Trees (1997) 11: 265–270

ORIGINAL ARTICLE

Hervé Sinoquet · Pierre Rivet

Measurement and visualization of the architecture of an adult tree based on a three-dimensional digitising device

Received: 10 April 1996 / Accepted: 26 August 1996

Abstract A method for the measurement of the three-dimensional (3D) architecture of trees is proposed. The method works at the shoot level and simultaneously describes the plant topology (i. e. branching pattern), the plant geometry (i. e. spatial co-ordinates of the tree entities) and the shoot morphology (i. e. number of shoots and fruits, basal diameter). The method combines a 3D digitising device (3SPACE FASTRAK, Polhemus) associated with software DiplAmi designed for digitiser control and data acquisition management. Plant images may be reconstructed from the data set by using the ray tracing software POV-Ray. The method was applied to the architectural description of a 20-year-old and 7-m-high walnut tree. Visual comparison between a tree photograph and an image synthesised from digitising is satisfactory. Information that can be derived from the data set at both the whole tree and the shoot levels is respectively illustrated from shoot morphology distributions and from spatial distribution of leaf area and fruit. Spatial distributions of leaf area and fruit are in agreement with previous results and hypotheses involving light gradients within the crown. Finally, methods for describing the 3D tree architecture are discussed as well as the feasibility of the method when applied to such a large tree.

Key words Tree architecture · Topology · Geometry · Shoot scale · Digitising

Introduction

Several models for tree architecture dynamics have been developed in the last decade. They may compute realistic descriptions of the tree structure, using various techniques: e. g. stochastic approach (De Reffye et al. 1991), fractals (Chen et al. 1994), and L-systems (Prusinkiewicz et al. 1994). Some models describe a tree population grown in given conditions from botanical principles while others try to compute tree architecture as the result of botanical informations and complex interactions between the tree structure and its environment (e. g. space competition, Blaise and de Reffye 1994; light competition, Takenaka 1994). Because underlying principles are related to meristem activity, all these models deal with growth units which define a shoot scale.

Testing these models needs measurement methods for the three-dimensional (3D) architecture of the tree. Tree architecture description should include a botanical sense, i. e. branching and topological relationships between the plant units (Hallé et al. 1978), and a geometrical sense, i. e. the spatial location, orientation, size and shape of the vegetation elements (Ross 1981).

This paper presents a new method for the 3D description of tree architecture. It uses a 3D digitising device combined with a software designed for a simultaneous acquisition of topology (successive levels of branching), geometry (3D co-ordinates) and morphology parameters at the shoot scale. The method was applied to a 20-year-old walnut tree in order to identify difficulties associated with large plant size and great number of growth units.

H. Sinoquet (✉) · P. Rivet
Unité Associée Bioclimatologie-PIAF, INRA, Domaine de Crouelle, F-63039 Clermont-Ferrand Cedex 02, France

Materials and methods

3D-digitiser

The device is a FASTRAK 3D-digitiser from Polhemus (Colchester, Vt., USA). The digitiser measures spatial co-ordinates of any point within an active volume. The device consists of a system electronics unit, a magnetic generator and a pointer to locate onto the measured points (Polhemus 1993). The magnetic source generates three perpendicular low-frequency magnetic fields from a triad of electromagnetic coils. The pointer includes a triad of electromagnetic coils where currents are induced when placed in the magnetic fields. Current intensities in each pointer coil induced by each source coil are related to the location and orientation of the pointer within the active volume (Raab et al. 1979). The size of the volume depends on the generator power: it is a sphere of 1-m-radius if the standard source is used, but a sphere of 4-m-radius with the Long Ranger option used in this application. The system unit controls the magnetic source, collects the data from the pointer, computes the positions and orientations and communicates with a microcomputer via an RS-232C connection.

From Polhemus' specifications, the resolution of the 3D-digitiser for measuring spatial co-ordinates is 0.05% of the distance between the source and the pointer, while the standard error in locating a given point is 0.8 mm. Digitising on maize leaves in the laboratory showed that the standard error in measuring co-ordinates is less than 1 mm (Moulia and Sinoquet 1993). Finally the only practical limitation is that other magnetic sources or large metallic objects have to be removed from the active volume because they modify the magnetic fields.

Data acquisition

Measurement of the tree architecture is driven by a software called DiplAmi. It was written in 1995 by Pierre Rivet and runs under Windows 3.1 on PC computers. DiplAmi is especially designed for simultaneous data acquisition on branching, spatial co-ordinates and shoot morphology.

The description of the plant topology uses coding proposed by Godin and Guédon (1996). The plant is described in terms of axis, segments and growth units. The axis of level 1 is the trunk, it bears axes of level 2 which are the branches connected to the trunk. Axes of level 3 are branches connected to the main branches, and so on. A segment is defined as a portion of woody part without branching. A growth unit is defined as a growth flush, it is therefore a leafy part. In case of walnut, the annual shoot may be made of two or three growth units because of possible polycyclism. An axis is then a combination of segments and growth units if the terminal bud gave an annual shoot. This description with only three types of entities does not allow one to look into the tree history: the age distinction is only made between plant parts developed during the current year and during the former years, i. e. in terms of growth units and segments, respectively.

Relationships between the tree entities are described by three operators: symbol / means 'is made up of' (e. g. an axis A is made up of segments and growth units); symbol > means that the next entity comes from the same meristem as the previous entity (e. g. the succession of segments making up a branch, or the succession of growth units making the annual shoot, if no sylleptic branching occurs during the current year); symbol + means branching, i. e. the next entity comes from an axillary bud borne by the previous entity.

In practice, the tree description begins at the base of the trunk. The basal portion of the trunk may be described as a set of segments until the first branch is reached. This one is then defined as a new axis and described as a set of segments until branching occurs. This way of describing each new axis of greater level before the end of the current branch allows one not to miss tree parts. When the distal tip of a branch is reached, the operator goes back to the previous branching level, i. e. to the proximal tip of the last digitised axis. The 'end of axis' information does not need to be coded since it is implicitly contained in the branching level data. Such a way enables one to describe any branching pattern, including stem or branch forking, or sylleptic growth.

All branches and shoots are digitised and topologically described. At the same time, the diameter of each entity is measured with a Vernier calliper. In addition, the number of leaves and fruits on the growth units are recorded in order to provide a bulk description of shoot morphology. Leaf area of a shoot is estimated separately from its basal diameter. The relationship has to be calibrated from a set of shoots sampled on similar trees. In this application which deals with a shoot scale, the shoot description as a leaf distribution is disregarded.

Software DiplAmi arranges data in an ASCII file, each line of which contains the data on one entity. Additionally, DiplAmi allows one to configure the digitiser (e. g. defining a reference frame) and build the files requested to create plant images.

Plant images

Plant images are created by using freeware POV-Ray (Persistence of Vision Raytracer, version 2.2, released by POV-Ray team in 1993), which is a ray-tracing software devoted to image synthesis. POV-Ray allows one to define the elements of a scene from numerous shapes. In this application, branch parts are represented as frustrums and cylinders, the co-ordinates, orientation and diameters of which are given from data measured on the tree. POV-Ray also allows one to define the geometry (i. e. location and direction) of the light sources illuminating the scene, and that of the camera looking at the scene. Software DiplAmi allows one to convert the information on tree architecture into the input file format of POV-Ray.

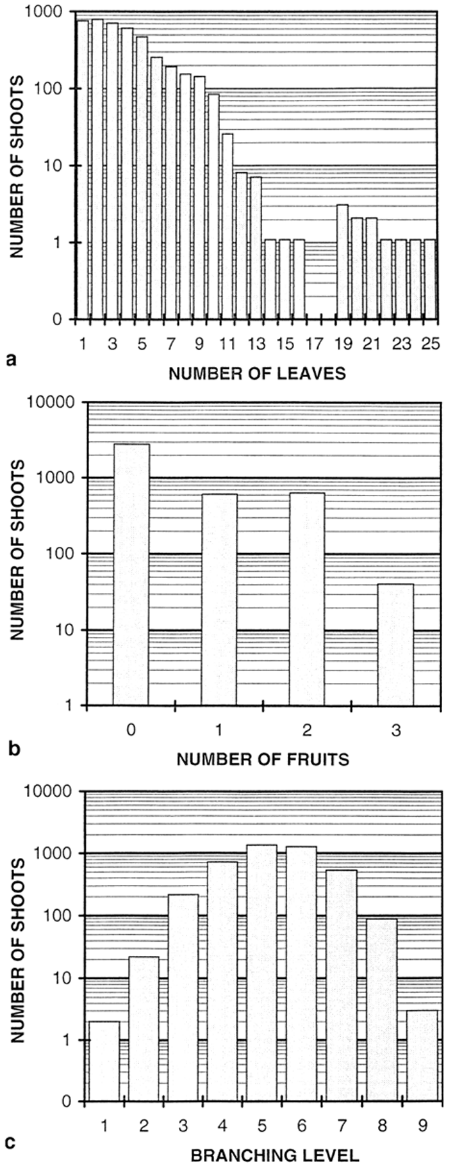

Fig. 1 Shoot distribution of a 20-year-old walnut tree as a function of number of leaves (**a**), number of fruits (**b**), branching level (**c**)

Illustration of the method

The method of 3D-description of the tree architecture was applied to a 20-year-old walnut (*Juglans regia* L. cv. Parisienne) trained as open-vase. The tree was grown in a hedgerow orientated in a north-east/south-west direction.

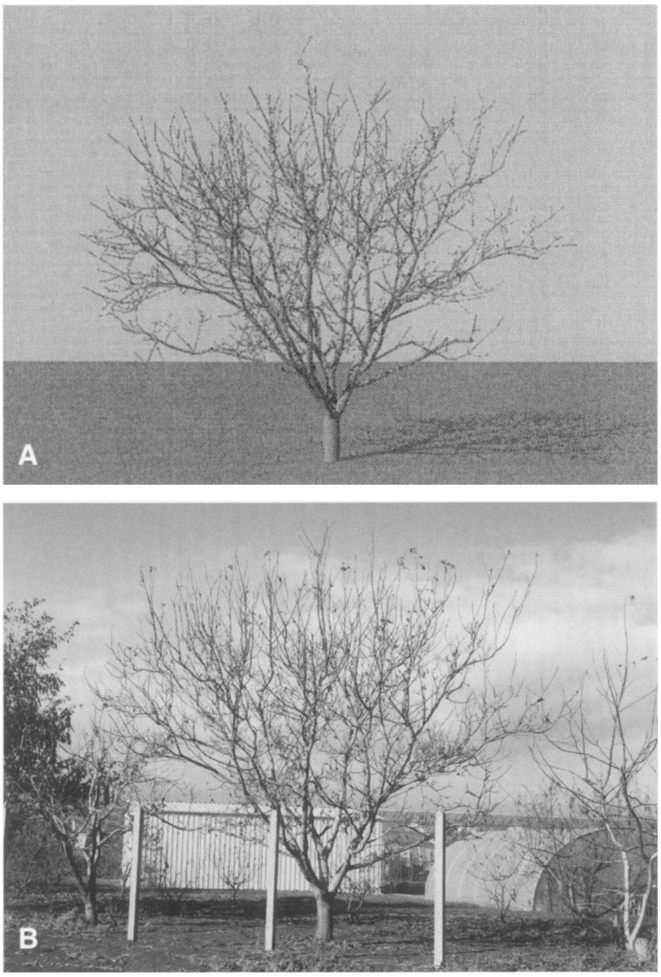

Fig. 2 Comparison between a ray traced image synthesised from digitising (**a**) and a photograph (**b**) of a 20-year-old walnut tree taken after leaf fall. Sun and view configurations are the same on the two pictures

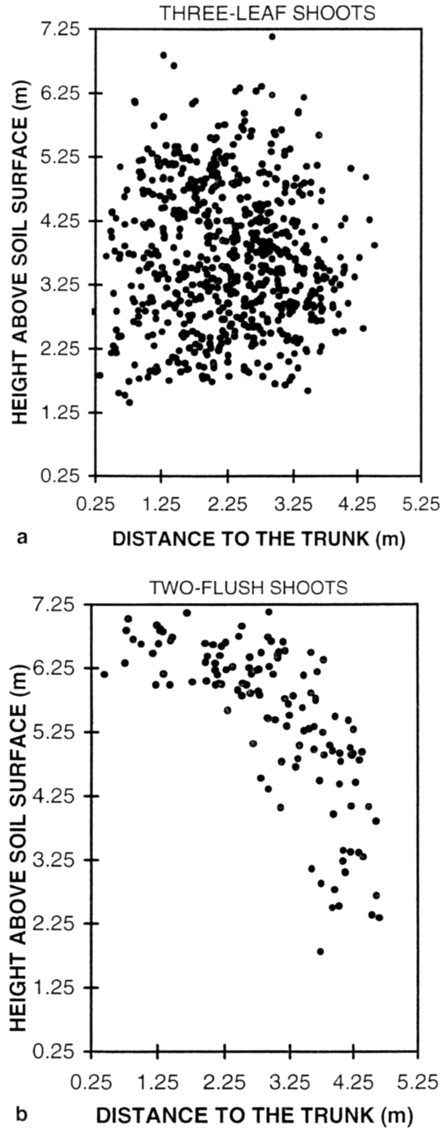

Fig. 3 a, b Spatial location of shoots within the crown of a 20-year-old walnut tree as a function of radial distance to the trunk (*X*-axis) and altitude (*Y*-axis): **a** three-leaf shoots; **b** two-flush shoots

Tree height estimated from the height of the highest shoot was 7.1 m while the lowest shoot was 1.2 m above the soil surface. Tree radius ranged from 4 to 5 m. Assuming the crown was an ellipsoid led to a canopy volume about 250 m^3. The digitised tree included 4213 growth units bearing 16 224 leaves and 2007 fruits. Branching level of shoots ranged from 1 to 9.

The data set allowed us to derive shoot distributions as a function of leaf number, fruit number and branching level (Fig. 1), i. e., disregarding the spatial information. Only 3% of the total shoot number included two growth units, meaning that polycyclism was weak in a tree of this age. Small shoots (i. e. from 1 to 5 leaves), medium shoots (from 6 to 10 leaves) and large shoots (more than 10 leaves) represented 79, 20 and only 1.3% of the total shoot number, and bore 57, 38 and 5% of the total leaf number, respectively. Only 31% of the total shoot number bore fruits. Shoots with 1, 2 and 3 fruits represented 47, 49 and only 3% of the fruited shoots, respectively, but about ⅔ of the fruits were attached to two-fruit shoots. Most shoots (92%) were attached to branches whose level was between 3 and 7.

The quality of the spatial information was visually assessed by comparing pictures of the tree resulting from digitising with photographs taken after leaf fall in late October (Fig. 2). Sun and view configurations are the same on the two pictures. Though only visual, the comparison shows that the digitised tree is very close to the real tree. Main branches have similar locations and mutual shading between branches is correctly rendered in the digitised tree. This implicitly indicates that shoot location within the tree is likely to be correctly estimated. The effect of wind on branch movement is shown in the upper branches (Fig. 2 a) which may look like broken lines. This appears to be the main limitation of the method.

Figures 3 – 5 illustrate the spatial information that can be derived from the data set. Figure 3 a and b shows the spatial distribution of three-leaf and two-flush shoots. Three-leaf

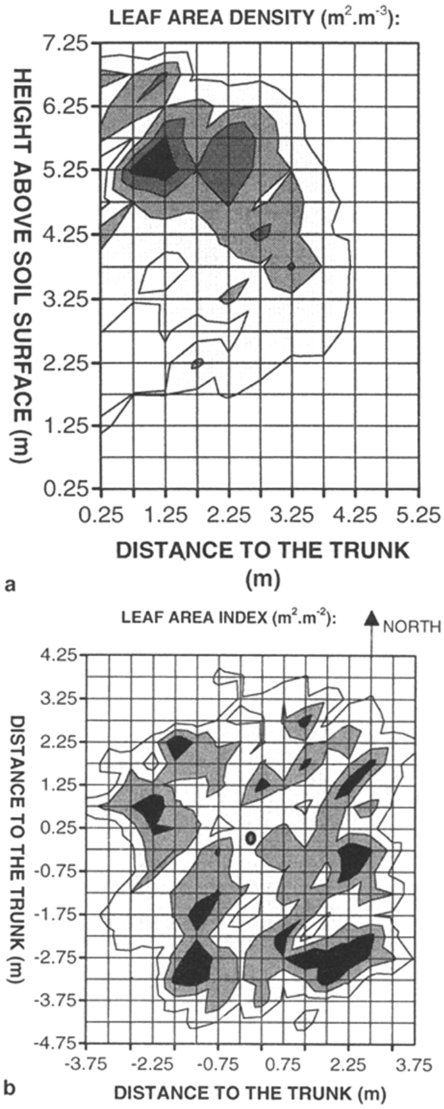

Fig. 4 a, b Spatial distribution of leaf area within the crown of a 20-year-old walnut tree: **a** isolines of leaf area density ($m^2.m^{-3}$) as a function of radial distance to the trunk (*X*-axis) and height (*Y*-axis); **b** isolines of leaf area index ($m^2.m^{-2}$) in the horizontal plane (i.e. integrated over heights)

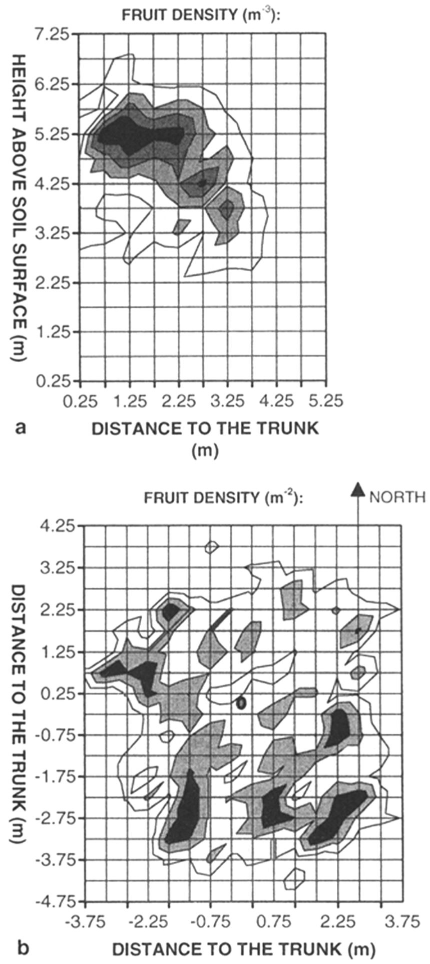

Fig. 5 a, b Spatial distribution of fruits within the crown of a 20-year-old walnut tree: **a** isolines of fruit density (m^{-3}) as a function of radial distance to the trunk (X-axis) and height (Y-axis); **b** isolines of fruit density (m^{-2}) in the horizontal plane (i.e. integrated over heights)

shoots are distributed in the whole tree volume with a smaller density in the periphery of the crown. In contrast, two-flush shoots are located only in the periphery of the crown. This result is supported by the vigour gradient from the outer to the inner part of the tree crown, which is related to light gradient (Hardwick 1986; Sprugel et al. 1991).

Figure 4 shows the spatial distribution of leaf area density. The relationship between shoot leaf area and shoot diameter was established from shoots sampled in another walnut tree of the same age and variety, on the same hedge. Isolines of leaf area density as a function of height and radial distance from the trunk clearly shows that leaf area density is larger in the upper part of the tree canopy (Fig. 4a). Within the upper hemisphere, a gradient of leaf area density exists from the centre of the outer of the crown. Isolines of leaf area index (i.e. cumulated leaf area above a unit soil area) in the horizontal plane also shows large azimuth variations in leaf area density (Fig. 4b). First, extension of the tree crown from the trunk location was larger in the south than in the north. Second, leaf area density was greater in the south part of the canopy. Third, there is a decrease in leaf area density along a north-east/south-west axis, i.e. the hedgerow direction where light competition from neighbouring trees occurs. These results agree with observed changes in leaf area density within tree crowns (e.g. Whitehead et al. 1990; Cohen et al. 1995). Foliage density generally increases with light availability. The underlying hypothesis is that shoot leaf area depends on reserves stored in the parent shoot, i.e. on parent shoot photosynthesis during the previous year which is higher in well-lit zones and smaller in shaded areas. Tree architecture models based on this principle (Takenaka 1994; Kellomäki and Strandman 1995) simulate denser foliage density in the periphery of the crown, as the result of enhanced shoot development and self-thinning in sunlit and shaded parts, respectively. Such leaf area distribution also allows the tree to optimise its photosynthetic productivity (Takenaka 1994).

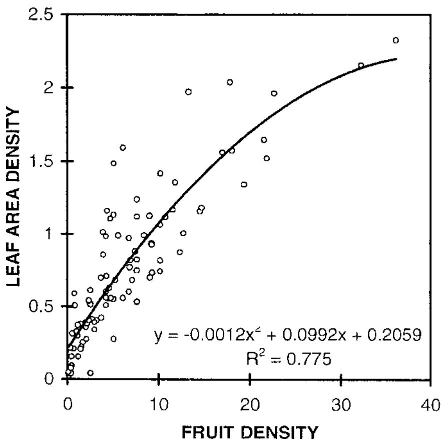

Fig. 6 Relationship between spatial distributions of leaf area density ($m^2.m^{-3}$) and fruit density (m^{-3}) within the crown of a 20-year-old walnut tree. Spatial distributions are expressed in terms of radial distance to the trunk and height

Figure 5 shows the spatial distribution of fruit density. Isolines of fruit density in both the vertical (Fig. 5a) and horizontal (Fig. 5b) planes present the same tendencies as those of leaf area distribution. The relationship between both spatial distributions expressed as a function of altitude and radial distance is good (Fig. 6). In agreement with this result, fruit distributions within crowns have also been related to light availability (e.g. Klein et al. 1991; Kikuchi et al. 1994). In addition to the photosynthetic history of the parent shoot, fruited shoots have to supply assimilates to fruit during the current season in order to avoid abortion. Although the antagonism between vegetative and reproductive shoots, higher fruit and foliage concentrations are ultimately located close to the assimilate sources.

Discussion

Some methods for the description of tree architecture deal with only one of the two aspects of the plant structure: topology (Hallé et al. 1978) or geometry (Ross 1981). Other approaches put together both aspects (Honda 1971; De Reffye et al. 1988): in that case, the information on topology is associated with measurements of branching angle and internode lengths, which allows one to to derive the 3D positions of the tips of the branches, assuming that internodes are linear. The method proposed here also puts together both aspects, and may be regarded as an improvement of the previous ones. First, the estimation of the 3D coordinates is easier, and probably more accurate, and second, the measurement method proposed in this paper also includes a rough description of the leafy shoots, which allows us to derive fine information on the spatial distribution of leaf area and fruits.

With regard to topology, description can only be direct, i.e. from visual and manual measurement on the plant. Given the tree size and the great number of entities within a crown, the description of whole trees is tedious and time-consuming, so that sampling schemes associated with symmetry or similitude hypotheses have been adopted (e.g. Whitehead et al. 1990). Data sets derived from the whole description of tree topology could potentially make it possible to test sampling schemes, by comparing measured and reconstructed topologies. This is an important research direction because simplification of the procedures of tree architecture description would increase the productivity of the architecture measurements, which is presently very low.

With regard to plant geometry, description methods may be split into direct and indirect methods (see Sinoquet and Andrieu 1993; Andrieu and Baret 1993 for recent reviews). The first ones involve direct measurement of the location and orientation of the entities while the second infer geometry parameters from radiation measurements, using photographs or light sensors. Some indirect methods have been developed for tree structure characterisation at the whole plant level (e.g. Van Elsacker et al. 1983; Koike 1985) but they are unsuitable for a description at the shoot level; for example, a number of shoots within the crown are hidden by the outer foliage. In the case of a simple plant like maize, 3D-reconstruction of the plant geometry from stereovision photographs was reported to be difficult because of mutual masking between vegetation elements (Ivanov et al. 1995). The authors had to sequentially remove the upper foliage layers in order to see the lower leaves on the photographs. Although not reported, it is probable that the masking problem also exists in the theodolite method proposed by Smith et al. (1992) for describing kiwi plants. The other problem associated with indirect methods is that distinction between shoots does not obviously appear on a photograph, especially because optical properties of the leaf elements do not show any inter-shoot difference. With regard to direct measurement, harvest and digitising in two-dimension (2D) or 3D are the only methods proposed in the literature. Two or three-dimensional harvest is destructive, it may be regarded as an extension of the Monsi and Saeki's stratified-clipping method (1953), and it has been used to describe the 2D structure of a citrus orchard (Cohen and Fuchs 1987). Two-dimension digitising from plant photographs has been applied to graminae where masking between leaves may be partially avoided (e.g. maize, Bonhomme and Varlet-Grancher 1978). Three-dimension digitising of foliage canopies has involved various techniques (see the review by Moulia and Sinoquet 1993): articulated arms (Lang 1973), ultrasound propagation (Sinoquet et al. 1991) and current induction in magnetic fields as proposed in this paper. The latter appears to be the most convenient: (i) unlike the ultrasonic digitiser, it is insensible to masking and to wind and temperature fluctuations; (ii) unlike articulated arms, the pointer is not cumbersome; and (iii) the measurement volume is largest if the Long Ranger option is used. All direct methods however are somewhat tedious because the operator has to reach every foliage location in the vegetation volume.

This experiment was aimed at defining the feasibility of the method when applied to a large tree. Difficulties in 3D digitising were associated with the experiment duration, the accessibility in space to the tree elements, and weather conditions. The experiment duration was about 2 months with 20 days spent in the tree. The rate of data acquisition was about 800 points per day, with large variations due to location within the tree. The experiment duration has to be compared with the time period when the tree is fully leafed. Given walnut polycyclism, the last flush ends in mid-July while leaf fall happens with temperatures below 0 °C, usually in October in our conditions. This allows 3 months for the maximum duration of the experiment. Other species (e. g. *Fagus sylvatica*) are fully leafed some weeks after bud breaking, so that time availability for measurement is greater. Accessibility to the vegetation elements is mainly determined by the size of the crown, both in height and width. Main constraints for scaffolding are that magnetic digitising is not possible with metallic objects within the measurement volume. The web made of ropes attached to woodden ladders made the whole shoots accessible, given one ladder moving during the experiment and climber qualities for the operators. Finally, unfavourable weather conditions are rainfall because the equipment is not water-proof, and wind because of the movements of the tree structure – up to 50 cm in the highest terminal shoots. This means that every kind of digitising should be impossible in windy areas.

Acknowledgements We are grateful to B. Adam and S. Ploquin for time spent with us in the tree, M. Crocombette for his help in building the scaffolding, and J. S. Frossard for his advice on safe climbing. We also thank E. Costes (INRA-Montpellier, France), J. Dauzat and C. Godin (CIRAD-AMAP, Montpellier, France) for their help in defining topology coding, and the POV-Ray team coordinated by C. Young (E-mail address: 76702.1655@compuserve.com) for POV-Ray free-ware.

References

Andrieu B, Baret F (1993) Indirect methods of estimating crop structure from optical measurements. In: Varlet-Grancher C, Bonhomme R, Sinoquet H (eds) Crop structure and light microclimate. INRA Editions, Paris, pp 285–322

Blaise F, De Reffye P (1994) Simulation de la croissance des arbres et influence du milieu: le logiciel AMAPpara. In: Tankoano J (ed) Proc 2nd African Conference on Research in Computer Science, October 12–18, Ouagadougou. ORSTOM Editions, Paris, pp 61–75

Bonhomme R, Varlet-Grancher C (1978) Estimation of the graminaceous crop geometry by plant profiles including leaf width variations. Photosynthetica 12: 193–196

Chen SG, Ceulemans R, Impens I (1994) A fractal based *Populus* canopy structure model for the calculation of light interception. For Ecol Manage 69: 97–110

Cohen S, Fuchs M (1987) The distribution of leaf area, radiation, photosynthesis and transpiration in a shamouti orange hedgerow orchard. I. Leaf area and radiation. Agric For Meteorol 40: 123–144

Cohen S, Mosoni P, Meron M (1995) Canopy clumpiness and radiation penetration in a young hedgerow apple orchard. Agric For Meteorol 76: 185–200

De Reffye P, Edelin C, Françon J, Jaegger M, Puech C (1988) Plant models faithful to botanical structure and development. Comput Graphic 22: 151–158

De Reffye P, Elguero E, Costes E (1991) Growth units construction in trees: a stochastic approach. Acta Biotheor 39: 325–342

Godin C, Guédon Y (1996) Conception d'une méthodologie d'analyse des plantes à l'échelle macroscopique. In: Tendances nouvelles en modélisation pour l'environnement, January 15–17, Paris. C.N.R.S., Paris, pp 17–22

Hallé F, Oldeman RAA, Tomlinson PB (1978) Tropical trees and forests. An architectural analysis. Springer, Berlin Heidelberg New York

Hardwick RC (1986) Physiological consequences of modular growth in plants. Philos Trans R Soc London Ser B 313: 161–173

Honda H (1971) Description of the form of trees by the parameters of the tree-like body: effects of the branching angle and the branch length on the shape of the tree-like body. J Theor Biol 31: 331–338

Ivanov N, Boissard P, Chapron M, Andrieu B (1995) Computer stereo plotting for 3-D reconstruction of a maize canopy. Agric For Meteorol 75: 85–102

Kellomäki S, Strandman H (1995) A model for the structural growth of young Scots pine crowns based on light interception by shoots. Ecol Model 80: 237–250

Kikuchi T, Shiozaki Y, Asada T, Arakawa O (1994) Light and fruit distributions within a canopy of 'Fuji' apple trees trained to a traditional open-system in Japan. J Jpn Soc Hort Sci 62: 761–768

Klein I, Weinbaum SA, DeJong TM, Muraoka TT (1991) Relationship between fruiting, specific leaf weight, and subsequent spur productivity in walnut. J Am Soc Hortic Sci 116: 426–429

Koike F (1985) Reconstruction of two-dimensional tree and forest canopy profiles using photographs. J Appl Ecol 22: 921–929

Lang ARG (1973) Leaf orientation of a cotton crop. Agric Meteorol 11: 37–51

Monsi M, Saeki T (1953) Über den Lichtfaktor in den Planzengesellschaften und seine Bedeutung für die Stoffproduktion. Jpn J Bot 14: 22–52

Moulia B, Sinoquet H (1993) Three-dimensional digitising systems for plant canopy geometrical structure: a review. In: Varlet-Grancher C, Bonhomme R, Sinoquet H (eds) Crop structure and light microclimate. INRA Editions, Paris, pp 183–193

Polhemus (1993) 3SPACE FASTRAK User's Manual, Revision F. Polhemus, Colchester, Vt., USA

Prusinkiewicz PW, Remphrey WR, Davidson CG, Hammel MS (1994) Modeling the architecture of expanding *Fraxinus pennsylvatica* shoots using L-systems. Can J Bot 72: 701–714

Raab FH, Blood EB, Steiner TO, Jones HR (1979) Magnetic position and orientation tracking system. IEEE Trans Aerosp Electron Syst 15: 709–718

Ross J (1981) The radiation regime and the architecture of plant stands. Junk, The Hague, The Netherlands

Sinoquet H, Andrieu B (1993) The geometrical structure of plant canopies: characterization and direct measurement methods. In: Varlet-Grancher C, Bonhomme R, Sinoquet H (eds) Crop structure and light microclimate. INRA Editions, Paris, pp 131–158

Sinoquet H, Moulia B, Bonhomme R (1991) Estimating the three-dimensional geometry of a maize crop as an input of radiation models: comparison between three-dimensional digitising and plant profiles. Agric For Meteorol 55: 233–249

Smith GS, Curtis JP, Edwards CM (1992) A method for analysing plant architecture as it relates to fruit quality using three-dimensional computer graphics. Ann Bot 70: 265–269

Sprugel DG, Hinckley TM, Schaap W (1991) The theory and practice of branch autonomy. Annu Rev Ecol Syst 22: 309–334

Takenaka A (1994) A simulation model of tree architecture development based on growth response to local light environment. J Plant Res 107: 321–330

Van Elsacker P, Keppens H, Lemeur R (1983) A simple photographical method for analyzing the radiation interception by an individual tree. Agric Meteorol 29: 285–298

Whitehead D, Grace JC, Godfrey MJS (1990) Architectural distribution of foliage in individual *Pinus radiata* D. Don crowns and the effect of clumping on radiation interception. Tree Physiol 7: 135–155