

COVERAGE ACCURACY USING CURVED SWATHS WITHIN AGRICULTURAL FIELDS

*USING CUBIC SPLINES TO SMOOTH EDGY CURVES IN ROUTE PLANNING FOR
AGRICULTURAL MACHINERY*

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August 2010



WAGENINGEN UNIVERSITY

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A minor-thesis submitted in partial fulfilment of the degree of Master of Science
at Wageningen University and Research Centre,
The Netherlands.

May 2010
Wageningen, The Netherlands

Thesis code number: GRS-80424
Thesis Report: GIRS-2010-12
Wageningen University and Research Centre
Laboratory of Geo-Information Science and Remote Sensing

Summary

The development of guidance systems in farm machinery pushed also the development of pre-planning of machine operations on the field because of the possibility of inserting calculated routes in the interface of the self-steering machines. Majority of algorithms developed for calculating routes are focused on optimizing the work of machine through straight paths. But in many agricultural fields it is unsuitable or undesirable the use of straight pattern of work for its coverage because of operational or environmental limitations, creating a demand for curved path types. Existing algorithms working in path planning for curved patterns use a given curved reference to develop parallel paths exactly adjacent to it; this references are given as a composite of edges to be followed by a machine in an attempt of approaching a curved path, but many times this references provide a poor approach of a curve and demanding the machine to make instantaneous rough turns at an edge. These instantaneous turns results in coverage problems of overlap and non-covered areas, besides the potential damage on the machine itself.

In this thesis methods were proposed for reducing the roughness problems of curves. One method used by previous authors to reduce the roughness problem in machine routes was by adding edges in a curved pattern using spline interpolation, creating smooth path curves.

Methods were also proposed to assess paths created for their coverage accuracy. The coverage issues herein tested were: within the turns inside the path, between a path created near the border (headland) and the border of the field itself, and between sequences of parallel curved paths created. The assessment retrieved, for each of the issues the overlapped and the non-covered area.

An algorithm was built for creating curved paths using natural cubic spline within fields, using offsetted edges sampled from field border as reference for the interpolation.

The algorithm was applied in six case studies for assessment of the coverage issues. The use of spline proved capable of creating smooth paths reducing (or eliminating) problems created by rough turns, but still keeping (if not increasing) coverage problems due to the spline type herein used and also due to the limited number of edges used as reference. The addition of reference edges in the middle of the field borders increased the parallelism of the splined paths reducing significantly the coverage problems.

Reduction of roughness in curves by using splines increased the reproduction of machine behavior in fields, further study is still necessary for use of different spline types and for optimization of the the curved patterns in field.

Keywords: coverage planning, curves, splines in path planning, precision farming, robotics.

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1. Introduction

1.1. Background

Most farmers would like to have flat rectangular fields, which would allow them driving in one straight line pattern and save time and costs in field operations. Nevertheless, many fields are irregularly shaped.

Fields of complex geometry occur all around the world., Oksanen and Visala, 2007 studied the issue of complex geometry of fields in the Uusimaa county (Finland) using shape indexes (convexity, compactness, rectangularity, moments, triangularity and ellipticity), and concluded that the majority of fields (75%) cannot fit properly in the shape indexes defined or can be classified as complex shape.

When complex shapes are studied, convexity and compactness are often taken as main characteristics or properties that affect operation of farm machinery, since concave edges of fields interrupt straight driving of machinery. However, curved boundaries (which can be convex) may also make a straight driving pattern unsuitable because it would increase the number of maneuvers and, consequently, the non-working time of a machine.

Another issue that affects the driving pattern of machinery is the slope of fields. It is well known that working fields (like contour tillage) perpendicular to the direction of the slope on the surface reduces soil loss by erosion (FAO Soils, 1996). Tilling and planting perpendicular to a natural slope creates a series of dams which redirect and slow down runoff. This allows water to soak into the ground or to flow gently between the rows to grassed headlands at the edge of the field or to grassed waterways within the field. On short slopes, cross-slope farming can reduce erosion by up to fifty percent (Agriculture and Agri-Food Canada, 2010). But, in practice, a slope hardly (if ever) follows a straight pattern.

Carvalho et al. (2008) found that soil loss for corn rows sown perpendicular to a 9% slope amounted to 3.877,1 kg.ha⁻¹ compared to 12.399,8 kg.ha⁻¹ for corn lines sown in downhill direction. The impact of direction was found to be larger than that of crop choice and coverage crops. Sparovek and Schnug (2001) suggested practices such as contouring, terracing and waterways to drain excessive runoff to be combined with tillage and other management practices. The authors also discussed the impacts of such practices on crop performance and production costs since mechanical tillage operations and harvesting are more efficient with straight line planting than when following contour lines. Furthermore, terraces greatly reduce mechanical harvesting efficiency because conventional machines do not operate on terraces and cannot cross them. Sparovek and Schnug (2001) also suggested that in smoother parts of the field, contouring and terracing could be combined in a way to avoid or reduce their impact on efficiency of mechanical operations by avoiding dead rows near terraces, but making terraces more parallel to them.

Figure 1 shows an example of the influence of slopes on the cropping pattern.



Figure 1. Example of sugar-cane established in curved patterns against slope for erosion control in Piracicaba, Brazil.

Path planning, in an agricultural perspective, is a term used for defining in advance how a machine is going to move inside a field, for example aiming that this machine stays working as long as possible on the activity which it was developed for, reducing the non-working time (like maneuvering, loading and offloading) or reducing overlap of this machine on the area, avoiding overuse of agricultural inputs. Path planning has been an active field of research in the past years because of the development and improvement of guidance and self-steering systems on machines (Keicher and Seufert, 2000).

The advance in geo-positioning systems, applied in guidance and self-steering of farm machinery, creates a demand for coverage path-planning, where eventually machinery can operate free of human intervention (robots), Spekken and Bruin (2010) developed an algorithm capable of retrieving a complete route (working pattern and maneuvers) to be followed by a machine on field also optimizing the efficiency of the operation, but the algorithm is still limited in working the field in a straight pattern.

Research activities concerning automatic guidance of agricultural vehicles — or implements — have led to various solutions. Sensors, including mechanical ones, global navigation satellite systems (GNSS), machine vision, laser triangulation, ultrasonic and geomagnetic, generate position, attitude and direction-of-movement information which are essential inputs for control algorithms. Actuators, like hydraulic valves, are used to transform guidance information into changes of position and direction (Keicher and Seufert, 2000). In

general, a dedicated pre-planning of the routes and tasks of the operation has been shown to improve overall efficiency (Palmer et al., 2003).

Different factors play a role in the definition in path planning. Stoll (2003), for example, considered operation strategy, neighboring area, field geometry, field specific data, machine specific data and terrain relief.

Auto-guidance devices have become more common in agricultural field machines. An auto-guidance device is installed on the tractor or on the self-propelled machine and it either automatically (electro-hydraulic steering) or semi-automatically (light bar to show steering request) keeps the vehicle on-lane based on accurate satellite positioning. Support for straight driving lines is available in all of them, but special facilities for curved lines or headland driving are rarely provided (Oksamen et al., 2007).

Oksamen et al. (2007), proposed an algorithm based on the idea to follow the shapes of field edges rather than forcing the tracks into straight lines. He posed that this is how some farmers would operate most of their fields, following the shape of some edge or rounding the field as a spiral. An example of such procedure can be seen in Figure 2.

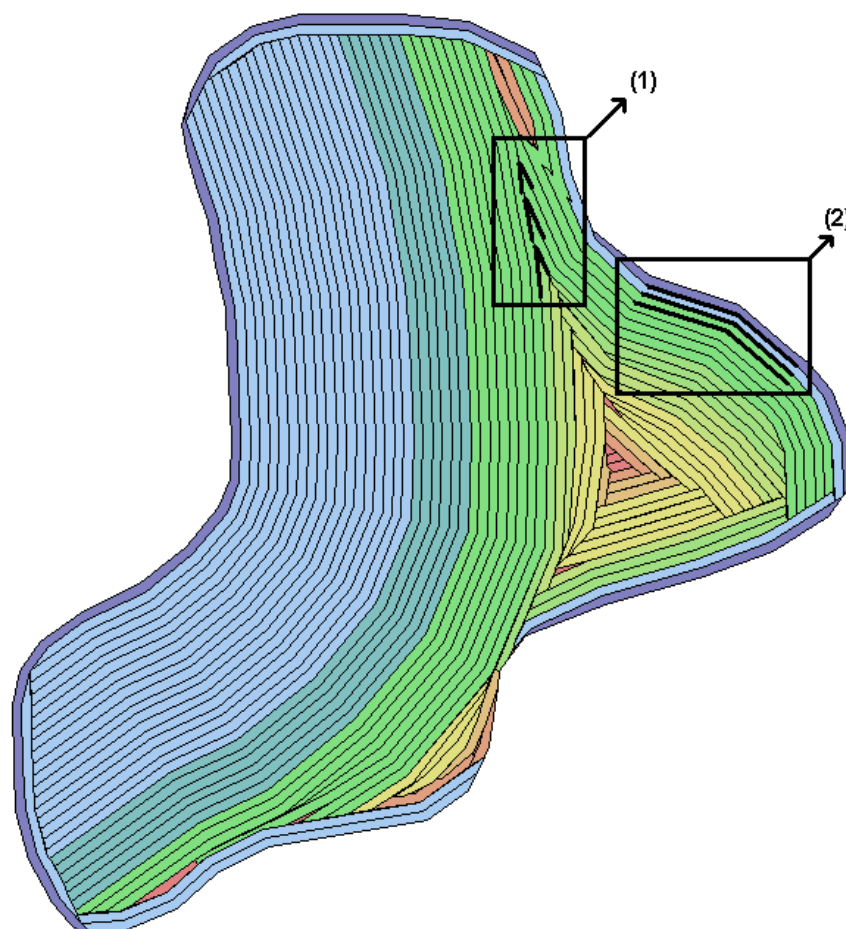


Figure 2. Example of machine path generated by following the field edges (Oksamen et al., 2007). The boxes and their identification is explained in the text.

The way in which the author defined the paths is through offsetting the edges of the field in inward direction, or outwards (for field obstacles).

The rectangles in figure 2 point to some routing problems to be solved: (1), offsetted field edges may collide into sharp changes of direction and (2) the offset of the field edges may create edgy turns that do not reproduce a smooth curve which could be followed by a machine.

1.2 Problem definition

In actual path planning, curved paths are basically defined by the offsetting of field vertices that are sampled from a curved border of a field. However, paths created between the offset vertices (path-points), are not exact curves but polylines representing a curve. The problem is that, because of the sampling strategy used, the change of direction from one path-point to another create a rough turn unsuitable to be followed by a machine.

Figure 3 shows a harsh turn from a path defined from an offset of the border.



Figure 3. Harsh turn created by a tractor following a path previously defined by an offset of the field boundary. (Hoeksche Waard, Netherlands)

These immediate turns push (or may even damage) parts of the machine that may not respond so instantaneously. Also a machine with large width, such as a sprayer boom, will have problems in such a turn because the immediate move of the bars in a harsh turning angle will leave areas with: overlap area in one side of the machine, and non-covered area on

the other side. For example, a sprayer-boom with a width of 20 meters makes an instantaneous turn of 15 degrees, it generates simultaneously an overlap and a non-covered area of 13 square meters at opposite sides of the boom.

Figure 4 shows a field with an offset of the field sides, the double lines on the border represent curved terraces for erosion control. The black dots are vertices of the field boundary which are offset in inward direction and the numbers represent the angle that a machine has to turn instantaneously at the point.

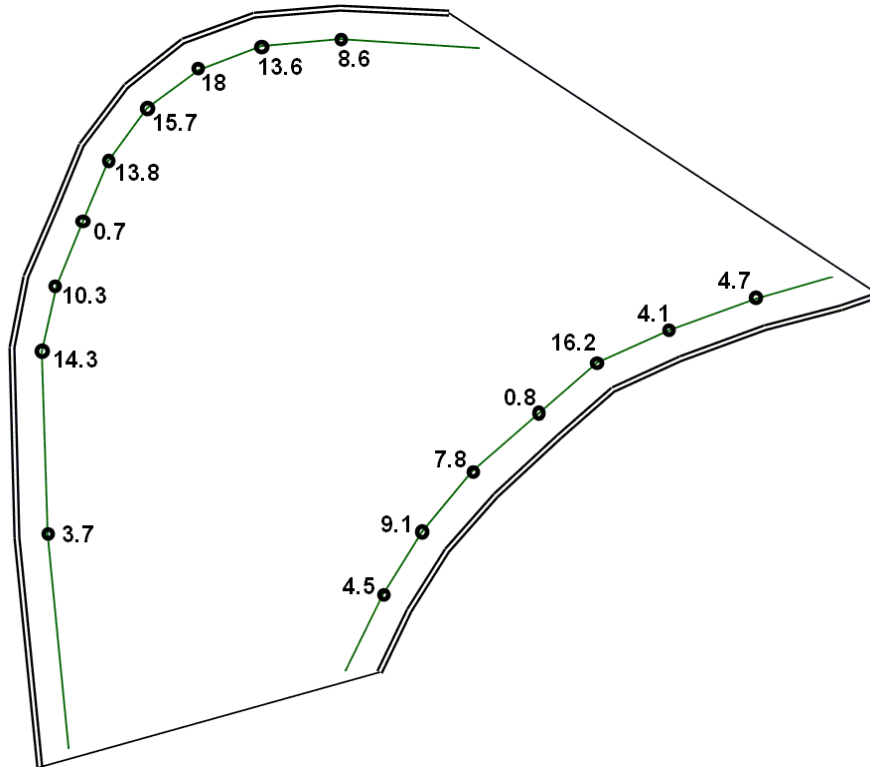


Figure 4. Example of field a offset of the edges displaying the turning angle between edges (in degrees) on a field with curved borders represented by the double lines.

In Figure 4, a sprayer-boom with 20m of width following one time the offset of both terraces would create simultaneously an overlap area and non-covered area (on the black dots displayed in the Figure) of 129 square meters, apart from the potential damage to the equipment.

Given the increase in use of guidance systems for machinery and the pre-planning of the machine routes that may be used as input for these systems, it is necessary to apply a methodology that reduces the impact of the harsh turns on offset edges of the field, allowing the machine to follow smooth curved paths.

In route planning, Walther et al. (no date) used B-splines for calculation of path planning for mobile robot navigation. The author used external sensors together with real-time path calculation creating a smooth motion in human centered environments.

Maekawa et al. (2009) also used B-spline curve interpolation to generate smooth continuous paths for autonomous vehicles for mining transport. Results of his implementation can be seen in Figure 5.

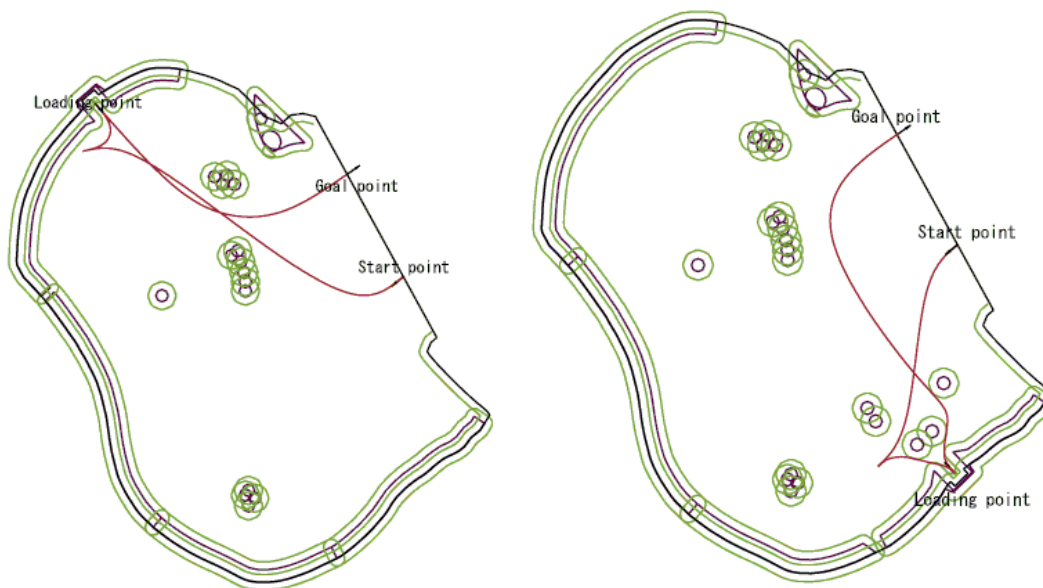


Figure 5. Results obtained by Maekawa et al. (2009) for routes of mining transporters. The red lines indicate the obtained routes and the green lines indicates the buffer of safety from borders and obstacles.

The routes obtained, as the ones given in Figure 5, have no aim to accurately cover a given space, but only to lead a machine from one point to another avoiding collision with obstacles. Therefore, the use of the B-spline method, where the control points are not reached by the vehicle but only influence the degree of curvature, assuring a collision free path.

Studies and methods for smoothing routes in path planning for autonomous vehicles is already available. In coverage planning, there is availability of methods to create curved paths in fields, but there are still no methods that were applied for smoothing the machine paths and to observe and evaluate it's effect in the coverage.

1.3 Objective and research questions

Given the problems originating from offsetting of field boundaries to produce curved paths for agricultural operations, the objective of this work is to study and develop methodologies that allow to obtain smooth curves that can be used for navigation of agricultural machines along curved contours.

Research questions:

1. Which methods can be used to reduce the roughness of the turns produced on a planned path for a machine when following curved contours of a given field.
2. How can suitability of the methods be assessed?
3. How can the methods be implemented in a path planning algorithm?
4. Which are the results for measures of RQ2 on a set of test fields?

2. Methodology

In this thesis, a curved path is described by a sequence of path-points (edges) with in-between line segments that may change direction at each vertex position. Adjacent paths are aimed to be parallel to each other and should follow a given reference (e.g. a curved boundary of a field or an elevation contour) as closely as possible. For the coming examples and case studies, curved field boundaries will be used as reference. The implementation of the methods are described later in section 2.6.

2.1. Roughness problem in curved paths

This section is related to research question 1.

The most common strategy for creating curved path is by offsetting the field vertices; because it assures the path to be parallel to the field boundary since the curved path becomes a reproduction, in shape, of the border. The smoothness (or roughness) of a curved border is determined by the frequency of vertices and the shape of the physical boundary it represents (see Figure 6). Offsetting a border with a high frequency of points creates a smoother curved path. Increasing the frequency of vertices when measuring a curved border of a field is one solution to solve the roughness problem.

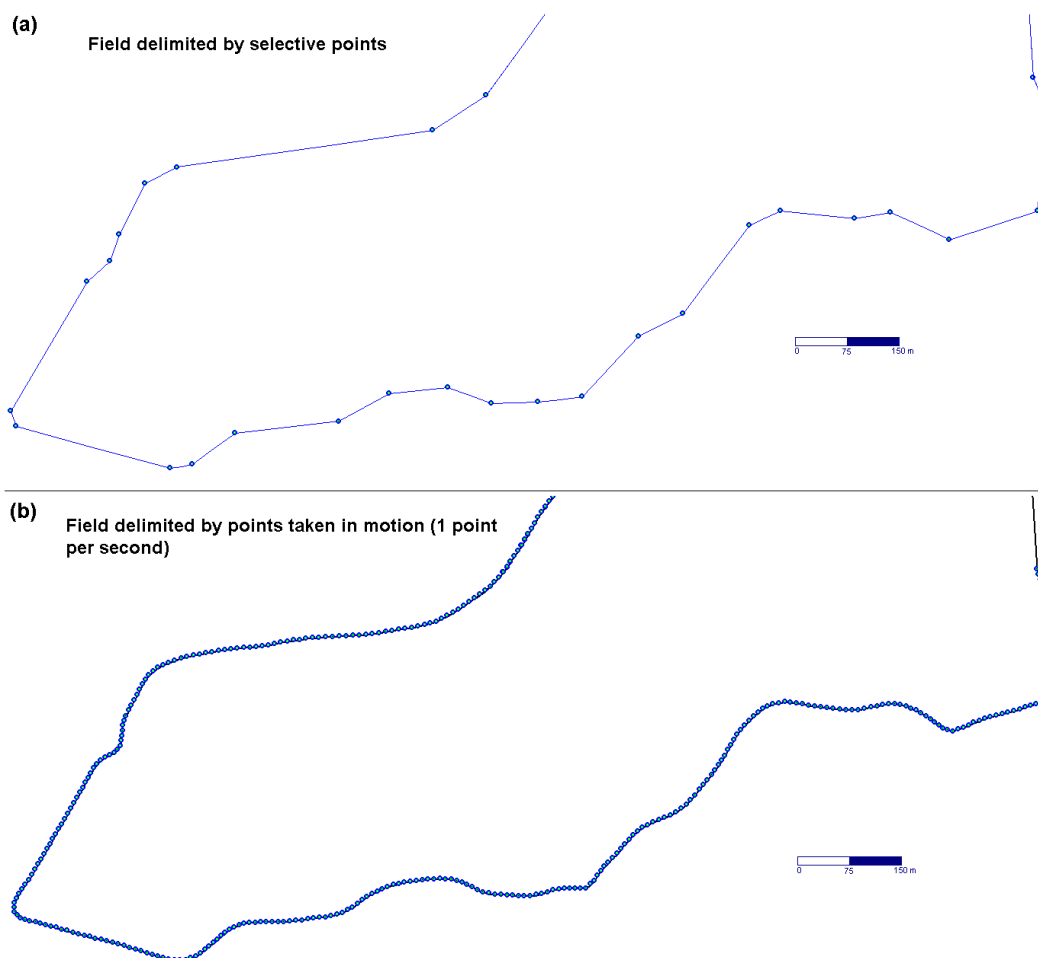


Figure 6. Differences in reproduction of field with curved borders by different frequencies of edges limits.

For practical purposes, fields are represented by a limited number of edges that are deemed to represent the field's shape as good as possible. In-field measurements can be done by a limited selection of points to represent a curved boundary; and also many processing algorithms, including for path planning, simplifies the field shapes for efficiency in processing and correcting possible irregularities of measurements.

With a limited number of edges to be offset to create a path, and the necessity to obtain a smooth curved path from them, one strategy is to add more edges in curved pattern between them, this can be done through spline interpolation.

2.2 Splines

A spline curve is a mathematical device allowing us to easily to build an interface that will allow the user to design and control the shape of complex curves and surfaces. The general approach is that the user enters a sequence of points, and a curve is constructed that generally follows this sequence. The points are called control points. A curve that actually passes through each control point is called an interpolating curve; a curve that passes near to the control points but not necessarily through them is called an approximating curve (House, no date). Examples of this curves can be seen in Figure 7.

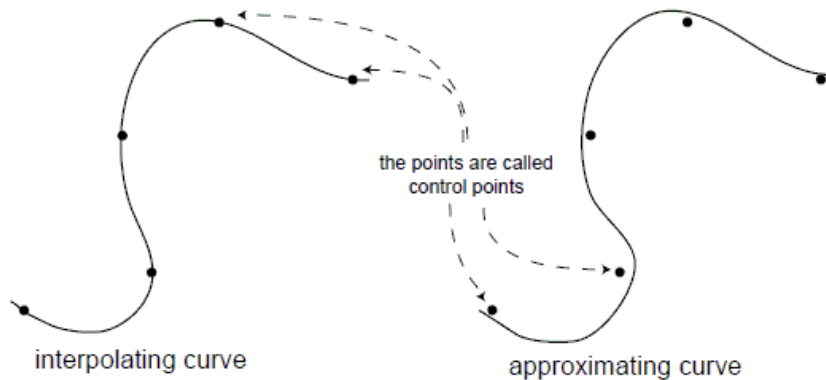


Figure 7. Example of an interpolated and approximated curved passing to a sequence of control-points. Extracted from House (no date).

A cubic spline, in a given a set of pair of control points, is determined by a cubic polynomial ($y=ax^3+bx^2+cx+d$) between each pair of points. To make sure that curves join together smoothly, the first and second derivative at the end of one curve must equal the the first and second derivative start of the next one. Computing the natural cubic spline essentially involves solving a system of simultaneous equations to make sure this happens (Lambert, no date).

There are different types of cubic splines. Natural and closed splines are types of spline where the interpolation passes through the control points, and they differ because a natural

spline has separate end-members (or edges of a spline line), while in close splines one end-member connects to the other determining a closed polyline. B-splines and Bezier curves are types of splines where the interpolation does not pass through the control points but in between/near them, in the Bezier curves, the interpolation passes only through the end-members and is only approximated by the other control points (see example of approximation in Figure 7), while in B-splines the interpolation has the characteristic of local control, meaning that one point affects only locally and not the whole curve (Lambert, no date).

This thesis makes use of natural cubic splines, where the path is created by interpolation passing through the control points that are defined by the offset of field vertices. A curved path usually has two open edges (initial and final edges of the path) that are the end-members for the spline.

2.2.1 Calculation of a natural cubic spline

This example is extracted from VBforum (no date).

Consider a set of three data points (x_1, y_1) , (x_2, y_2) and (x_3, y_3) (these points can be seen in the plot of Figure 8) through which a cubic spline is to be created. This spline is composed of two cubic equations connecting a pair of data points. These two equations are of the form:

$$y = a_1x^3 + b_1x^2 + c_1x + d_1 \rightarrow \text{first equation that connects point } x_1, y_1 \text{ to point } x_2, y_2$$

$$y = a_2x^3 + b_2x^2 + c_2x + d_2 \rightarrow \text{second equation that connects point } x_2, y_2 \text{ to point } x_3, y_3$$

The first and second derivatives of these equations are extracted:

$$y' = 3a_1x^2 + 2b_1x + c_1 \rightarrow \text{first derivative of the first equation}$$

$$y'' = 6a_1x + 2b_1 \rightarrow \text{second derivative of the first equation}$$

$$y' = 3a_2x^2 + 2b_2x + c_2 \rightarrow \text{first derivative of the second equation}$$

$$y'' = 6a_2x + 2b_2 \rightarrow \text{second derivative of the second equation}$$

The two equations share x_2 as a common point. Since there are a total of 8 unknown coefficients, 8 equations are needed.

1. $0 = 6a_1x_1 + 2b_1 \rightarrow y_1'' = 0$ (boundary condition at free end)
2. $y_1 = a_1x_1^3 + b_1x_1^2 + c_1x_1 + d_1 \rightarrow y_1 = f(x_1)$ in equation 1
3. $y_2 = a_1x_2^3 + b_1x_2^2 + c_1x_2 + d_1 \rightarrow y_2 = f(x_2)$ in equation 1
4. $y_2 = a_2x_2^3 + b_2x_2^2 + c_2x_2 + d_2 \rightarrow y_2 = f(x_2)$ in equation 2
5. $3a_1x_2^2 + 2b_1x_2 + c_1 = 3a_2x_2^2 + 2b_2x_2 + c_2 \rightarrow$ 1st derivative at x_2 matches in both splines
6. $6a_1x_2 + 2b_1 = 6a_2x_2 + 2b_2 \rightarrow$ 2nd derivative at x_2 matches in both splines
7. $y_3 = a_2x_3^3 + b_2x_3^2 + c_2x_3 + d_2 \rightarrow y_3 = f(x_3)$ in equation 2
8. $0 = 6a_2x_3 + 2b_2 \rightarrow y_3'' = 0$ (boundary condition at free end)

The boundary conditions (equations 1 and 8) are called “natural” boundary conditions where the second derivative (which determines the curvature) is 0.

These equations can be represented in a matrix form $Ax = b$ (Note: “.” means zero)

$$\begin{array}{cccccccc|cccc}
 6x_1 & 2 & . & . & . & . & . & . & a_1 & = & 0 \\
 x_1^3 & x_1^2 & x_1 & 1 & . & . & . & . & b_1 & = & y_1 \\
 x_2^3 & x_2^2 & x_2 & 1 & . & . & . & . & c_1 & = & y_2 \\
 . & . & . & . & x_2^3 & x_2^2 & x_2 & 1 & d_1 & = & y_2 \\
 3x_2^2 & 2x_2 & 1 & . & -3x_2^2 & -2x_2 & -1 & . & a_2 & = & 0 \\
 6x_2 & 2 & . & . & -6x_2 & -2 & . & . & b_2 & = & 0 \\
 . & . & . & . & x_3^3 & x_3^2 & x_3 & 1 & c_2 & = & y_3 \\
 . & . & . & . & 6x_3 & 2 & . & . & d_2 & = & 0
 \end{array}$$

Given the location of three points as (0,0), (0.5, 0.125) and (1,1) the output matrix will be:

$$\begin{array}{cccccccc|cccc}
 0 & 2 & . & . & . & . & . & . & a_1 & = & 0 \\
 0 & 0 & 0 & 1 & . & . & . & . & b_1 & = & 0 \\
 0.125 & 0.25 & 0.5 & 1 & . & . & . & . & c_1 & = & 0.125 \\
 . & . & . & . & 0.125 & 0.25 & 0.5 & 1 & d_1 & = & 0.125 \\
 0.75 & 1 & 1 & . & -0.75 & -1 & -1 & . & a_2 & = & 0 \\
 3 & 2 & . & . & 3 & -2 & . & . & b_2 & = & 0 \\
 . & . & . & . & 1 & 1 & 1 & 1 & c_2 & = & 1 \\
 . & . & . & . & 6 & 2 & . & . & d_2 & = & 0
 \end{array}$$

Resulting on the equations:

$$1.5x^3 - 0.125x \text{ and } 1x^3 - 0.375x$$

Where the x values are added to the first equation in the interval of [0,0.5], and on the second equation in the interval of [0.5,1]. The interpolation of values using these two equations can be seen in Figure 8.

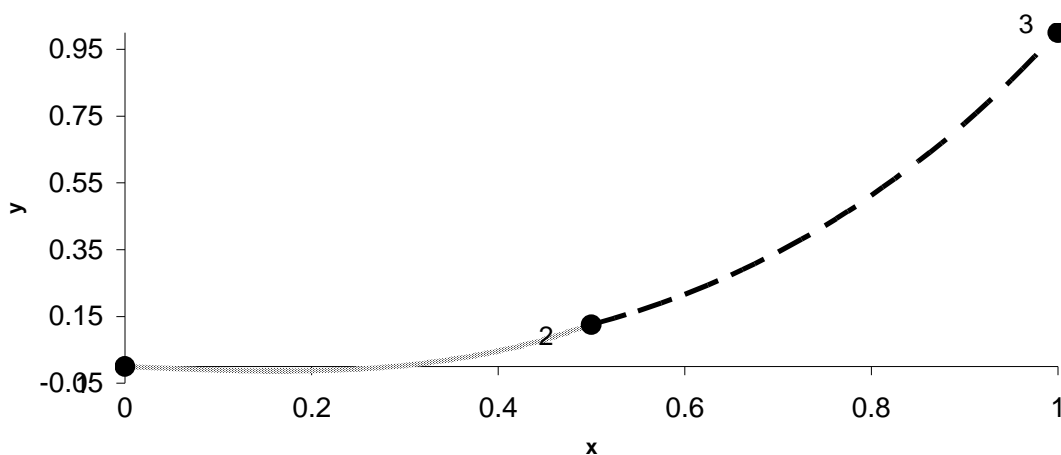


Figure 8. Results of a spline made of 2 cubic equations passing through 3 points.

In this given example (of Figure 8) y is a function of x; but in a 2-D interpolation, both locations (x and y) have to be retrieved

A modification of this calculation is done in order to create a parametric cubic spline. In this approach, the parameter that is fed into the cubic equations is not the X value but an index value proportional to the distance between the edges. This is exemplified in Tables 1 and 2.

Table 1. Example of a set of vertices in which an index is created by the accumulated distance between the coordinates on a scale between 0 and 1..

X	Y	Accumulated Distance	Index Distance
0	0	0	0
1	1	1.41	0.21
2	1	2.41	0.35
3	3	4.65	0.68
1	2	6.89	1

This index value takes the parameter position in the spline cubic equations:

Table 2. The index assumes the place of the parameter in the cubic equations in the spline.

X	Index Distance
0	0
1	0.21
2	0.35
3	0.68
1	1

Y	Index Distance
0	0
1	0.21
1	0.35
3	0.68
2	1

Using the index, one first calculation is done retrieving an X interpolated value from an index parameter (in an equation of the type $x=a_x i^3 + b_x i^2 + c_x i + d_x$) and a second calculation retrieves an Y interpolated value for the same index parameter (positioning an equation $y=a_y i^3 + b_y i^2 + c_y i + d_y$). Each calculation follows the concepts given in the calculation example of given in the beginning of this sub-section.

The result of the points calculated for the example given in Table 1 can be seen in Figure 9.

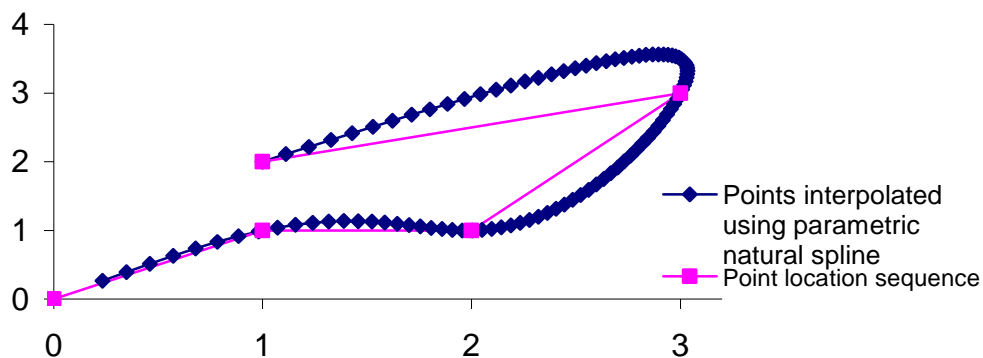


Figure 9. Natural parametric cubic spline retrieved from a sequence of 5 points.

2.2.2 Creating machine paths

In this thesis, paths are created by offsetting sampled field edges and linking them into a path and also by interpolating between offset edges using natural cubic spline interpolation. Example of created curved paths can be seen in Figure 9.

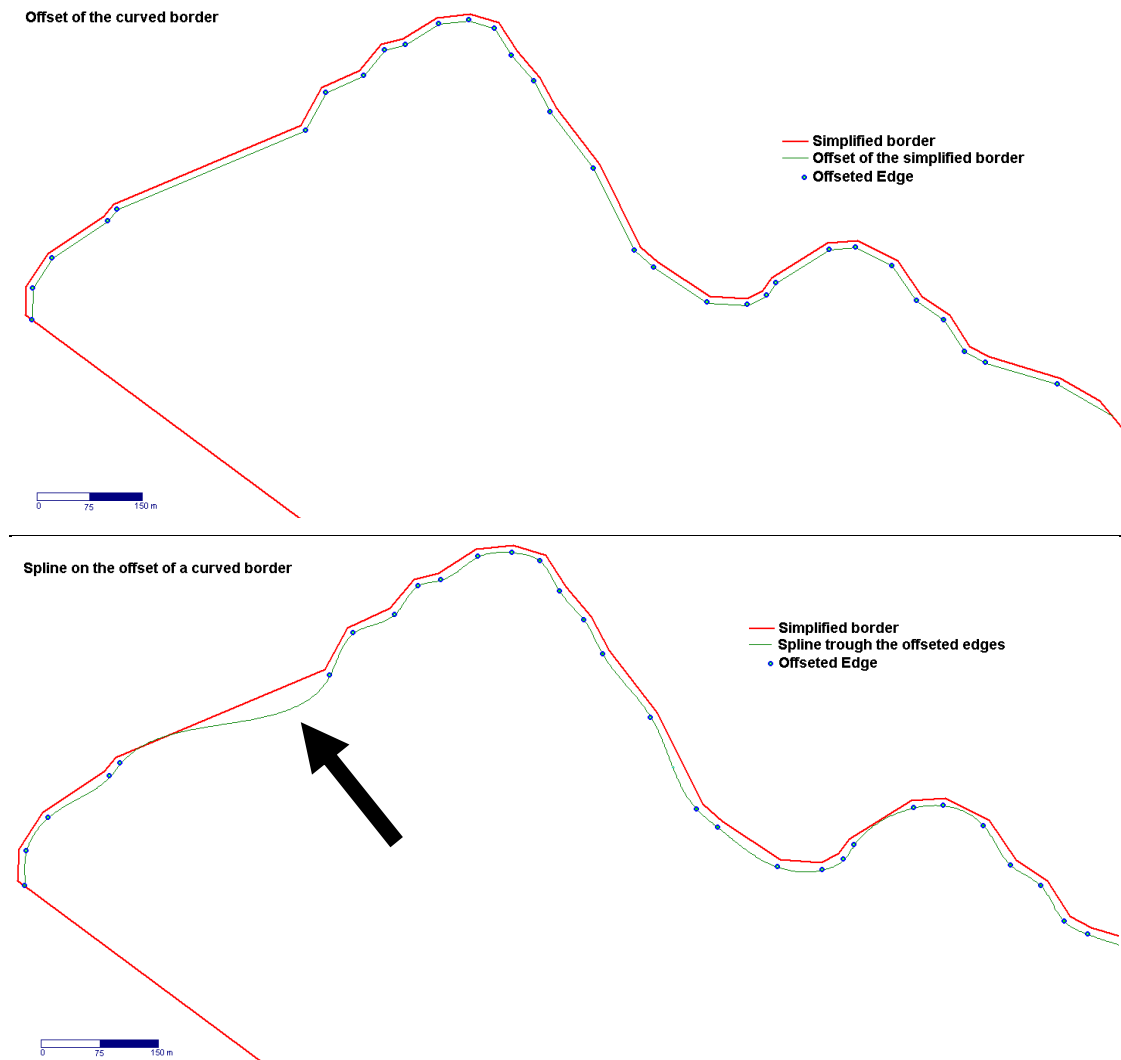


Figure 10. Paths created near a curved border by offsetting field edges (example above) and by using spline interpolation (example below).

In Figure 10, the black arrow points to an undesirable effect of the spline interpolation when smoothing a path. This effect is explored later on in the case-studies in chapter 3.

2.3 Assessment of curved paths

This section is related to answering research question 2.

In this thesis a field is a 2-D polygon defined by a set of edges with x and y coordinates. The width of the machine is required to calculate the distance between a machine path (near a field border) and the border of the field and also for determining the distance between adjacent machine tracks.

The aim is to fully cover the field with the machine operation and also to avoid overlap as much as possible. Efficiency can thus be assessed by the sum of non covered surface and overlapping surface.

The area wrongly covered in the created machine paths were calculated by:

- Area problems within a path;
- Area problems between a swath and the field's inner boundary;
- Area problems between adjacent swaths;

The way how these coverage problems affect the coverage is explained in the following sub-sections.

2.3.1. Area problems within a path.

As explained in the introduction, when an agricultural machine (like a sprayer for example) with an specific width performs an immediate turn, it generates simultaneously overlap and non-covered areas. Figure 11 exemplifies this effect when a machine is following a given path with immediate turns.

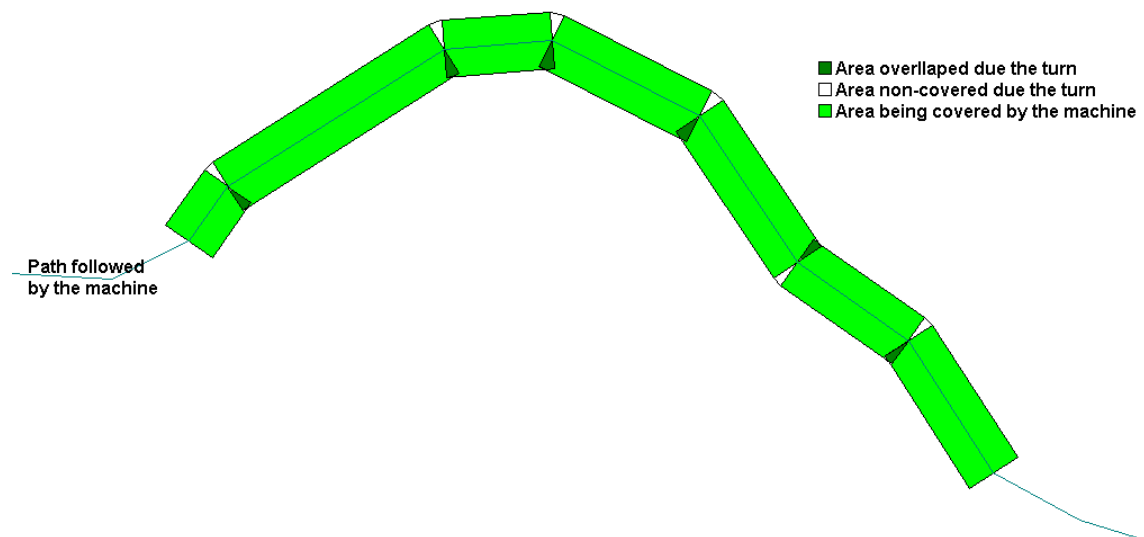


Figure 11. Simultaneous overlap and non-covered areas at edge turns along a curved machine path.

The problem of coverage within a path studied here focused on the value of the angle (in degrees) between each turn. Only turns above a specified threshold value were considered for measuring the impact of the problem because, in soft turns (under the threshold value),

the response time of the machine for changing it's direction of work is gradual, allowing a more proper coverage.

2.3.2. Area problems between a swath and the field's inner boundary

A curved path created near the border of the field is and assessed in relation to the original field. The path is buffered by the machine width originating the respective field area covered by the machine, this be seen in Figures 12 and 13 where the covered area would be a headland near a curved border. The area of the buffer that does not cover the border of the field, and the area of this buffer outside the field boundary are stored assessing the accurateness of the generated path.

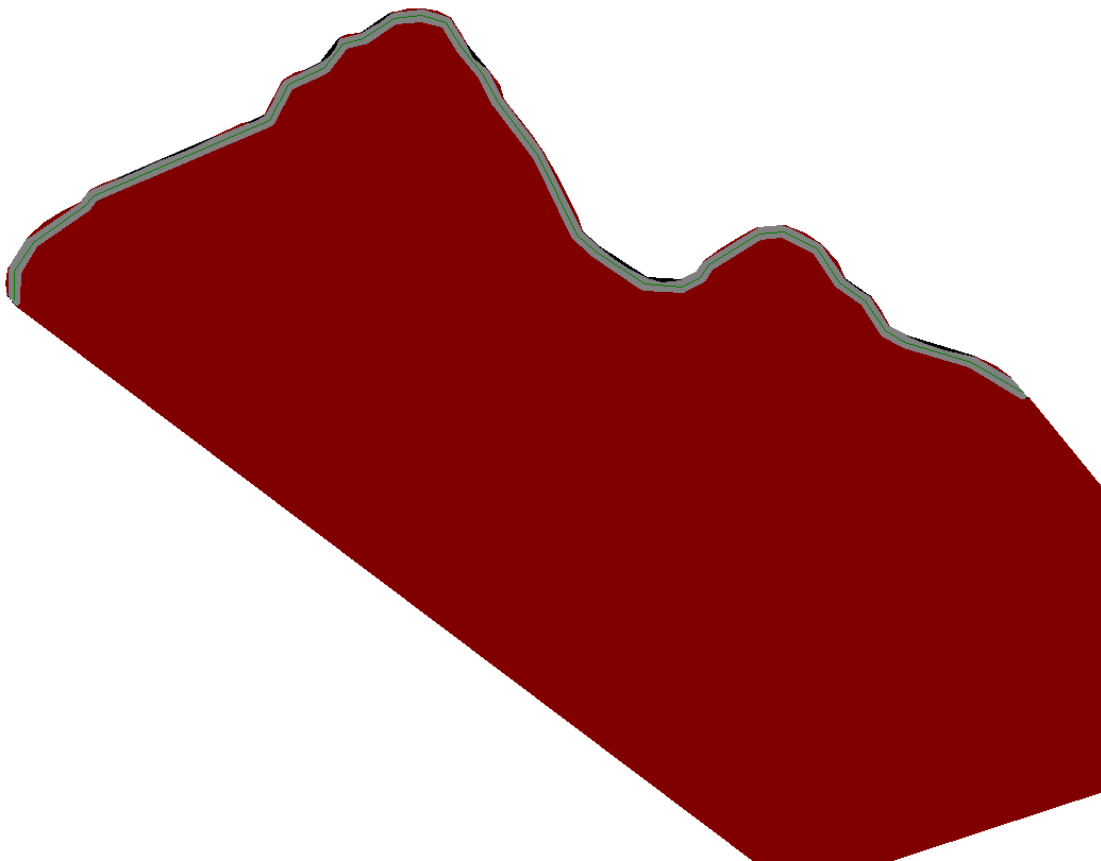


Figure 12. Example of a buffer of a path curved path (headland) created near a field border

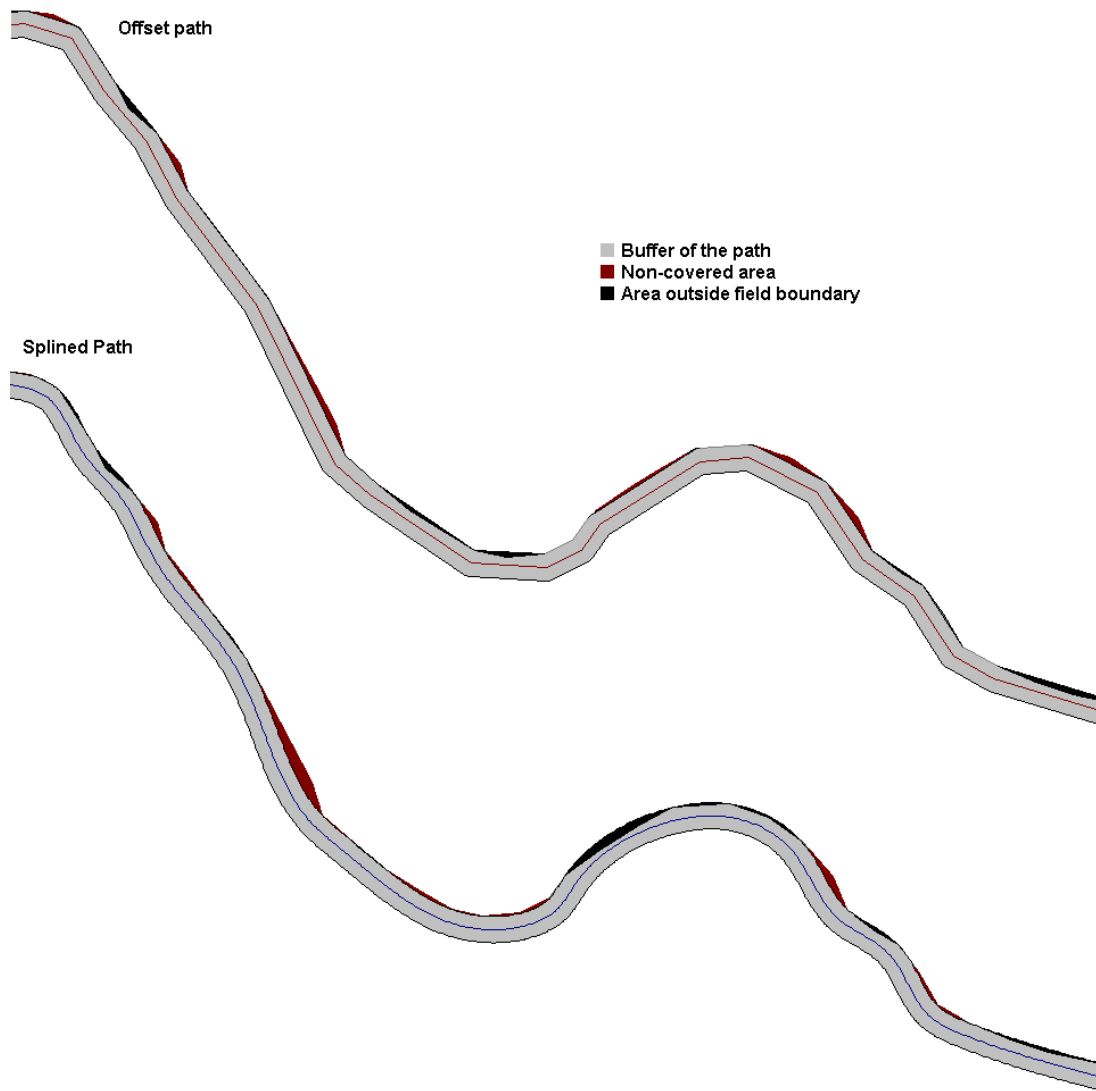


Figure 13. Overlap and non-covered areas originated between a path and the field's boundary (clipped from Figure 12).

2.3.3. Area problems between adjacent swaths

When sequential offsets are applied to a curved convex boundary, the distances between them (in the same path) decrease to the point that some edges disappear, increasing the roughness of the turn and reducing the accuracy for interpolation. This effect can be observed in Figure 14.

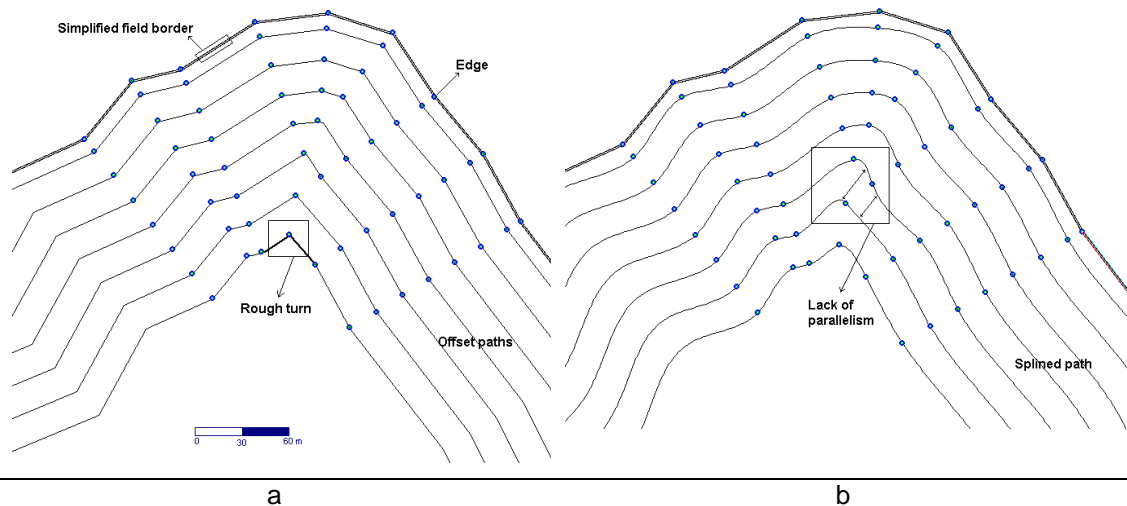


Figure 14. Example of problems in path generated by sequential offsets (a) and spline interpolation between the offset edges (b).

To assess this effect, parallel swaths were buffered and intersected among themselves to retrieve the overlap non-covered areas.

2.4. Two references used for assessing and for creating paths

For the assessment, the curved border used as reference must be as more representative as possible from the reality in order to evaluate how parallel is the path from it. But these path created is not offsetted from such a highly defined border, otherwise the paths will be always perfectly parallel to the field boundary, and the interpolation will have low (or no) effect. So the paths were offsetted from a representative sample of the field edges, to achieve this, the methodology herein applied was a simplification of the original field.

2.4.1. Field simplification

A field boundary in the real world can be seen as an infinite sequence of points. A large sample of accurately measured points along the field's boundary gives a more accurate representation of the shape of the field than a small sample. In this work the largest sample is used as a reference towards the effect of interpolating between a smaller sample. From a given field represented by a large sample of edges, the aim is to resample these edges to a new field that keeps the shape and the area as closely as possible to the original field. This sampling procedure is also known as a simplification of the field's boundary.

One known algorithm for line simplification is the Douglas-Peucker algorithm (Douglas and Peucker, 1973) that was first suggested by Ramer et al., 1972. In this algorithm one first given point is linked to a final point, and a verification is done with each of the points in between to see whether they stay within a threshold distance (typically denoted by epsilon) from the line that connects the two points. If for any point the threshold is surpassed the point is retained and the algorithm recursively checks the sequence between this new end point and the start point. Figure 15 displays some results found by Ramer (1972) using the above algorithm.

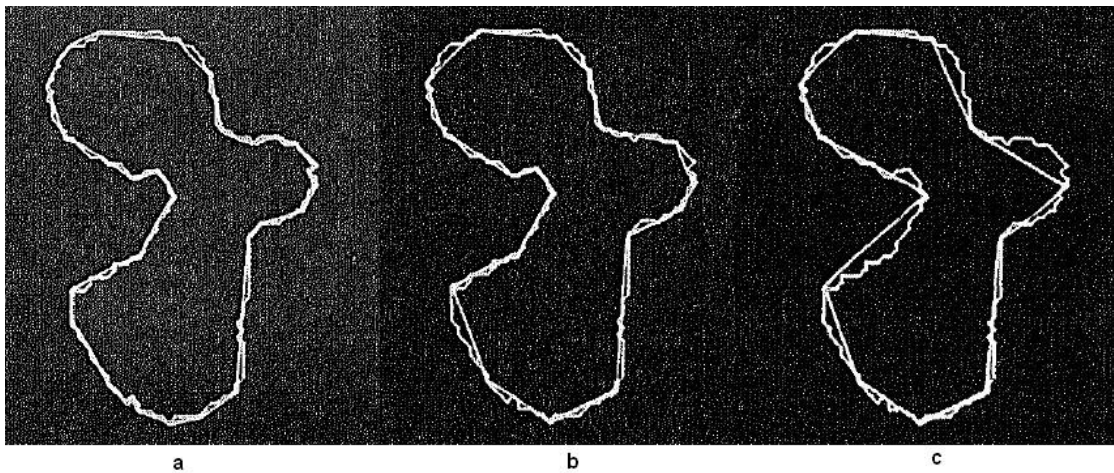


Figure 15. Example of a given polygon simplified by three different simplification thresholds (a, b and c). Extracted from Ramer (1972).

The offset and the interpolation occurs from the sampled edges (simplified field), but in the assessment of the path towards the field border, the original field (with higher number of edges) is used.

2.5. Improvement of the spline interpolation in the paths

The behavior of curved points interpolated by a spline are affected by the spline type and the number of control-points used (see chapter 2.2).

Adding new edges (or control points for the spline) in the exact middle of two straight edges (middle of one straight border-line) of the field, not changing the shape of the field, will increase the number of offset points also increasing the parallelism of a spline interpolation towards a field border. This procedure was applied into some case studies in order to evaluate it's effect.

2.6. Implementation

This section is related to research question 3. It focuses on the details of the tools and processes used to obtain the results. First there is a description of the tools that were built.

2.6.1. Environment

A program was developed in Microsoft Excel© spreadsheet using Visual Basic. The familiarity of this author with the Excel and Macro environment and the existence of tools already developed inside spreadsheets allowed speeding up the analysis. After the curved paths were generated, they were exported to a text file that was read by an intermediate program, GPS Trackmaker® (Ferreira, 1998), which allows visualization and to export as shapefiles to be assessed in ArcMap 9.3.1™ (ESRI ®) environment. In ArcMap, a model was built for assessing overlap and lack of area coverage..

2.6.2. Tools developed

Spline tool

Spline algorithms are available for several programming packages. But most spline algorithms available are still not fit for geographic smoothing purposes. Cubic spline interpolators can be found like pypspline 0.13 in Phyton™ (Phyton software foundation, no date); Spline Toolbox™ 3.3.8 of MatLab® (MathWorks®, no date). However, in this thesis, the work was implemented in Microsoft Excel. SRS1 Software. LLC (SRS1 , no date) offers freeware for Excel with a Visual Basic routine for cubic spline calculation; this software was used as a basis for the geographic implementation of splines.

For this thesis, an available algorithm developed in Visual Basic language in an Excel macro was used as base for the spline algorithm (SRS1, no date). This base algorithm was developed to achieve Y coordinate values from given X coordinate parameters; an example of the calculation of this can be seen in the spline example in chapter 2.2.

This thesis is accompanied by the source code in a CD where the spline function is located with the name of Spline_Val, in the module G1_Spline, in the spreadsheet "Field_Simplification_Splinning.xls".

Polygon offsetting

One of the main tools of the algorithm, it offset the field sides inwards or outwards at a given distance value from the original respective sides.

This thesis uses a own approach for offset of polygon sides. The methodology herein used is based in a two step process: offsetting and correcting.

First step: offsetting

The algorithm loops through all edges of a given polygon (in this case the given polygon is a field plot). A parallel of unlimited length is created near the original side, the distance of this new parallel side is equal to the offset distance or it is equal to zero (if it is not user defined to be offset). This parallel is intersected to the parallels of the next and previous sides in order limit and define a new side, Figure 16 exemplifies this process.

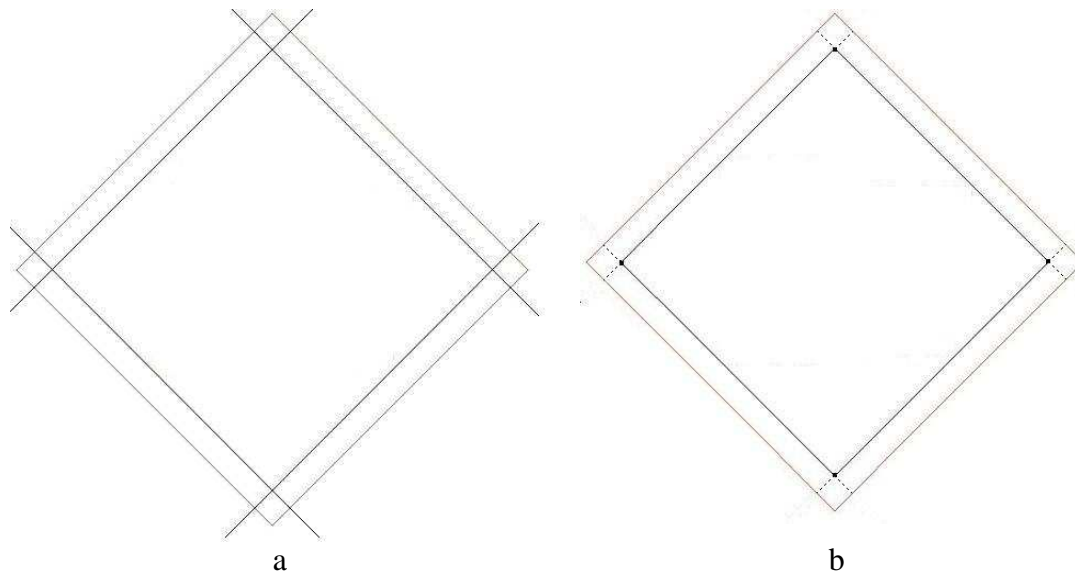


Figure 16. Example of the method used to create offset edges inside a polygon. In (a), parallels of unlimited length are created at the given offset distance from a original border. In (b) each parallel intersects with the next and previous parallels to obtain the new edges.

Second step: correcting

The first given step is capable of handling many offset purposes, but for many fields and/or offset distances the previous process alone is not capable of creating a correct offset path. This can be observed in Figure 17 where the offset field sides intersect themselves.

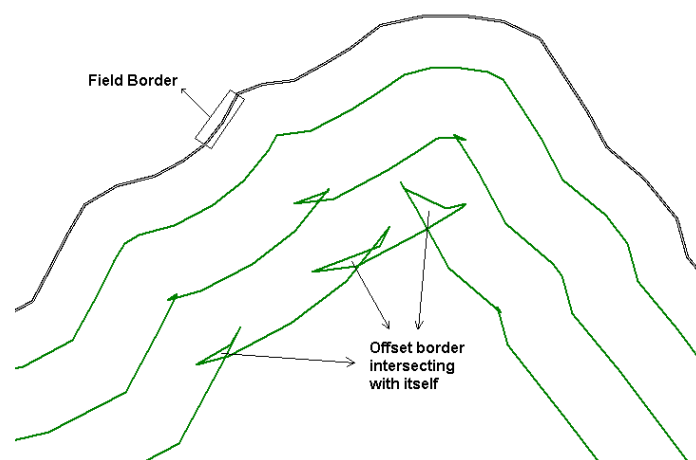


Figure 17. Self intersection of curves computed by offsetting.

From one self-intersected path (like identified in Figure 17) a new offset from all its edges is made outside its surroundings (see grey line in Figure 18). Suitable segments are not intersected by this new offset (green segments), but the segments that are intersected by it (red segments) are unsuitable and are excluded from the path.

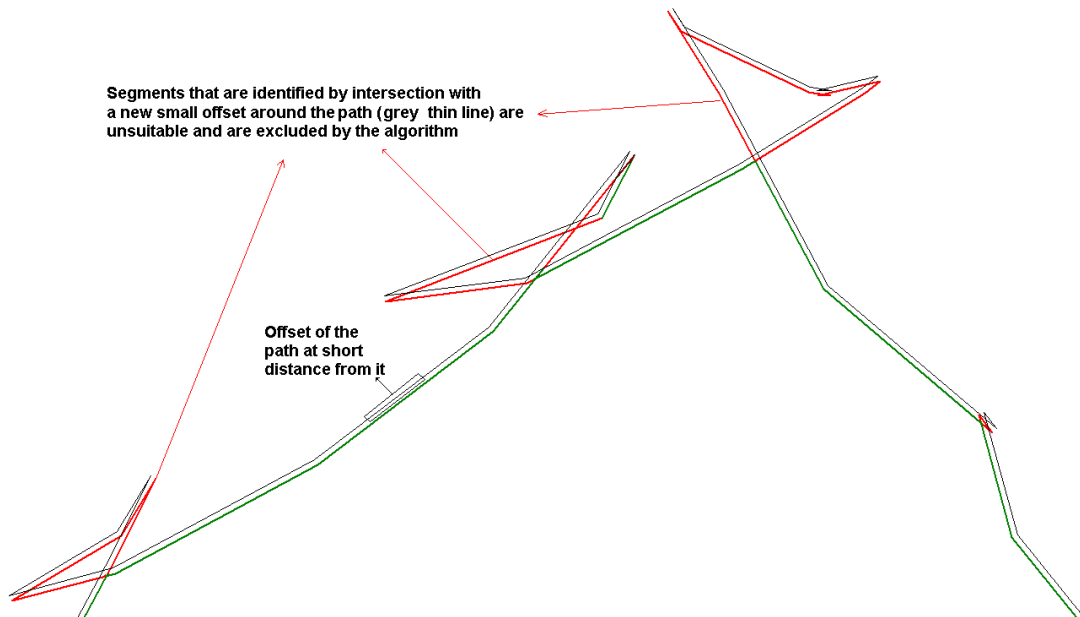


Figure 18. Example of identification of wrong segments that were identified by intersecting with a close offset of the path itself.

Results of the applied methodology for offsetting can be seen in Figure 19.

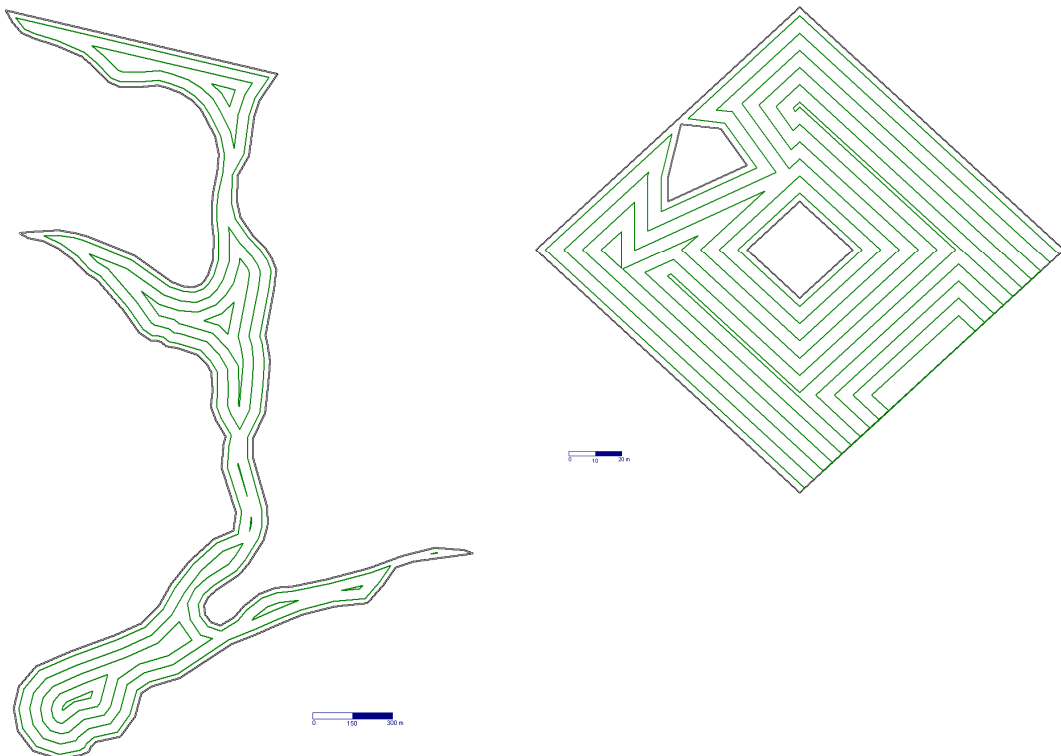


Figure 19. Results obtained from the application of the offsetting method used in this thesis.

Line simplification

The algorithm applied for boundary simplification is similar to the method of Douglas-Peucker (1973). The methodology used in this thesis follows the example given in Figure 20.

In Figure 20, we see in [a] two offsets created each side of a line at a given threshold distance from it; in [b] from one edge, a link is created into following edge sequentially advancing to the next one (lines in green) while this link does not intersect with any of the outer offsets, until the link makes an intersection (line in red), meaning that the previous edge to it was the farthest edge possible to be linked inside the given threshold; in [c] there is the complete sequence of edges sampled, observe that none of the lines touch the outer offsets.

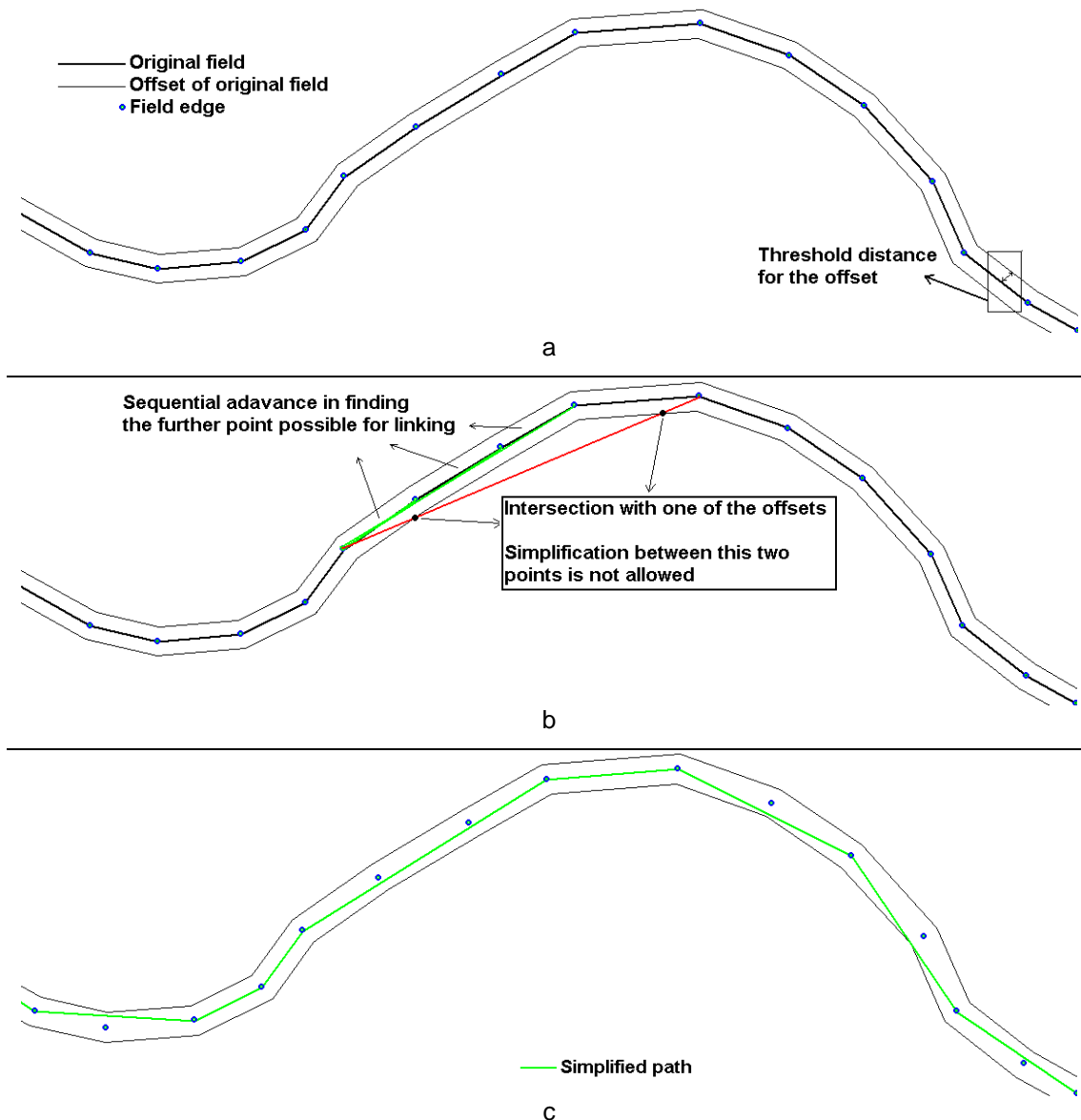


Figure 20. Description of work of the polygon simplification tool. The three steps in which points are sampled to form a new field

The choice of this method of simplification was because the of tools for verifying offset and polygon intersections had already been programmed, which allowed a fast development of the simplification tool. No comparison was done between this method and the Douglas-Peucker algorithm.

Retrieving angle and overlap area when turning between 2 line segments

This tool verifies the angle of change of direction between two line-segments (in this case, two following lines in a curved path). The calculation just uses the angle of one given segment and computes the difference with the angle of the next segment. The process can be seen in Figure 20.

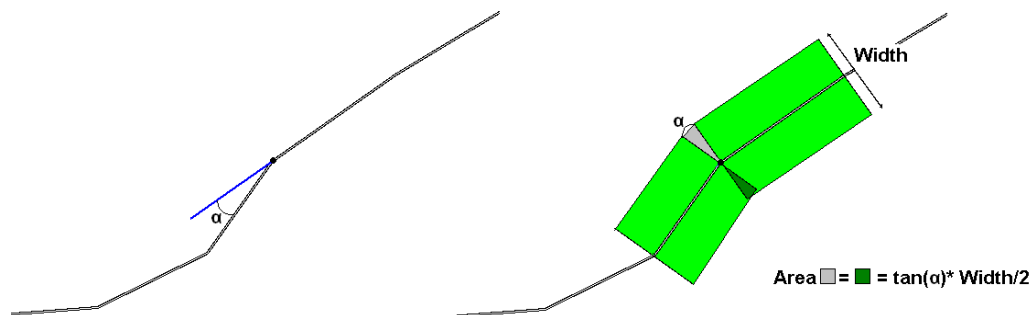


Figure 20. Explanation of the process for calculating the overlap and non-covered areas in the same path due to change in direction.

Like explained in the section 2.3.1, the only turns which have a change in direction (represented by α in Figure 20) higher than a given threshold are considered in the assessment.

2.6.3 Code box explaining the sequence of use of the tools and a more detailed explanation of the spline function:

```

Load Field_ID
Load Machine_Width
Simplify_Field (Field_ID, Field_Simplifier_Threshold)
Offset_Field(Field_ID, Machine_Width/2)

Load_Coordinates_to_Spline_Array(Spline_Array,X,Y)
Length_of_Path = Parametrize_Curved_Path(Spline_Array)
Index_Step=1 / (Length_of_Path / Distance_between_interpolated_points)
For i=0 to 1 Step Index_Step
    Spline(i,X,Y)
    Store_Interpolated_Value(X,Y)
End For

Function Spline(i, X_or_Y)
    NPC=Extract_Number_Of_Points_In_Curved_Path
    For j=2 to NPC
        Retrieve_X_or_Y_Values_For_Derivatives(X_or_Y, i )
        Calculate_and_Store_First_and_Second_Derivative( j-1 ,FD(j),SD(j) )
        Calculate_and_Store_First_and_Second_Derivative( j, FD(j), SD(j) )
    End For
    Find_Interval (i, Pair_Limits)
    Retrieve_Polynomial_Equation( i, Pair_Limits, FD(Pair_Limits), SD(Pair_Limits) )
    Calculate_Location_From_Equation(i,X,Y)
End Function

```

3. Case studies

3.1 Assessment of methods

This chapter is related to research question 4, where six case studies of fields with a curved border (see Figure 21) were chosen and paths were generated along their boundaries.

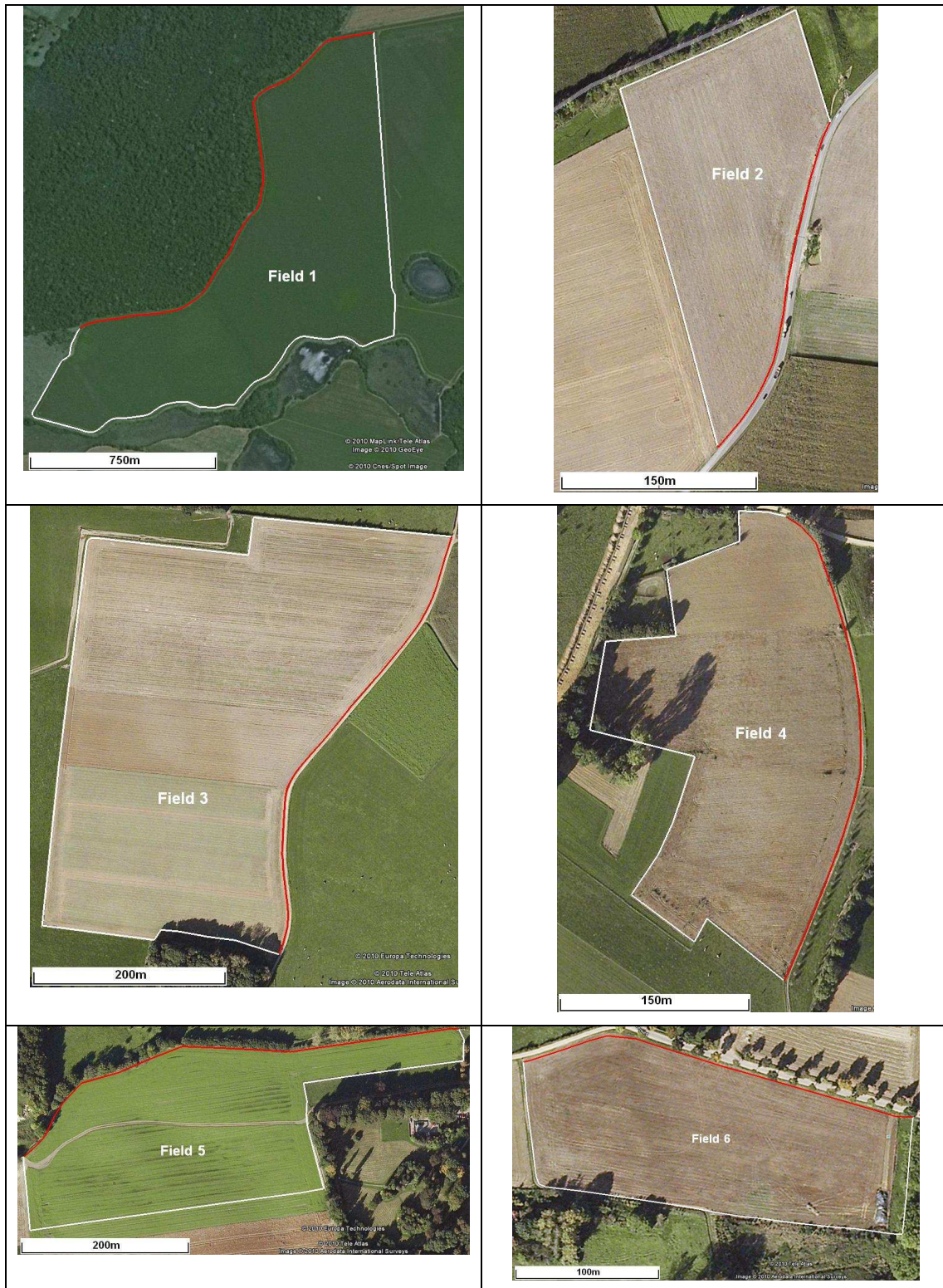


Figure 21. Identification of the fields used in the analysis and assessment. Borders are surrounded by a white line except by the curved borders in red used in the analysis.

The properties and parameters of the case studies used for data analysis and assessment are presented in Table 3.

Table 3. Simulation parameters of the case studies (Area, Type of measurement of field that was done and length of the curved border) and the settings chosen for assessing the paths created in the respective fields (Edges added to improve the spline interpolation, Simplification threshold and Distance between interpolated points by the spline).

Case study	Area (ha)	Type of measurement	Length of the curved border (meters)	Edges added to improve the interpolation	Simplification threshold (meters)	Distance between interpolated points (meters)
Field 1	100.76	Non-selective. Edge retrieved on motion using GPS receiver (1 point per second)	1972	No	5	2
Field 2	3.18	Selective, digitized in Google Earth	271.5	No	2	2
Field 3	12.35	Selective, digitized in Google Earth	490.5	No	2	2
Field 4	5.2	Selective, digitized in Google Earth	405.6	No	2	2
Field 5	6.6	Selective, field measurement using a GPS receiver	588.3	Yes	No	2
Field 6	2.6	Selective, field measurement using a GPS receiver	283	Yes	No	2

All fields were simplified at a given threshold (see simplification level in Table 3). From the assessment methods described in section 2.3 and 2.4 and improvement of paths from section 2.5, the fields were submitted to the following analysis:

- For fields 1, 2 and 3, two paths were created by the algorithm near the curved border of the fields: one offset path and one path with points interpolated using natural cubic spline. These paths were submitted to assessment of coverage of the path towards the original field border and also within the turns in the path.
- For field 4, a sequence of parallel paths smoothed by spline interpolation were created covering majority of the field, and the coverage was assessed between the paths.
- For fields 5 and 6, the assessment was done between two paths created by spline interpolation, one path used the original number of edges in the curved border, and the other one used additional edges created in between the existing ones.

3.1.1 Assessment of coverage of the path towards the original field border and also within the turns in the path.

Figure 22 displays a view of the assessment of the offset and splined paths created near the border of the Field 2.

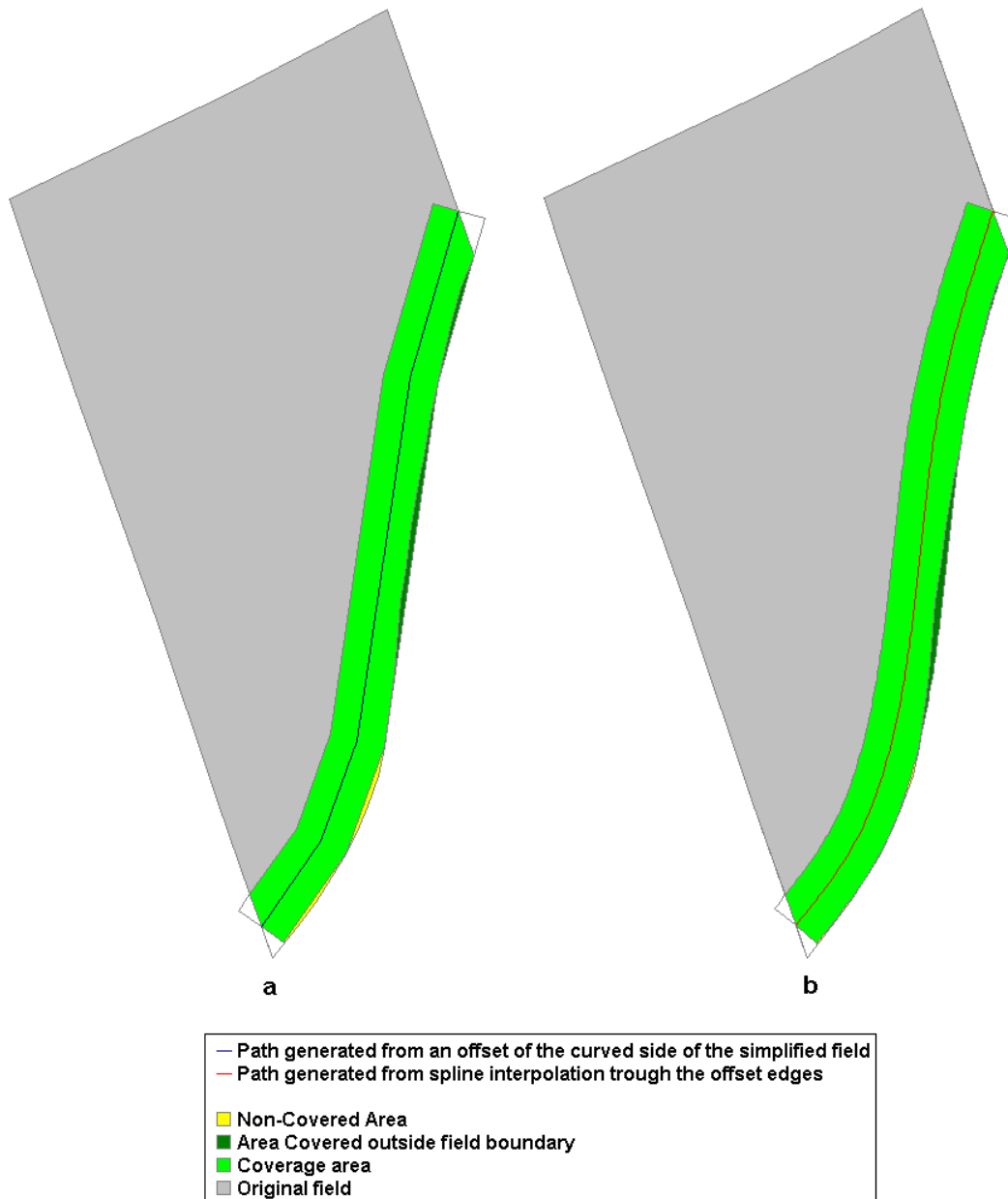


Figure 22. Illustration of differences in area coverage for the offset (a) and the spline (b) generated paths in Field 2.

In Figure 22 the curved border was simplified to 4 edges (see Table 4) and is possible to observe the smoothing effect between the path created by the offset of this edges (a) and the spline interpolation between them (b).

Table 4. Results obtained for three fields in analysis of accuracy of coverage near curved borders between offset paths and splined paths. Accuracy of coverage was done using the original field, while paths were retrieved parallel from a simplification of the field border.

	Field 1		Field 2		Field 3	
Offset/Spline	Offset	Spline	Offset	Spline	Offset	Spline
Simplification level (meters)	5.0	5.0	2.0	2.0	2	2
Number of points before -> after simplification	239 -> 24	239 -> 24	23 -> 4	23 -> 4	38 -> 7	38 -> 7
Length of the curved path (meters)	1897	2003	274	275	488	489
	Assessment of coverage of the path near the border of the field					
Area outside field boundary (m ²)	2600.00	3400.00	160.45	171.15	0.00	0.00
Area not covered near border (m ²)	1900.00	2000.00	82.44	30.50	213.15	280.40
	Assessment of coverage on turns for a minimum turn threshold					
Overlap area from turns higher than 10 degrees (m ²)	214.13	0	24.04	0	58.82	0
Non-covered area from turns higher than 10 degrees (m ²)	214.13	0	24.04	0	58.82	0
Overlap area from turns higher than 5 degrees (m ²)	228	0	30.98	0	78.23	0
Non-covered area from turns higher than 5 degrees (m ²)	228	0	30.98	0	78.23	0

The accuracy of coverage near a curved border for the three case studies was, in general, not improved when spline interpolation was used between the points. One example of this effect can be seen in Figure 23 in Field1, where the spline path extrapolated the limits of the field border in order to keep a smooth curvature.

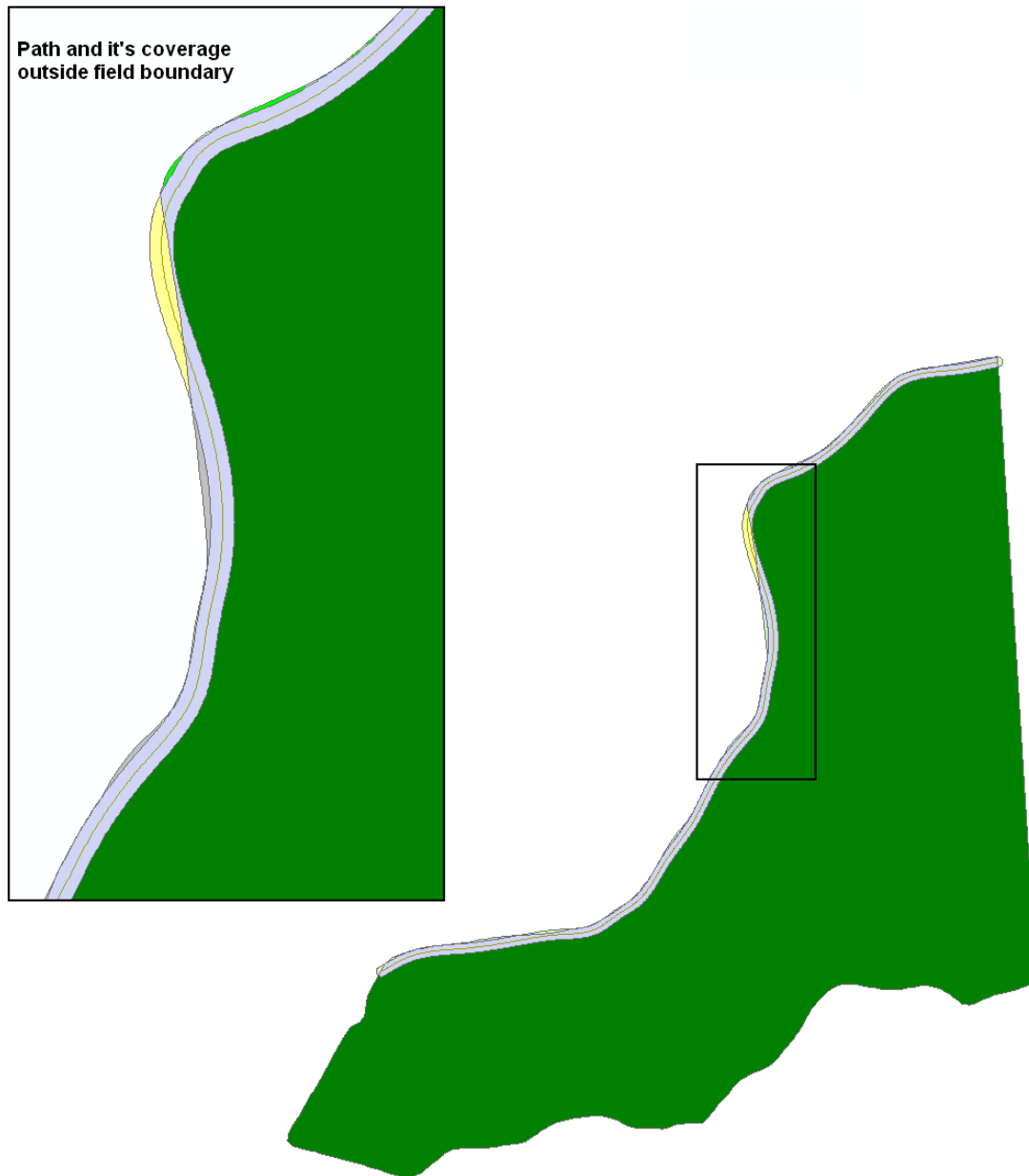


Figure 23. Example of extrapolation of the path outside the field boundary created by splinning.

In Figure 23, we can observe the reason for the high value of area outside field boundary found for Field 1 in Table 4.

For the coverage assessment between turns inside the path, no impact of coverage problems were found for splined paths, this can be seen in Table 4, where for two turn thresholds that could cause potential overlap and non-covered areas, no turn was found above the given threshold for the splined paths.

3.1.2 Assessment of multiple spline lines:

Field 4 was chosen for assessment of the multiple spline lines because it's shape allowed the definition of a more optimal curved path for it's coverage.

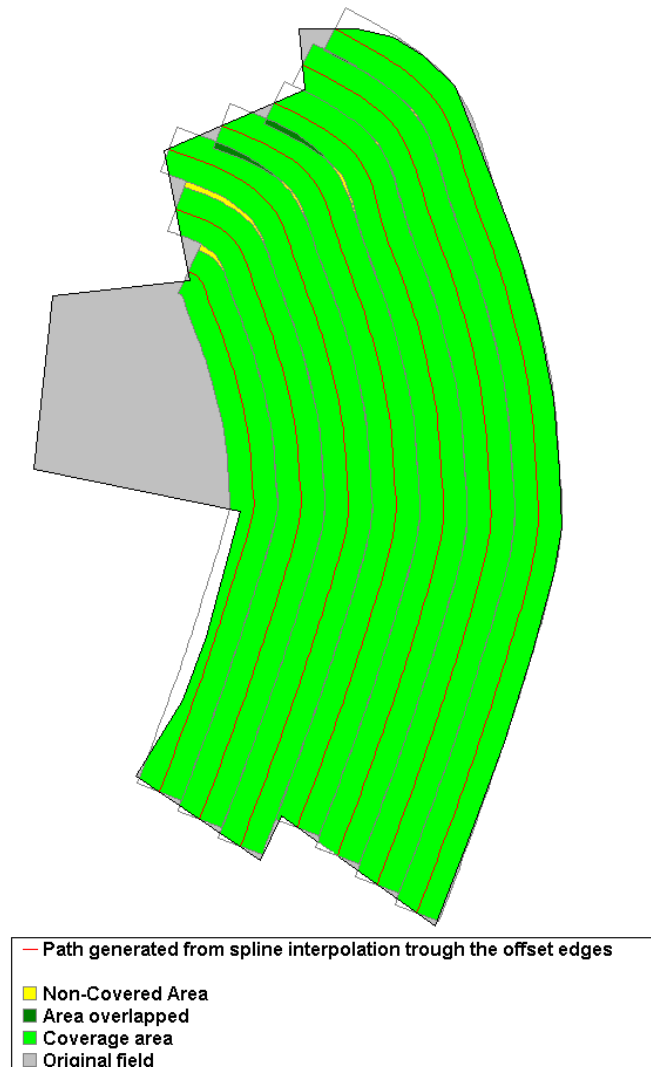


Figure 24. Illustration of the obtained for sequences of parallel paths created by spline interpolation in Field 4, and the coverage problems created.

The methodology of sequentially offsetting the curved border and interpolating between it was suitable only for the paths created closed the border. At a specific offset distance from border, edges started to be eliminated from the path (see explanation for this in Figure 14 in subsection 2.3.3) and the spline, with less control points, also started to lose parallelism with its neighbor swaths creating coverage problems. The overlap area obtained was of 273,7 square meters, and the non-covered areas were of 153.63 square meters which can be observed in Figure 24,

3.2 Improvement of spline interpolation in paths

The improvement was done following the method suggested in section 2.5, with addition of new edges in the exact middle of original edges of a curved border increasing the number of control points for the spline. The effect can be observed in Figure 25, where the parallelism of the interpolated path was increased in (b) with more points offset for interpolation in comparison with (a).

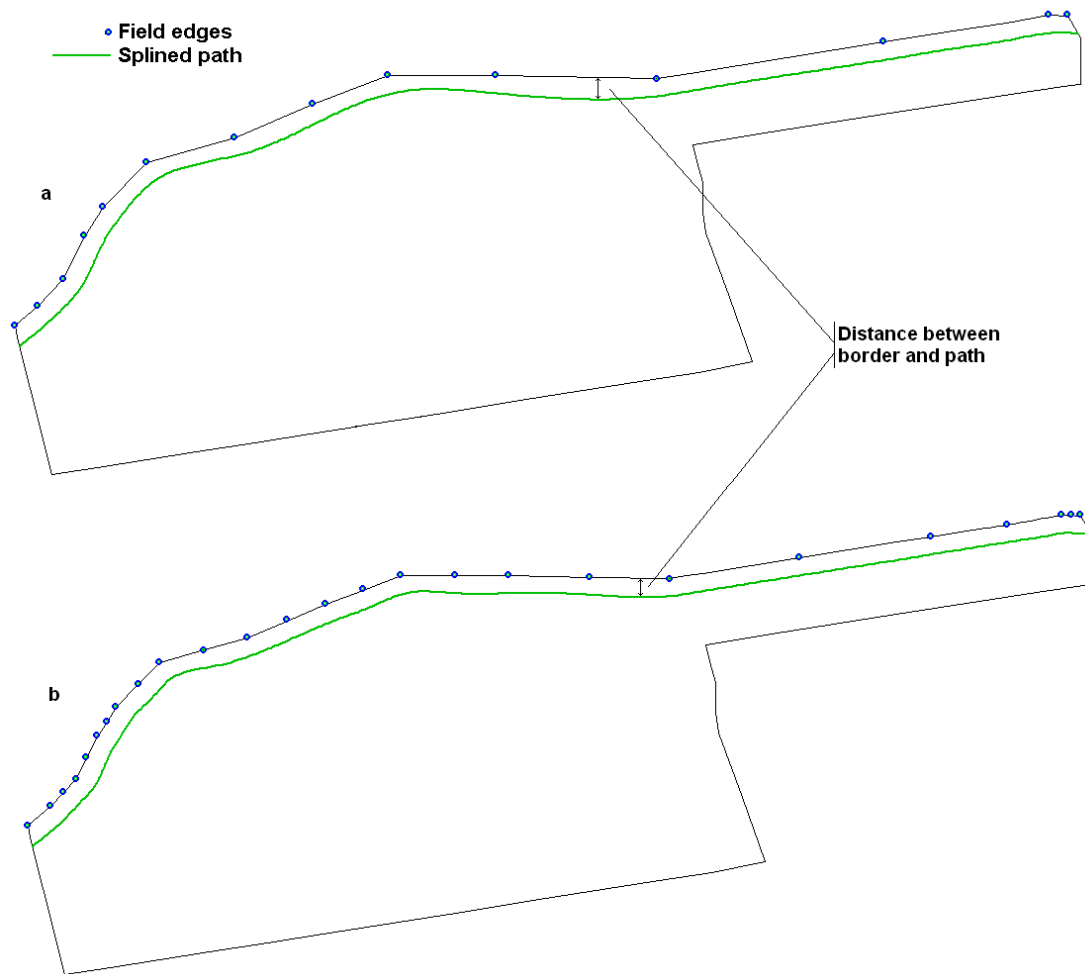


Figure 25. Difference in spline behavior near curved in Field 5 when points are added in the middle of edges.

In Figure 25, it is also pointed out the difference in distance between border and path between both outputs.

As expected, this had an influence on the accuracy of coverage. Figure 26 shows the improvement in coverage near the field border in (b) where this methodology was applied in comparison with (a) that had the original number of offset edges.

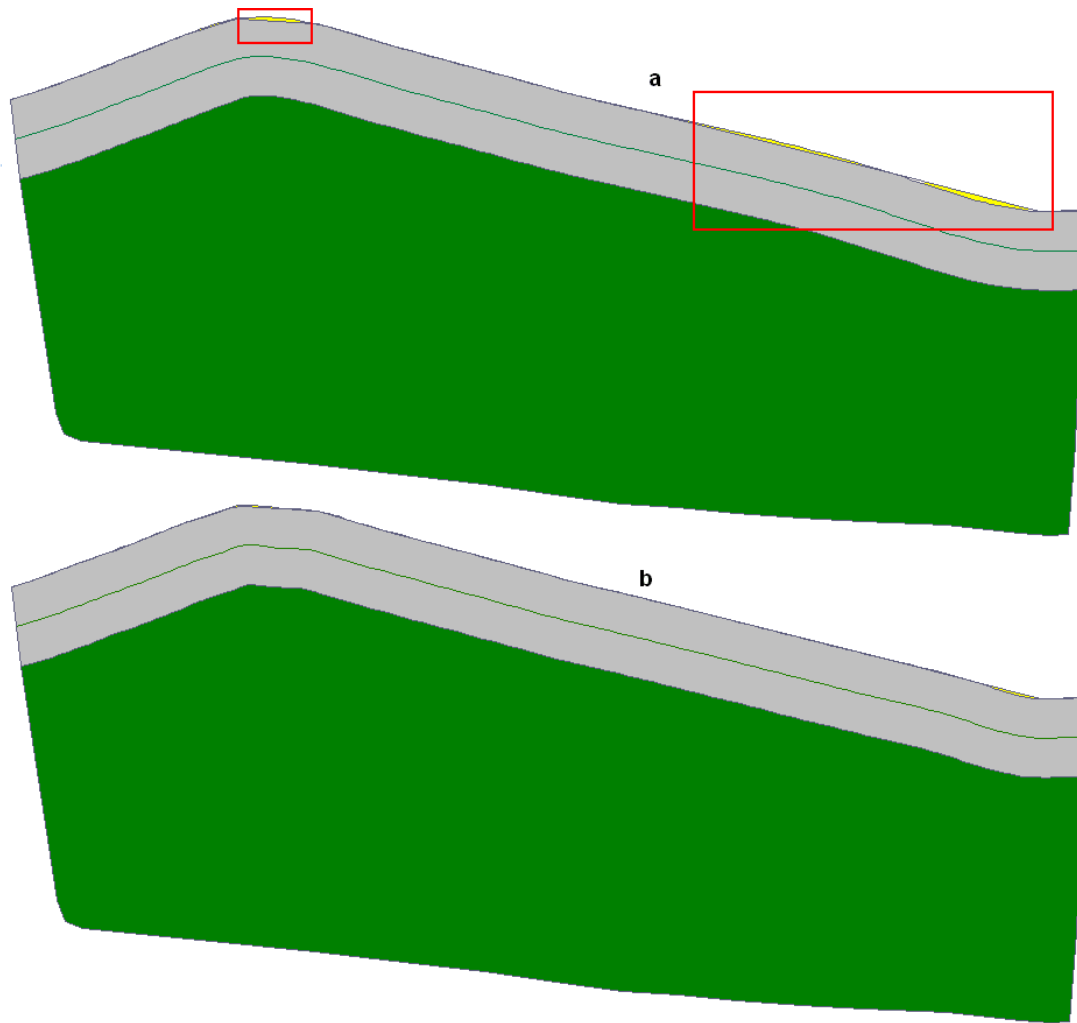


Figure 26. Comparison of coverage accuracy between paths created by splinning using the original number of edges in [a], towards using additional edges in between (like in Figure 25) in [b]. Red boxes enhance the coverage problems.

Table 5. Values found for area wrongly covered near field border for Fields 5 and 6 using splined paths created from the original number of edges and with the additional points of the methodology described in chapter 2.5 and visible in Figure 25.

	Field 5			Field 6		
	Original edges	Added edges	Decrease in coverage error	Original edges	Added edges	Decrease in coverage error
Length of the curved path (m)	594.04	593.45		281.5	281.3	
Area outside field boundary (m ²)	211.19	63.7	69.8%	50.66	8.33	83.6%
Area not covered near border (m ²)	193.36	58.32	69.8%	40.68	11.36	72.1%

Observe in Table 5 that the coverage error near the border decreased significantly when the approach was applied for both case studies.

4. Discussion

The proposed methodology for natural cubic spline interpolation between vertices in a curved path proved to be capable of creating smooth paths that are better suited for maneuvering machines in the field (see one example in Figure 22). This was possible to be obtained in all the in all case studies tried and can be observed also in Table 4 where potential edgy turns derived from an offset of a curved border were suppressed in the splined paths.

The intensity of the turning effect in edges is not only related to the roughness of the turn, but also to the speed of the machine, but this factor was not taken into consideration in this work. For accuracy in coverage near curved borders, no increase of coverage accuracy was obtained by the spline in comparison to offset of sampled edges and in most case studies, and the areas wrongly covered even increased for splined paths. This can be explained by the choice of spline type used in this work, where the change in the slope (or direction) created by control points in neighborhood has strong influence in the interpolation, a result of this effect can be seen in Figure 23. The use of other spline types which have stronger local control (like B-splines, mentioned in section 2.2) is a suggestion for further curved coverage planning studies.

Another approach to increase the parallelism of the actual spline type near a field border was to increase the number of field edges in the curved border without altering it's shape. The use of this approach in two case studies improved significantly (near and higher that 70%, see Table 5) the accuracy coverage of the path. But studies for a more accurate addition control points in between the edges still have to be done, once this approach herein blindly added those in the exact middle of the edges.

For multiple curved paths, the current methodology of offsetting limited field edges at any given distance is not suitable (the reasons for this can be seen in Figure 14 of section 2.3.3). One alternative for this can be a hybrid approach that splines interpolated edges in the original curved reference (like the field border) in short distances and offsets this references creating new smooth curved paths, this approach however stays as a point for further study.

5. Conclusion

The answers to the research questions are given below and demonstrate that the objective was achieved.

5.1 Answer to research questions

1. Which methods can be used to reduce the roughness of the turns produced on a planned path for a machine when following curved contours of a given field.

Most works available for curved agricultural path planning use references (like a field border for e.g.) for developing the path; therefore using references made of a high frequency of points is an alternative to obtain smooth paths (see Figure 6, chapter 2.1). This thesis focused in smoothing a sequence of given offset edges by adding more path points in between it through an interpolation capable of following curved patterns. To achieve this, natural cubic splines were used as an interpolation method. Previous work with spline methods in route planning exists, but few (or none) considered coverage planning.

2. How can suitability of the methods be assessed?

Accurateness of coverage can be measured by non-covered and overlapped areas. In this project three assessment methods for accurate coverage curved paths in fields were proposed: for assessing coverage problems created by harsh turns, for assessing the parallelism of paths created towards field borders and for assessing the parallelism between curved swaths created in the inner field. Simplification of the field-polygons by sampling it's edges was done in order to have a more rough representation of a curve that allows to assess the behavior of the interpolated points in relation to the original field (or a field that does not have it's edges sampled).

3. How can the methods be implemented in a path planning algorithm?

Packages for mathematical and graphical development of spline applications are available. In this work, an available spline algorithm, written in a programming language known by this author, was used as base for developing a spline application capable of interpolation two-dimensional coordinates (x and y) from a sequences of parameter points (see chapter 2.3.2 for spline implementation). Other tools were developed and implemented in the algorithm itself for offset of curved borders (necessary for retrieving the parameter points for splining) and for sampling points for curve simplification.

4. Which are the results for measures of RQ2 on a set of test fields?

Six case studies were applied in the suggested assessment-methodology. Spline proved to be a suitable option for reducing roughness and problem of coverage due to rough turns (see Table 4). The accuracy of coverage for splined paths was not improved in comparison with

offset of sample edges (see also in Table 4), but it was improved significantly when additional control points were merely added in between the existing point references (see Figures 25 and 26, and Table 5). Strategies for developing sequential parallel curved paths must be still developed once the approach herein used based on offsetting of field edges for which are some eliminated at specific offset distances creating lack of reference for the paths and lack of parallelism between the paths (see Figures 11 and 24).

5.2 Further work

Some points for further work are mentioned below:

- Study further the issue of number of and location of edges for splining and also the use of different spline types (like B-Spline), for increasing accuracy;
- Development of curved path made of an hybrid use of offset and spline. Were the paths are splined before being offsetted, increasing the number of edges (smooth edges) and making possible the offsetting of paths at long distances from a given curved reference keeping coverage accuracy.
- Study ways to optimize the machine work in fields when the use of curved patterns of work is compulsory because of environmental reasons.

References

- Agriculture and Agri-Food Canada, <http://www.peisland.com/agrtour/xslope.html>, Accessed 20/05/2010.
- Aichholzer, O., Aurenhammer, F., Alberts, D. and Gärtner, B.. 1995. A Novel Type of Skeleton for Polygons. *Journal of Universal Computer Science*, Vol. 1(12):752-761.
- De Carvalho, D.F.a b , Da Cruz, E.S.c , Pinto, M.F.d e , Silva, L.D.B.a b , Guerra, J.G.M. Características da chuva e perdas por erosão sob diferentes práticas de manejo do solo [Rainfall characteristics and erosion losses for different soil management practices]. 2009. *Revista Brasileira de Engenharia Agrícola e Ambiental*. Campina Grade, PB. V 13, n 1, pages 3-9. In portuguese.
- FAO Soils, *FAO Soils Bulletin – 70*, 1996. Erosion control practices. Land husbandry - Components and strategy. Natural Resources Management and Environment Department. Available in: <http://www.fao.org/docrep/t1765e/t1765e0l.htm>, Accessed 20/08/2010.
- Felkel, P. and Obdrzalek, S. 1998. Straight Skeleton Implementation. *Proceedings of Spring Conference on Computer Graphics*, Budmerice, Slovakia. pp. 210-218.
- Keicher, R. and Seufert, H., 2000. Automatic guidance for agricultural vehicles in Europe. *Computers and Electronics in Agriculture* 25, pp.169–194.
- House, Donald H. Splines. Course material. Division of Visual Computing, School of Computing, Clemson University. Available in: <http://www.cs.clemson.edu/~dhouse/courses/405/notes/splines.pdf>. Accessed in 20/08/2010.
- Lambert, Tim (no year). School of Computer Science and Engineering, the University of New South Wales. Sydney, Australia. Available in <http://www.cse.unsw.edu.au/~lambert/splines/>. Accessed in 28/07/2010
- Maekawa T., Noda T., Tamura S., Ozaki T., Machida K. 2010. Curvature continuous path generation for autonomous vehicle using B-spline curves. Elsevier. *Computer-Aided design* 42. pages 350-259.

- Mathworks, 2010. Spline Toolbox 3.3.8 - Create and manipulate spline approximation models of data – Official website (Online). Available in: <http://www.mathworks.com/products/splines/>. Accessed: 23/08/2010
- Oksanen T. and Visala, A., 2007. Path planning algorithms for agricultural machines. Agricultural Engineering International, The CIGR EJournal, Volume IX.
- Palmer, R.J., Wild, D., Runtz, K. (2003). Improving the Efficiency of Field Operations. Biosystems Engineering, 84 (3), 283-288.
- Python Software Foundation, 2009. Python Programming Language – Official website. (Online). Available: <http://www.python.org/pypi/pypyspline/0.13>. Accessed: 23/08/2010.
- Ramer, Urs. 1972. An Iterative procedure for the polygonal approximation of plane curves. New York University School of Engineering and Science. Published in: Computers graphics and image processing 1, pp. 244-256.
- Sparovek G., Schnug E., 2001. Soil tillage and precision agriculture. A theoretical case study for soil erosion control in Brazilian sugar cane production. Elsevier. Soil & Tillage Research 61. pages 47-54.
- Spekken M., de Bruin S., 2010. Optimizing routes on Agricultural fields minimizing maneuvering and servicing time. Thesis. Wageningen University and Research Centrum, Alterra.
- SRS1 software (no date). SRS1 Cubic Spline for Excel v1.02. Available in <http://www.srs1software.com/download.htm#spline>. Accessed 26/07/2010.
- Stoll, A., 2003. Automatic operation planning for GPS-guided machinery. Precision agriculture. Eds Stafford, J. and Werner, A. Wageningen: Wageningen Academic Publishers, pp. 657-644.
- VBForums (no date). Parametric Cubic Spline Tutorial. Available in <http://www.vbforums.com/showthread.php?t=481546>. Accessed 26/07/2010.
- Walther M., Steinhaus P., Dillman R (no date). Using B-splines for mobile robot path representation and motion control. Institute for Computer Engineering, Universität Karlsruhe.. Availabe in <http://www.iain.ira.uka.de/data/File/Publications/using%20b-splines.pdf>. Accessed in 23/08/2010.