(s(i, j))$

### 205 **2.3 THE ROBOTIC PLATFORM**

206 For testing and validating purposes a deterministic behaviour field robot was implemented. The  
 207 field robot AMS (autonomous mechanisation system) uses a modified conventional 20 kW tractor

208 (Hakotrac 3000, Hako-Werke GmbH, Bad Oldesloe, Germany) (Figure 4). The robot was built  
209 using the deterministic behaviour approach, wherein the mission (i.e., the route and the sequence  
210 of tasks) is planned in advance of the actual autonomous execution of the operation. The machine  
211 control system consists of a user interface that includes the mission definition, the high level  
212 control, and the low level control. It is based on the MobotWare system developed at Denmark's  
213 Technical University (Beck et al., 2010). The control system software for a task specific to a  
214 carried implement consists of a number of modules that include the projection of the GNSS  
215 measured position on the ground level, the filtering and temporal prediction of the position, the  
216 coordinate transformation of the implement reference point, the waypoint following, and the  
217 transverse and longitudinal control (depending on the operation) (Griepentrog et al., 2013).

218 The mission plan is defined in an XML formatted file (eXtensible Markup Language - IEEE  
219 Standard 1484.11.3-2005) (see next Section). The XML file is uploaded to the autonomous  
220 vehicle through the user interface. Mission files could be edited using an ASCII text file editor. A  
221 notebook computer communicates with the on-board robot computer through an Internet browser  
222 via a wireless local area network (WLAN). It is also used to display the graphical user interface  
223 for the navigation software and to upload the mission files.



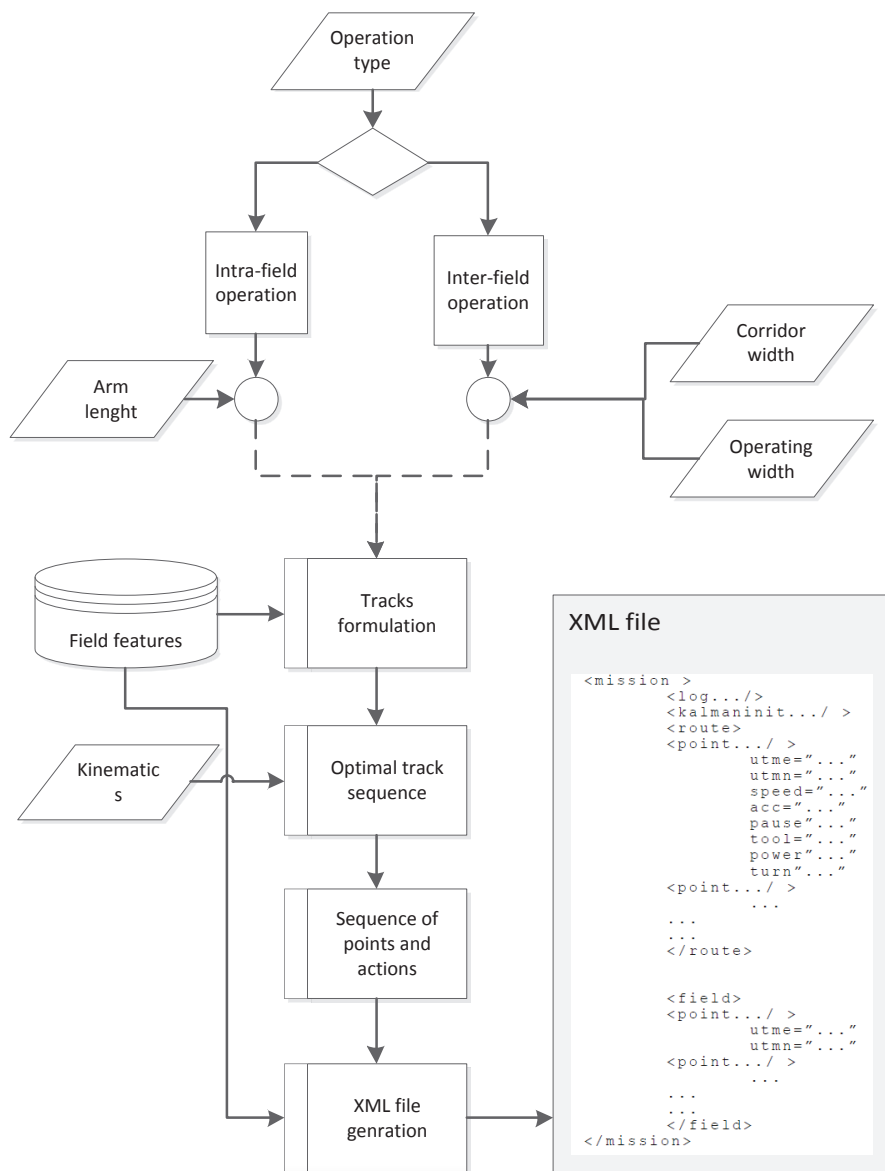
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**Figure 4. The AMS field robot.**

225 **2.4 THE MISSION PLANNING SYSTEM**

226 A complete mission plan for the autonomous vehicle was developed that includes the generation  
227 of the sequence of way-points, the actions that must be taken at each way point, and the  
228 operational status and the corresponding parameters while moving between subsequent way-  
229 points (Figure 5). The path is defined as a sequence of waypoints connected via either straight-  
230 line segments or predefined turning routine templates (e.g.,  $\Omega$ -turn and Tau-turn).

231 The first tags of the XML file relate to the mission initialisation. This includes defining the data  
232 to be logged in this mission (<log>) and how the Kalman filter should be initialised  
233 (<kalmaninit>). The latter is a standard path tracker that minimises the cross-track error in the  
234 connections between the waypoints. The waypoints are within the route tag described by a  
235 number of attributes that include its coordinates (in the Universal Transverse Mercator (UTM)  
236 coordinate system format), the speed and acceleration for driving to a particular waypoint from  
237 the preceding waypoint, and the actions that should be taken at that point, such as a potential stop  
238 at the waypoint (e.g. to adjust the carried implement), the raising or the lowering of the carried  
239 implement, the starting or stopping of the PTO (power take-off) shaft, and the predefined turning  
240 routine that should be executed (if a turn has to be performed) for connecting the current and the  
241 next route waypoint. Finally, the tag <field> provides the field polygon points that define the  
242 boundary within which the motion of the vehicle is restricted.



243

244

Figure 5. The mission planner architecture

### 245 3. EXPERIMENTAL RESULTS

246 A number of orchard operation examples were performed and are presented to demonstrate the  
 247 above-mentioned route planning method and mission planning system. The experimental orchard  
 248 is located the KU-LIFE Taastrup campus, Denmark [55° 40' 08.57" N, 12° 18' 16.47" E] and  
 249 consists of 8 tree rows, each with an average length of 133.5 m and an inter-row distance equal to



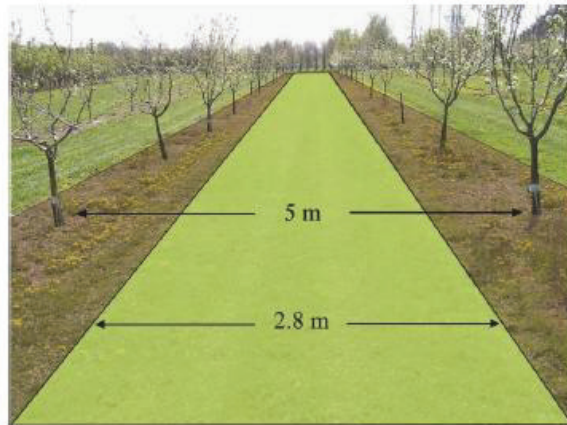
250 5 m (Figure 6). For all of the executed operations, the entry and exit points were both located in  
251 the southeast corner of the orchard (the entry and exit nodes in the graph are coincident).



252

253

(a)



254

(b)

255

256 **Figure 6. Part of the experimental orchard (a); the mowing area (green) and the weed spraying area (brown) (b).**

257 The operations performed were a) grass cutting in the corridors and b) weed spraying a width of  
258 1.1 m in each side of a row. All of the operations were executed twice, once by implementing the  
259 conventional track sequence, in which the vehicle follows a continuous pattern (i.e., the  
260 consecutive tracks covered by the machine are adjacent), and once by implementing the  
261 optimised track sequence (B-patterns) included in the mission planner. The comparison of the

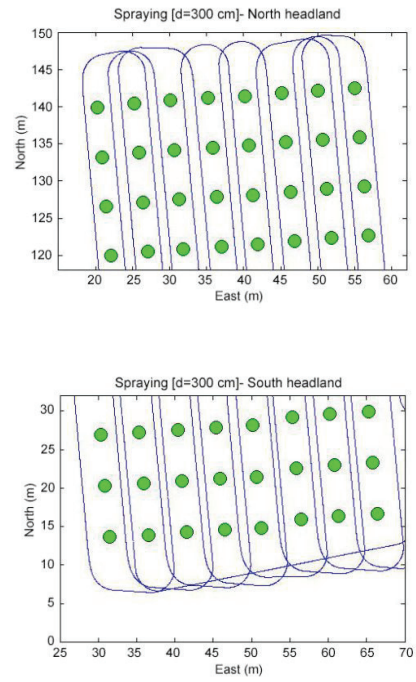
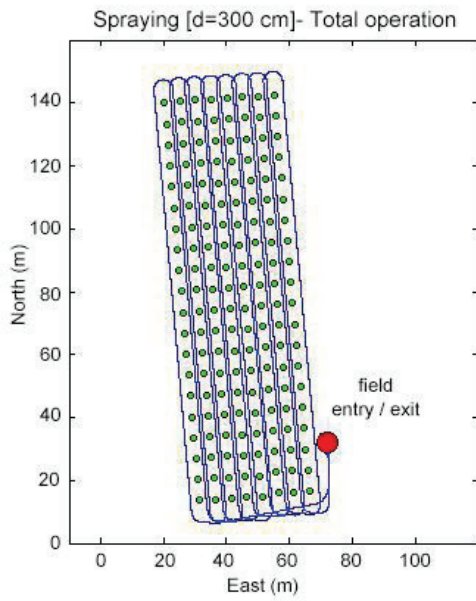
262 operational elements between the two cases (conventional vs. optimal) is presented in Table 1.  
263 Although the optimization criterion is the non-working travelled distance, a side effect of the  
264 reduction of the non-working distance is the reduction of the non-working operation time.  
265 Therefore, it seemed appropriate to include also time-specific results in Table 1. However, the  
266 non-working time is a relative measure of performance of the route planning method since it is  
267 dependent on the speed that headland turns are performed which varies between different  
268 vehicles, in the case of field robots, or different operators, in the case of conventional machines.  
269 Thus, the presented results on non-working time should be seen as indicative in terms of the  
270 potential savings of the route planning method since they are case depended in terms of the  
271 implemented vehicle.

### 272 **3.1 WEED SPRAYING**

273 A one-way oriented implement was adjusted on the right side of the autonomous tractor. The  
274 telescopic arm allowed for variable values of distance  $\mu$ . Five weed spraying operations were  
275 performed using distances ( $\mu$ ) of 180 cm, 200 cm, 250 cm, 280 cm, and 300 cm. Selectively, the  
276 optimal planned operations for arm lengths of 300 and 200 cm are depicted in Figures 7a and 7b,  
277 respectively.

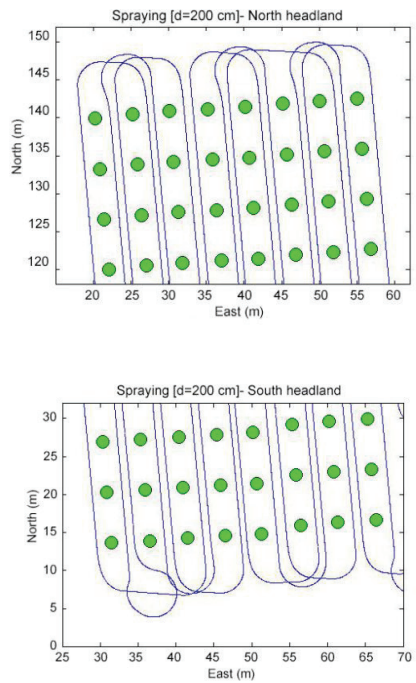
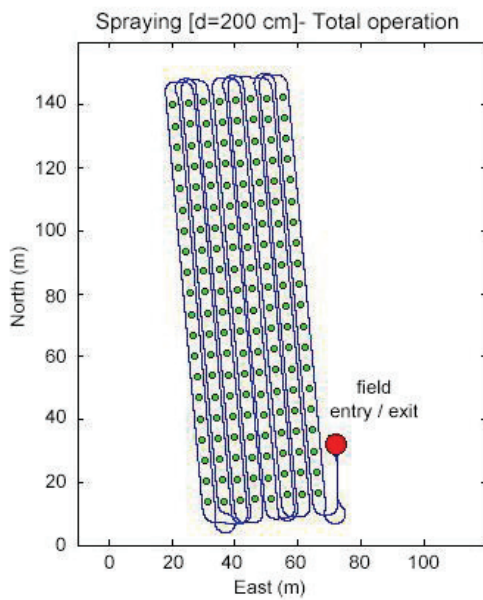
278

279



280

(a)



281

282

283

(b)

Figure 7. Intra-row weed spraying operation for arm distances (a)  $\mu=300$  cm and (b)  $\mu=200$  cm according to the optimal planning.

284 The track sequences for the optimal planning were as follows:

285  $\mu=180\text{ cm}, \quad \sigma^* = \langle 2\ 5\ 8\ 3\ 6\ 9\ 12\ 15\ 14\ 11\ 16\ 13\ 10\ 7\ 4\ 1 \rangle$

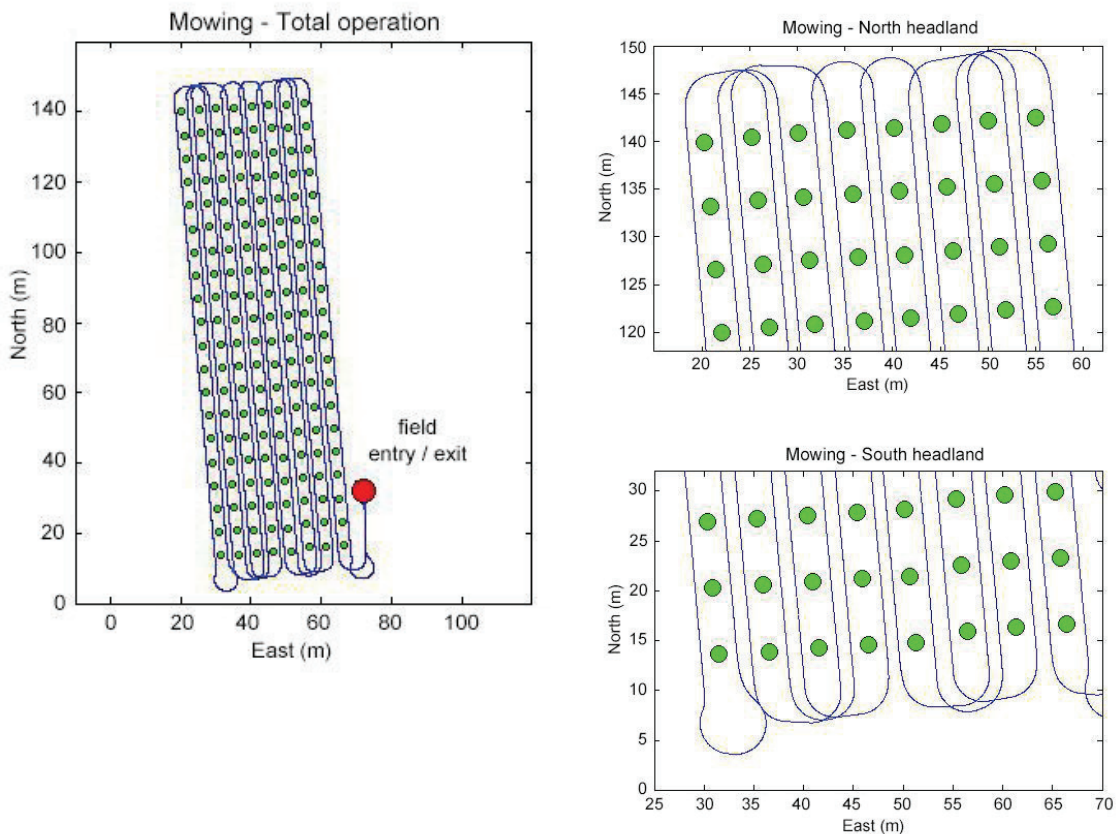
286  $\mu=200\text{ cm}, \quad \sigma^* = \langle 2\ 5\ 8\ 3\ 6\ 9\ 12\ 15\ 14\ 11\ 16\ 13\ 10\ 7\ 4\ 1 \rangle$

287  $\mu=250\text{ cm}, \quad \sigma^* = \langle 2\ 3\ 6\ 1\ 4\ 9\ 12\ 7\ 10\ 15\ 14\ 11\ 16\ 13\ 8\ 5 \rangle$

288  $\mu=280\text{ cm}, \quad \sigma^* = \langle 2\ 3\ 6\ 7\ 10\ 15\ 14\ 11\ 16\ 13\ 12\ 9\ 8\ 5\ 4\ 1 \rangle$

289  $\mu=300\text{ cm}, \quad \sigma^* = \langle 2\ 1\ 4\ 3\ 6\ 5\ 8\ 7\ 10\ 9\ 12\ 11\ 14\ 13\ 16\ 15 \rangle$

290 During the spraying operation with the arm displacement at 300 cm, the numerical ordering of the  
 291 generated tracks was not coincident with the spatial one. The spatial ordering of the tracks as they  
 292 appear in Figure 8, from left to right, is 1, 3, 2, 5, 4, and so on.



293

Figure 8 – Mowing operation according to the optimal planning.

294 **3.2 MOWING OPERATION**

295 The operating width of the mower was 1.4 m, and two passes in each inter-row corridor were  
 296 required (app, 2.8 m). For this specific case, the number of the tracks in each sub-field was  
 297  $|T_1|=|T_9|=1, |T_i|=2, i=2, \dots, 8$ . The optimal track sequence was  $\sigma^* = \langle 2\ 5\ 8\ 11\ 14\ 10\ 13\ 16\ 15$   
 298  $12\ 9\ 6\ 3\ 7\ 4\ 1 \rangle$  (Figure 8).

299

300 **Table 1. Measured distance and time elements during experimental operations**

Operation	Type	Distance				Time			
		Total (m)	Savings# (%)	Non-working (m)	Savings# (%)	Total (s)	Savings# (%)	Non-working (s)	Savings# (%)
<b>Spraying</b> $\mu=300$ <b>cm</b>	B-patterns	2,393	2.2	257	17.5	2,893	2.5	628	10.7
	Conventional	2,447		312		2,968	7.9	703	
<b>Spraying</b> $\mu=280$ <b>cm</b>	B-patterns	2,425	5.5	290	32.5	2,967		743	25.4
	Conventional	2,565		429		3,220	5.9	996	
<b>Spraying</b> $\mu=250$ <b>cm</b>	B-patterns	2,466	3.3	331	20.1	3,064		871	18.0
	Conventional	2,549		414		3,256		1,063	
<b>Spraying</b> $\mu=200$ <b>cm</b>	B-patterns	2,382	6.0	246	38.4	2,867	6.1	572	24.5
	Conventional	2,535		399		3,052		757	
<b>Spraying</b> $\mu=180$ <b>cm</b>	B-patterns	2,362	6.3	226	41.1	2,821	8.6	555	32.4
	Conventional	2,520		384		3,087		821	
<b>Mowing</b>	B-patterns	2,374	6.4	239	40.2	2,850	8.6	597	31.0
	Conventional	2,535		399		3,119		866	

301 # Depending on the element, distance or time, the savings was estimated as:

302 
$$\frac{[\text{Value}]_{\text{Conventional}} - [\text{Value}]_{\text{B-pattern}}}{[\text{Value}]_{\text{Conventional}}} \cdot 100\%$$

303

304

305 **3.3 SIMULATION EXPERIMENTS**

306 In order to demonstrate the applicability of the approach in several orchard formats, e.g.  
 307 polygonal, and orchards with curved rows, a number of simulated experiments were executed and  
 308 presented. The simulations regard the cases of two virtual orchards formats, namely one  
 309 polygonal-shaped orchard and one with curved tree rows. For each virtual orchard, two mowing  
 310 operations were considered, one involving two passes in each inter-row corridor (inter-row  
 311 distance: 5 m, operating width: 1.4 m) (Fig 9a and Fig 9b, for the polygonal and curved shape,  
 312 respectively), and a second one involving three passes in each inter-row corridor (inter-row  
 313 distance: 6 m, operating width: 1.2 m) (Fig 9c and Fig 9d, for the polygonal and curved shape,  
 314 respectively), and one spraying operation (arm displacement at 200 cm) (Fig 9e and Fig 9f, for  
 315 the polygonal and curved shape, respectively). A comparison between the optimized and  
 316 conventional (track-by-track) routes, in terms of non-working travelled distance, for the simulated  
 317 cases is given in Table 2.

318 **Table 2. Comparison between the non-working distances travelled of the optimized and the conventional routes**  
 319 **in the simulated experiments**

	Case		Total travelled distance (m)	Savings (%)	Non-working travelled distance (m)	Savings (%)
Mowing	Polygon-shaped / 2 inter-row passes	B-patterns	786,8	8.2	161.5	30.4
		Conventional	857,2		231.9	
	Polygon-shaped / 3 inter-row passes	B-patterns	1187,4	8.4	255.4	30.0
		Conventional	1296,9		364.9	
	Curved-shaped / 2 inter-row passes	B-patterns	1013,1	9.3	138.4	43.0
		Conventional	1117,5		242.8	
	Curved-shaped / 3 inter-row passes	B-patterns	1522,2	8.7	227.2	39.1
		Conventional	1667,8		372.8	
Spraying	Polygon-shaped	B-patterns	798,2	6.4	170.2	24.4
		Conventional	853,2		225.2	
	Curved-shaped	B-patterns	1063,7	5.1	176.9	24.3
		Conventional	1120,6		233.8	

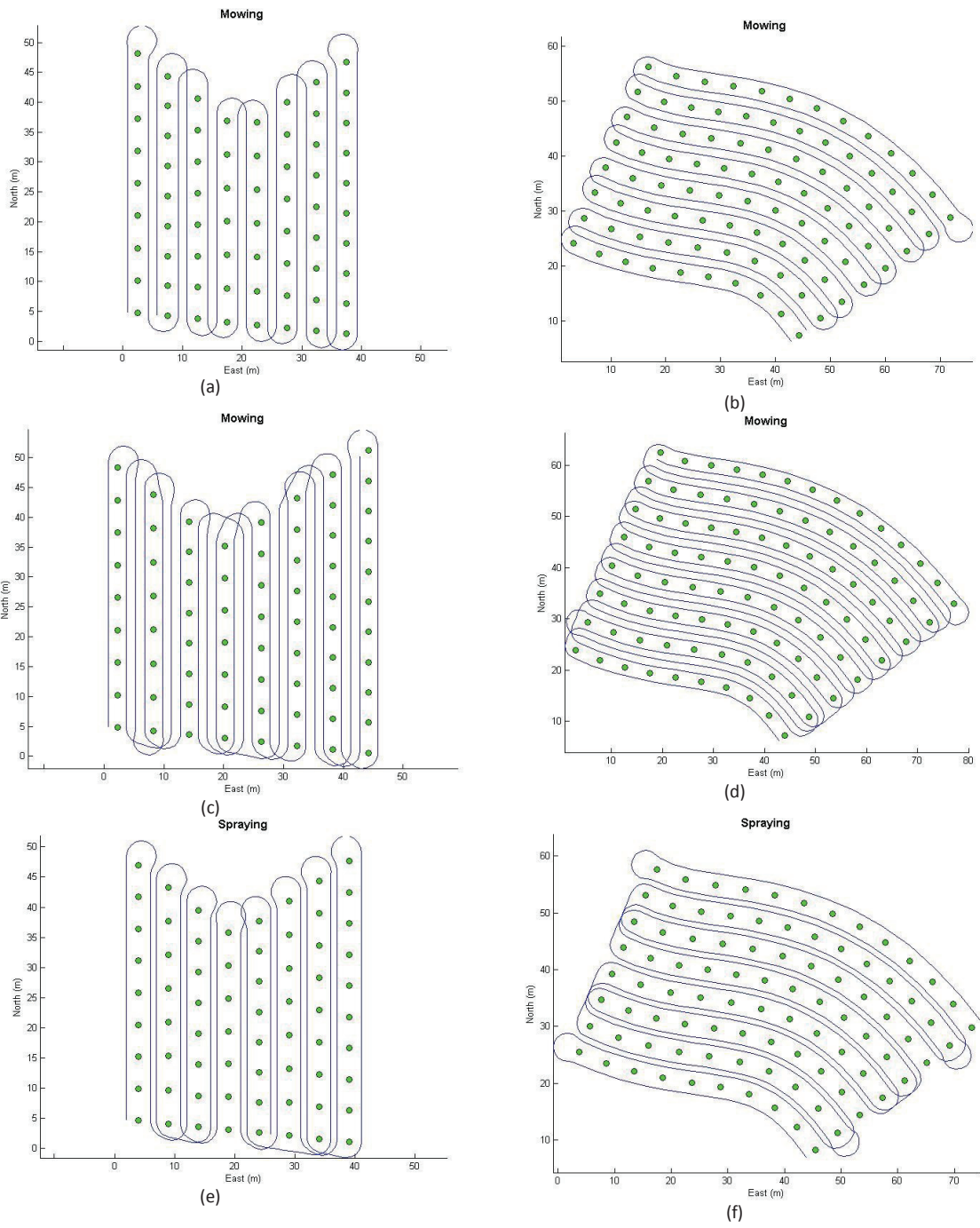


Figure 9. The optimized routes for various simulated cases

325 The presented route planning approach is an adaptation of the B-pattern method in the sense that  
326 it provides a framework to encode orchard operations into the TSP cost matrix. For the  
327 implementation of the route planning the position of every tree is not really needed. The GPS  
328 positions of two trees at the “lower” and “upper” edge of a tree-row are needed to form matrices  
329  $U_R$  and  $U_L$ . As long as the two geo-referenced points that define the upper and lower end of each  
330 row can be found, the methodology can be used. In this paper known GPS coordinates were used.  
331 In another scenario, these points could be extracted from georeferenced aerial images; the same is  
332 true for row heading angle. In practical situations (curved or nonlinear or crooked rows), the two  
333 end-points of each row should be fed to the robot but reactive navigation will be necessary.

334 In the experimental operations, the  $\Omega$ -turn was executed in the cases for which the robot’s  
335 kinematic restriction ( $2r_{\min} > s(i, j)$ ) did not allow for the execution of a  $\Pi$ -turn. This was based  
336 on the fact that in this specific orchard, there was sufficient space in the headlands areas for the  
337 execution of  $\Omega$ -turns. If this were not the case, the robot would be restricted to executing a Tau-  
338 turn instead of a  $\Omega$ -turn because of the reduced required space for manoeuvring (identical to that  
339 required in the case of a  $\Pi$ -turn). However, the optimal sequence would be identical because for  
340 this specific robot, the turning time for a Tau-turn is similar to that required to execute an  $\Omega$ -turn  
341 between the same initial and final track.

342 As listed in Table 1, in the case in which the  $\mu$  distance was adjusted to 250 cm, the non-working  
343 distance during turning was measured to be 312 m, whereas in the case in which the  $\mu$  distance  
344 was adjusted to 180 cm, the non-working distance was 216 m. It can be observed that different  
345 adjustments of distance  $\mu$  can result in a relative decrease of up to 31% of the non-working  
346 distance when comparing the optimal solutions for both cases. This decrease in the non-working  
347 distance translates to a greater decrease (when comparing the optimal solutions for both cases) in  
348 the total operational time (in this specific case, 3.2%). However, the specific experimental



349 orchard has a shape that can provide high field efficiency specific to the orchard shape (long  
350 length-short width rectangular). In cases in which the turning time is a considerable part of the  
351 total operational time, the reduction is considerably higher. This provides the opportunity for an  
352 offline estimation of the non-working travelled distance for various values of the parameter  $\mu$  and  
353 for the selection of an optimal one for the specific orchard and the specific kinematics that apply  
354 to the agricultural vehicle performing the operation.

## 355 **5. CONCLUSIONS**

356 A route planning approach for orchard operations has been developed and validated. At its core,  
357 the planning method has the generation of optimal route planning based on the adaptation of the  
358 B-patterns area coverage approach developed for arable farming operations. The resulting  
359 operation plans are optimal when using the non-working travelled distance as the criterion.  
360 Experiments have verified that the operational efficiency can be improved significantly over that  
361 of the conventional non-optimised method of executing orchard operations using conventional  
362 machines. Specifically, as shown by the experimental results, the reduction in the non-working  
363 time ranged between 10.7% and 32.4%, and the reduction in the non-working distance ranged  
364 between 17.5% and 40.2%, resulting to savings in the total travelled distance ranged between  
365 2.2% and 6.4%. The next steps for this planning method relate to its expansion to autonomous  
366 orchard operations constrained by the carrying capacity of the machine (e.g., spraying operations)  
367 and to multiple neighbouring orchard operations. This further research will provide a complete  
368 route planning system for autonomous orchard vehicles. .

369

370

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422

423

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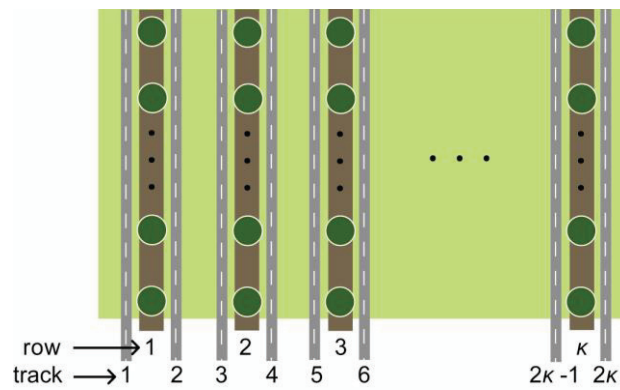
$$\frac{[\text{Value}]_{\text{Conventional}} - [\text{Value}]_{\text{B-pattern}}}{[\text{Value}]_{\text{Conventional}}} \cdot 100\%$$

**Table 2. Comparison between the non-working distances travelled of the optimized and the conventional routes in the simulated experiments**

	Case		Total travelled distance (m)	Savings (%)	Non-working travelled distance (m)	Savings (%)
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	Curved-shaped / 2 inter-row passes	B-patterns	1013,1	9.3	138.4	43.0
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	Curved-shaped	B-patterns	1063,7	5.1	176.9	24.3
		Conventional	1120,6		233.8	

# Figure

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**Figure 1.** The derived tracks for intra-row orchard operations.

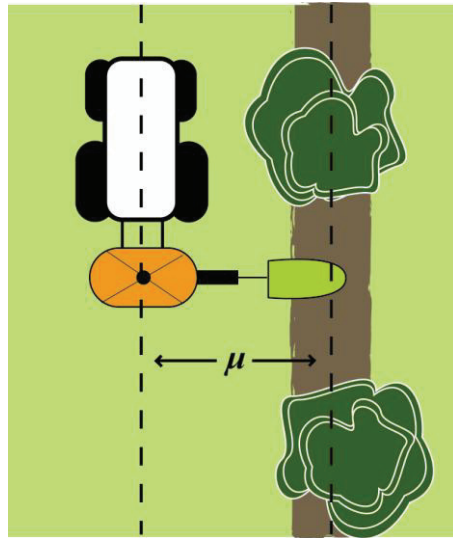
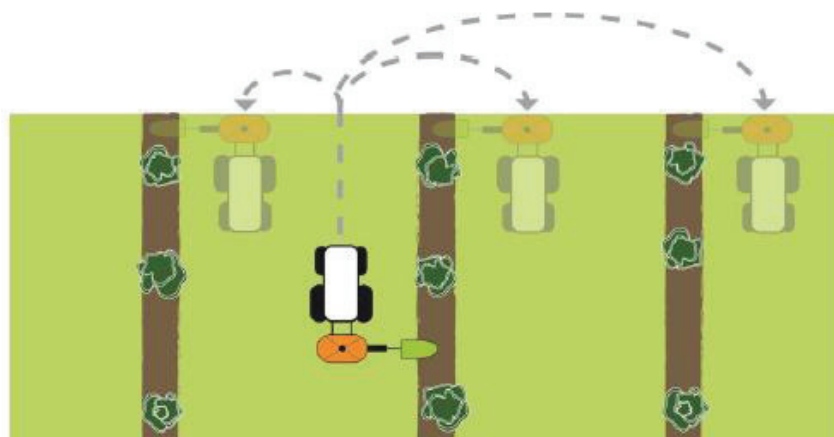
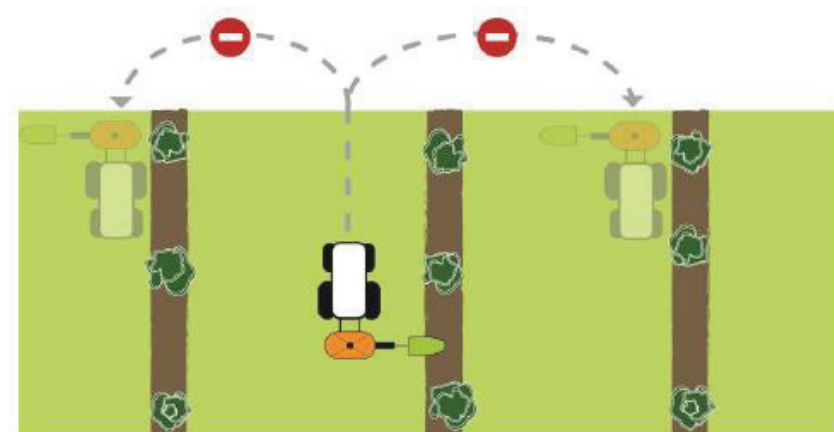


Figure 2. Vehicle positioning in intra-row operations





(a)



(b)

Figure 3 – Disallowed transitions for a robot carrying a one-way oriented implement.

**Figure**  
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**Figure 4. The AMS field robot.**

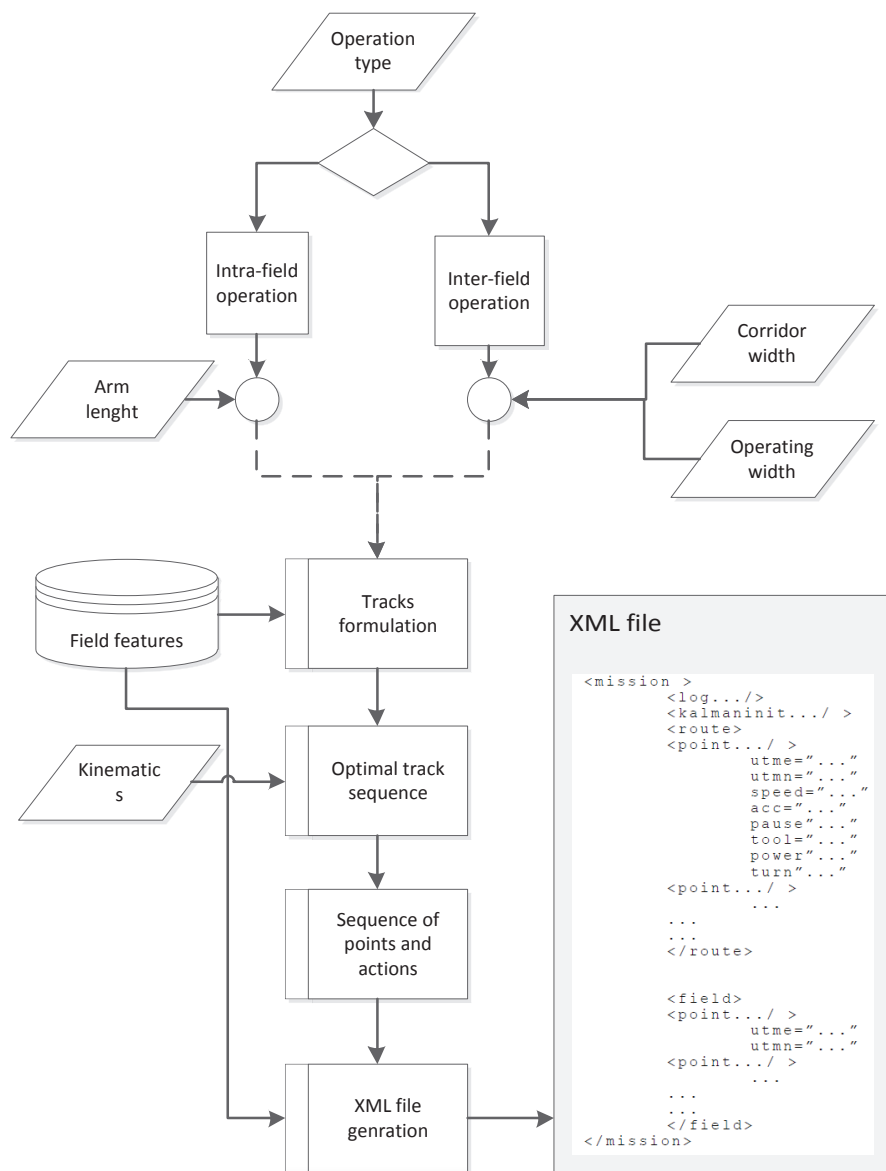
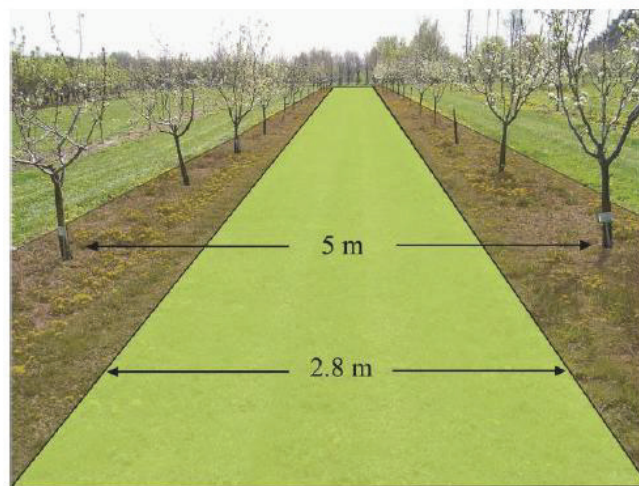


Figure 5. The mission planner architecture



(a)



(b)

Figure 6. Part of the experimental orchard (a); the mowing area (green) and the weed spraying area (brown) (b).

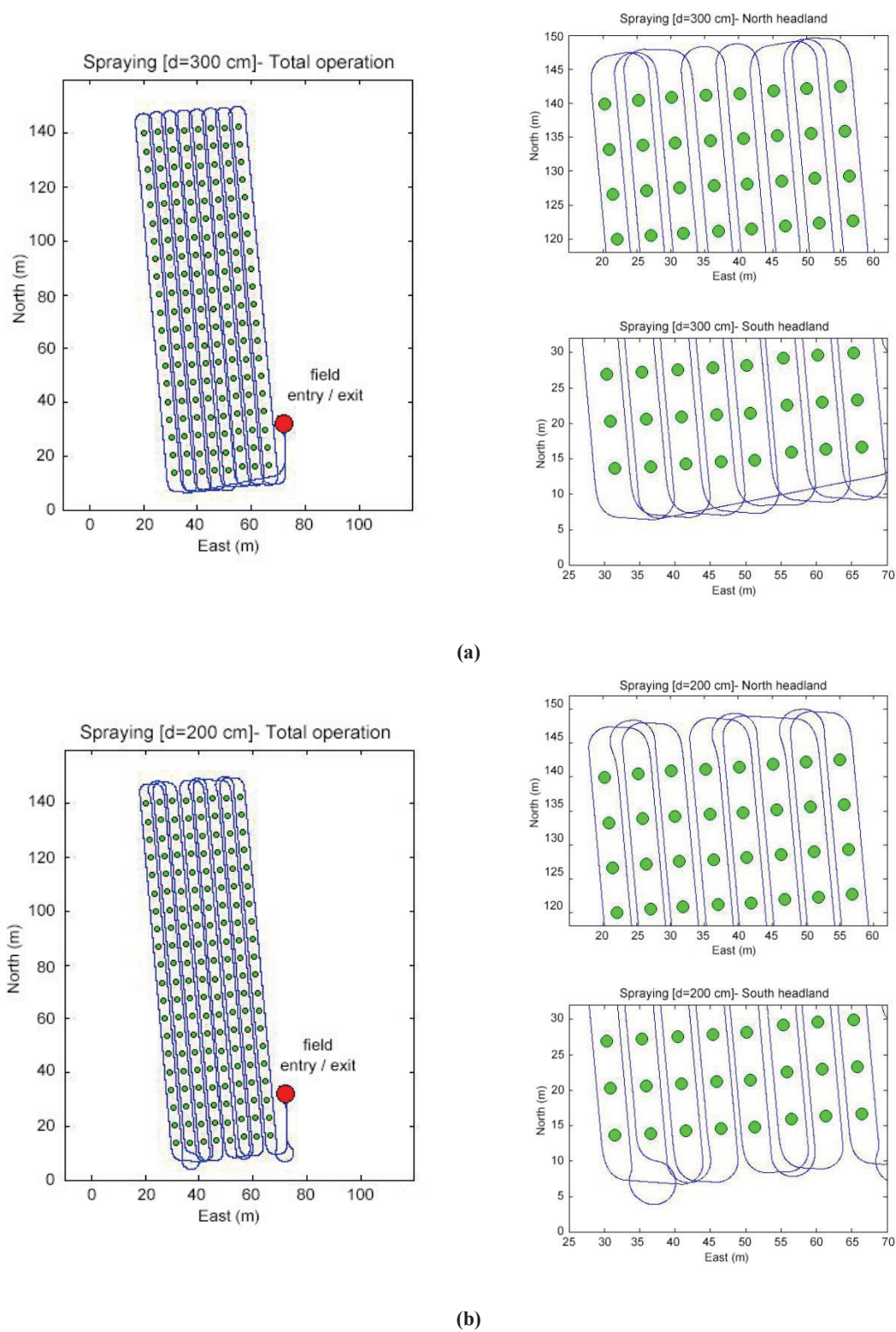


Figure 7. Intra-row weed spraying operation for arm distances (a)  $\mu=300$  cm and (b)  $\mu=200$  cm according to the optimal planning.

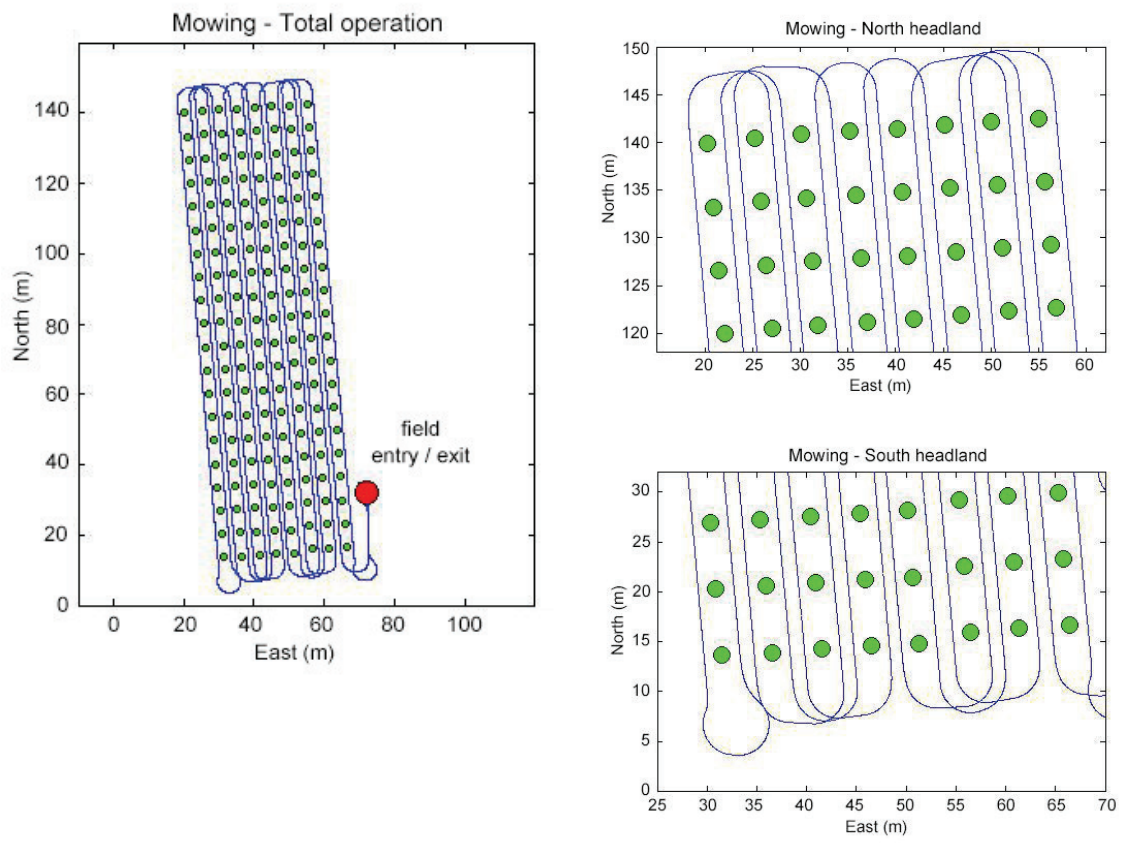


Figure 8 – Mowing operation according to the optimal planning.

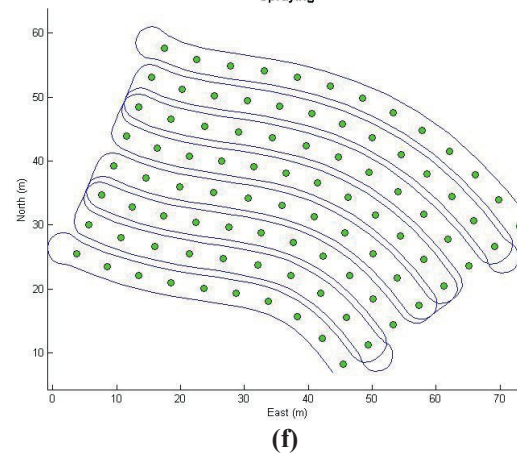
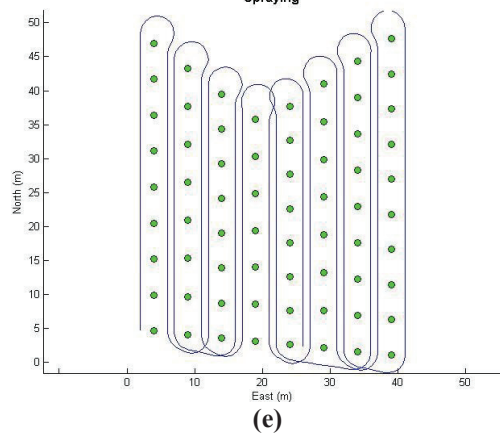
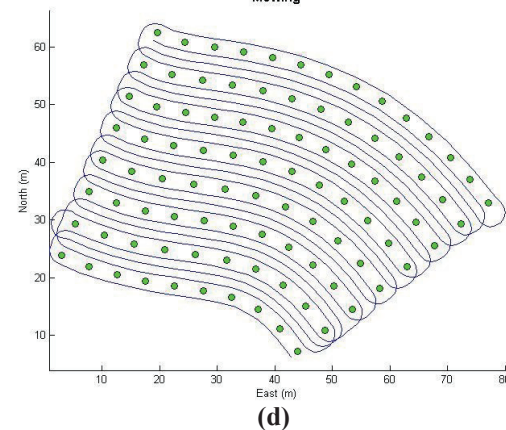
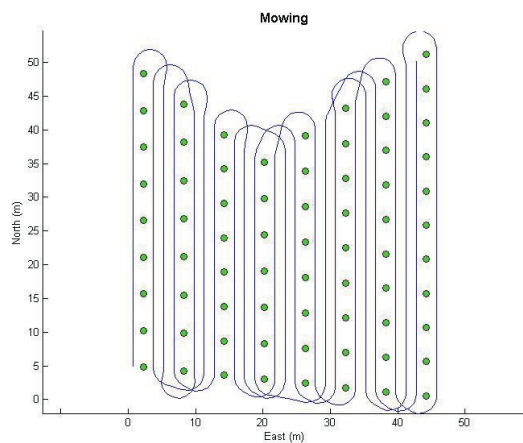
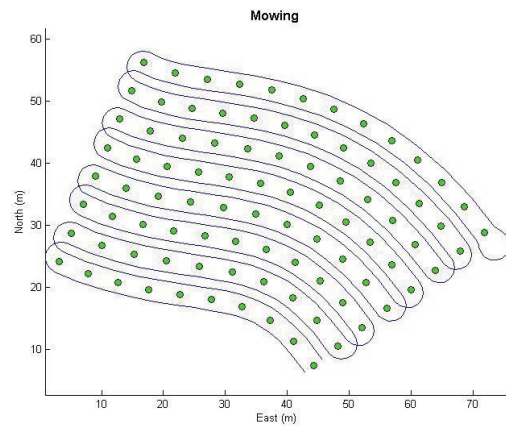
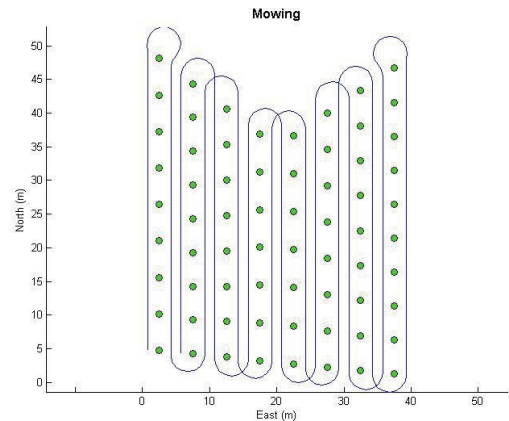


Figure 9. The optimized routes for various simulated cases