Incorporating vegetation into visual exposure modelling in urban environments

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Visual exposure modelling establishes the extent to which a nominated feature may be seen from a specified location. The advent of high-resolution light detection and ranging (LiDAR)-sourced elevation models has enabled visual exposure modelling to be applied in urban regions, for example, to calculate the field of view occupied by a landmark building when observed from a nearby street. Currently, visual exposure models access a single surface elevation model to establish the lines of sight (LoSs) between the observer and the landmark feature. This is a cause for concern in vegetated areas where trees are represented as solid protrusions in the surface model totally blocking the LoSs. Additionally, the observer’s elevation, as read from the surface model, would be incorrectly set to the tree top height in those regions. The research presented here overcomes these issues by introducing a new visual exposure model, which accesses a bare earth terrain model, to establish the observer’s true elevation even when passing through vegetated regions, a surface model for the city profile and an additional vegetation map. Where there is a difference between terrain and surface elevations, the vegetation map is consulted. In vegetated areas the LoS is permitted to continue its journey, either passing under the canopy with clear views or partially through it depending on foliage density, otherwise the LoS is terminated. This approach enables landmark visual exposure to be modelled more realistically, with consideration given to urban trees. The model’s improvements are demonstrated through a number of real-world trials and compared to current visual exposure methods.

Keywords: visibility analysis; vegetation mapping and modelling; urban applications

1. Introduction

Visibility models may be used in the planning phase of developments, for example, to calculate the visual impact of a new wind farm or to find the most hidden path for a motorway extension. They have also been used in location-based services (LBSs) to calculate what a user may see, and therefore enable context-relevant data filtering and customised content delivery (Bartie and Mackaness 2006). In all applications, model fidelity has improved as more comprehensive digital data sets have become available, yet little consideration has been given to how vegetation may be accommodated within these models. Vegetation is a special case because its impact may be seasonal, and the observer is able to see partially as well as clearly through the canopy layer. This research focuses on how a vegetation map may be incorporated into a visibility model able to report the visual exposure of nominated landmarks in urban environments.
There are two main types of visibility models: isovist and viewshed models. Isovist modelling is suited to urban areas, establishing the expanse of continuous visibility around an observer by accessing building footprint polygons (Tandy 1967, Benedikt 1979), whereas viewshed analysis (Tandy 1967, Lynch 1976) using terrain models is more commonplace in rural regions. The introduction of light detection and ranging (LiDAR) techniques enables high-resolution georeferenced elevation data sets to be captured across large areas in minimal time suitable for producing digital surface models (DSMs) in urban environments (Palmer and Shan 2002, Rottensteiner and Briese 2002). As a result, viewshed calculations are now feasible within urban regions, as both topography and built form are captured within the surface model.

An issue that remains is how to handle non-surface urban vegetation, which appears in the DSM as solid blockades protruding from the ground. In this research, a basic vegetation map is incorporated to improve the model’s performance when calculating the visibility of landmark buildings in an urban environment. This model accesses a digital terrain model (DTM) to establish the observer’s elevation and a vegetation map to distinguish surface vegetation from buildings in the DSM. From this an adapted line of sight (LoS) algorithm is able to establish under canopy (UC) and through canopy (TC) views, summarising the visibility for each landmark as a number of metrics (e.g. façade area visible). This article begins with a general introduction to visibility modelling and an outline of the existing approaches for including vegetation within the visibility model (Section 2). This is followed by an explanation of the solution implemented here (Section 3) and a number of real-world trials to demonstrate the benefits of the enhanced model (Section 4).

2. Visibility modelling background

Geographic information systems (GISs) are able to carry out visibility calculations by accessing a DSM that stores elevation values for a region. The visibility calculations determine which locations can be connected by a straight line without being interrupted by the terrain (Franklin and Ray 1994). A good overview of the algorithms, storage formats and techniques to calculate visibility may be found in De Floriani and Magillo’s (2003) article. Much of the research has focused on improving the performance of the algorithm (De Floriani et al. 2000, Rana and Morley 2002, Rana 2003, Ying et al. 2006), which has become increasingly necessary since the introduction of high-resolution DSMs such as those sourced from LiDAR.

Modelling may be carried out on a point-to-point basis, or point-to-area as in the case of viewsheds (Fisher 1991, 1994, Lee 1994, Fisher 1995). Viewshed results are normally stored as Boolean rasters that represent visible and hidden cells. They have been used to assist in the siting of transmission masts, for calculating the visual impact of planned new developments (Fisher 1996) and for finding the most hidden routes from the surroundings (e.g. pipelines, military) or best views along a route (e.g. tourists) (Stucky 1998), among other things.

Caldwell et al. (2003) demonstrated how Complete Intervisibility Databases were able to answer new questions, such as giving an estimate of the percentage of a target visible, by summing the total number of visible cells within a defined zone. The introduction of the ‘visual exposure’ concept (Llobera 2003) established another new ability for visibility modelling, whereby a target’s exposure may be mapped across a terrain. Here, the model looks inwards at a designated feature, establishing how much of it may be seen from any surrounding location for a given visual property, such as the occupied horizontal field of view. Flow direction maps may be generated from these visual exposure maps to indicate in which direction an observer should move to attain a clearer, or more limited, view of a target.
The visual exposure model may be applied to urban features (e.g. a landmark building) by considering groups of cells, within a designated boundary, as a single entity. From this, summaries may be produced that describe a number of visual properties (e.g. visible façade area) for the feature (Bartie et al. 2008). This differs from viewshed and isovist modelling as the specific focus is on calculating how much of a surface feature can be seen, rather than mapping the visibility of the terrain itself. However, the results are subject to errors which result from the way vegetation is represented in 2.5D DSMs, as solid jagged topped barriers which block the LoS. Furthermore, when the observer is located among trees, the modelled view is calculated as if the observer were at tree top height, as read from the DSM. To improve this model, a visibility tool has been developed that begins the LoS calculation using an observer height offset from the ground level as stored in a DTM, while considering the profile from the DSM, and where designated permitting the LoS to pass partially through the DSM according to its visual permeability, thereby accommodating UC and TC conditions. The next section describes the implementation in an urban environment for the purpose of modelling landmark building visibility, beginning with the background to current methods for including vegetation in visibility modelling.

2.1. Visibility modelling incorporating vegetation background

There have been a number of previous studies which incorporate vegetation within the visibility model. Dean (1997) introduced the concept of visual permeability, proposing that a ray of light could pass through a modelled canopy layer, with a linear attenuation proportionate to the distance travelled in the canopy space. Dean’s model was updated by Llobera (2007) who considered visual permeability as photons travelling through a medium following the principles outlined in Beer–Lambert’s attenuation law. The model considers a beam of light as it passes through vegetation, experiencing an exponential drop in photon numbers for each unit of distance travelled, indicating the probability of viewing a region as determined by the spatial density and position of tree models on a landscape. The research demonstrates the possibility of the improvements to visibility modelling in rural regions and highlights a number of difficulties in sourcing high-quality vegetation maps, and information on tree species for such a purpose. Llobera concludes that the research has not been tested empirically and to do so would require an area dominated by one tree type. There is no consideration for how the technique may be incorporated into visual exposure modelling for use in urban regions nor how LiDAR-sourced DSMs and DTMs may be combined with remotely sensed imagery to produce vegetation models, which is the work presented in this article.

A compendium of LoS algorithms (US Army Corps of Engineers 2004) used within commercial and military GIS software identified a number of applications which are able to model the view under vegetation canopy. These make use of a second surface model which stores the canopy base heights (Baer et al. 2005). Although enabling UC views, concepts of partial visibility through the canopy layer and data collection are not discussed.

Other military models use probabilistic line of sight (PLoS) techniques (Stanford et al. 2003) to calculate the ability of different sensors to view targets. In these models, trees are represented as simple ‘ice cream cones’ with a number of parameters to define trunk widths, tree proportions and foliage density. A similar approach used by Liu et al. (2008) represents trees as intersected diamonds. From this, the visible regions on hillsides, and those blocked behind vegetation, can be calculated. Although these approaches are useful adaptations for rural scenarios, they do not cater for feature visibility modelling in urban areas, where the output required includes not only which raster cells can be viewed but also an indication of the vertical extent of each cell visible so that façade area calculations may be performed.
This article presents research on raster-based tree models generated by supplementing LiDAR DSMs with Quickbird remotely sensed imagery and a minimal ground survey. The intended use for this model is in urban regions, to establish which features of interest (FOIs) are visible from given locations, for use in LBSs as a filtering method for determining the relevance of surrounding items.

2.2. Urban visual exposure metrics background

Before developing concepts further, it is worth summarising the current urban feature visual exposure model. Visual exposure modelling quantifies how much of a facet may be seen from a given location (Llobera 2003). Using a LiDAR-sourced DSM, it is possible to calculate the vertical intercepts above the DTM for LoSs cast from an observer to FOIs (Figure 1a) enabling surface area calculations to be carried out for any FOI in a region (Figure 1b). The resultant ‘façade area’ quantifies the surface area of a FOI, which may be viewed from that location irrespective of viewing distance or angle, essentially establishing the size of the visible object. An additional ‘perceived area’ metric includes the distance and viewing angle factors. A more detailed explanation of the model and definitions of the metrics may be found in Bartie et al. (2010).

3. Accommodating vegetation within a new visual exposure model

One of the issues with modelling features in urban environments using LiDAR-sourced DSMs is the representation of vegetation as solid walls because of the 2.5D data structure limitations. For any visibility studies, this means that trees form total visual blockades completely blocking the LoS. The issue is twofold: first trees may allow some partial visibility of distant objects through their canopy layer and second the view either side of the trunk underneath the canopy layer is clear.

Furthermore if only a DSM is used then as the user moves into vegetated zones the view will be modelled as if the observer is standing on top of the vegetation (Figure 2a). One solution is to introduce a DTM bare earth model ensuring all observations begin at ground level; however, if the observer is positioned within a vegetated area, then the LoS ray will be immediately terminated as it reaches the surrounding DSM cells which are higher than the observer’s DTM value (Figure 2b). Therefore, the visibility model requires further

Figure 1. Visual exposure modelling: (a) side view of modified LoS and (b) façade area visible.
information to distinguish between the visual properties of the feature that occupies the gap between DTM and DSM. This can be accomplished by identifying the vegetated regions by means of a normalised differential vegetation index (NDVI), calculated using near-infrared and red bands from high-resolution Quickbird satellite imagery.

3.1. Building a vegetation map for use in visibility studies

The vegetation map is only required where a difference in elevation is noted between DTM and DSM, so that the visibility model may determine vegetated partially visible regions from solid structures (e.g. buildings, statues). These regions may be mapped using Quickbird imagery, which is supplied as four bands at 2.4 m and a 60-cm panchromatic band for image sharpening, to calculate the NDVI. Inevitably, there will be radial distortion errors introduced when using Quickbird imagery, which can be overcome to some extent by buffering the vegetated areas by a few metres and then clipping them against the elevated zones where there is a difference between DSM and DTM values. To ensure that vegetation does not encroach into the FOIs a final clipping operation was carried out to remove any overlapping areas from within the FOI polygons. An example of the process and resulting tree polygons are shown in Figure 3.

The NDVI information is used to determine vegetated regions from non-vegetated to select between the DSM and DTM values along the LoS path. However, more information on the tree leaf density and canopy base height is required to improve the visibility results. In urban areas, traditional remote sensing tree classification techniques do not work well because trees are found in low-density highly heterogeneous groups, often over grassy regions (Xiao et al. 2004). Comprehensive vegetation density information may be collected using terrestrial side looking LiDAR, as shown in Figure 4. Where this is not available a ground survey will suffice in providing approximate density information for the vegetated zones. The supplementary information is stored as attributes against each vegetation cell defined by the NDVI process, ensuring that the additional information is correctly spatially registered in the DSM and DTM cells. Through studying a winter aerial image, the deciduous trees were noted and the position and approximate widths of tree trunks were added to the data set.
3.2. Implementation

The vegetation map supplies information on the position, visual permeability and canopy base height so that the probability of the LoS passing through that region may be calculated. Canopy base height is recorded as the height above the DTM and captured during the ground survey using a range finder. Generalised values for a tree or group of trees may be sufficient.
depending on the accuracy required in the modelled output, although variations at cell resolution as collected by terrestrial LiDAR scans may also be stored. Each tree cell is assigned a Boolean value indicating if it is affected by seasonal variation, so that the model may switch the visual properties when run in summer or winter months. The trunk locations are stored as cells with a visual permeability rate of 0.00, a canopy base height of 0 m and assigned no seasonal change values irrespective of tree species.

Ideally terrestrial side looking LiDAR surveys would be used to collect comprehensive vegetation density maps for urban areas; however, this is not always feasible and therefore visual ground surveys are required. For this research, tree permeability rates were collected for the designated vegetation regions, as defined by the NDVI map, using visual assessment based on an image threshold technique, as shown in Figure 5. The permeability value gives an indication of the amount of light which can pass through the tree canopy from a side view, considering the tree to act as a filter. A value may be collected for the overall canopy, or separate readings may be taken for sections where the density is significantly different. This is then rasterised based on the tree depth from that sample point to give each cell in the vegetation map an approximate permeability rate, which describes the survival rate of a ray passing through that metre of canopy. For example, if the collected permeability rate for a section of canopy was 53%, where it was 3 m deep, then the average cell permeability may be calculated using Llobera’s (2007) formula,

\[
\text{Ray survival} = (1 - f)^m
\]

where \(f\) is the ratio of tree matter to defined canopy space and \(m\) is the depth the ray has passed through the tree. In this case, the ray survival (i.e. 0.53) and tree depth (i.e. \(m = 3\)) are known, therefore the average permeability rate (i.e. \(1-f\)) for a single cell may be calculated as 0.81 (i.e. \(0.53^{\frac{1}{3}}\)). This approach gives an approximate value for the cell permeability as a function of canopy density, reflecting the variety of tree instances in urban scenes.

The LoS should be considered as a narrow column of light projected from the observer to the FOI, subjected to obstacles along the way. The permeability value for a vegetated region describes the division between solid tree and air for that cell, representing a vertical column.
between the tree top and canopy base. The higher the permeability rate the more of the LoS light column will reach the FOI, the lower the rate the more of the LoS will be blocked.

To differentiate between the vegetation permeability values and those of the LoS ray, we introduce the term coverage index to express the ray’s current status along the path. The ray is assigned a starting coverage index of 100% and as it progresses towards the target is subjected to varying rates of decay appropriate to the medium it is passing through. When passing through air an atmospheric rate is used, but when passing through vegetated zones the rate is read from the vegetation raster map (i.e. the vegetated cell permeability values).

The ray is modelled as a 3D vector, along which a sample is taken at 1 m intervals from the raster layers, as shown in Figure 6. At each sample point the height of the ray above DTM is compared to the vegetation canopy heights, to establish if the ray is passing under, through or above the canopy layer. The model is therefore able to replicate the decrease in visibility associated with looking through deeper canopy sections, and as a result of looking up through more layers of canopy upon approaching an FOI.

Seasonal changes are not uniform across all trees depending on their age, condition and many other factors. Although the model may accommodate this level of detail current data capture costs are restrictive, but it is hoped this will improve in the future as more sophisticated high-resolution hyperspectral remote sensing techniques (Xiao et al. 2004) and ground-based LiDAR surveys (Omasa et al. 2008) become more commonly available. For the purposes of this article, the basic survey information and simple switch between summer and winter mode is sufficient to demonstrate the modifications to the algorithm. Figure 7 shows how the supplementary information is used within the vegetation model, storing information about tree canopy base height and permeability as additional pixel attributes.

3.3. Modification to the line of sight model to accommodate vegetation information

To accommodate the new information layers, a new visibility model is required. The model projects the vegetated zones found between the observer and target onto the FOI, so that the façade area visible may be adjusted according to the coverage index, giving an estimate of
the area of visible regions on the FOI (Figure 8). The FOI is considered as a set of target columns at the resolution of the raster DSM, in this case 1 m resolution. The visibility is calculated for each target column determining the area clearly visible and that behind vegetation as a function of the coverage index. As an example, if the coverage index for a ray at the FOI is 50% and vegetation covers half of a target column, then the final area visible
for that column would be 75% of the column height (50% of 50% in vegetation zone + 50% under and above the canopy).

The method is as follows (Figure 9):

(a) The angle to the steepest non-vegetated DSM cell is projected onto the FOI to find the Not Seen (NS) zone. If the target column is not visible, the calculation is terminated.

(b) Next the steepest gradient to a vegetated cell between the observer and target is determined, and the lowest canopy angle. This defines the above canopy (AC) and UC zones on the target column. The rays for these regions are subjected to an atmospheric rate of decrease. The NS zone always takes precedence when other zones are defined.

(c) The region on the FOI between the base of the AC zones and top of the UC zone is defined as the TC zone.

(d) The vegetated regions along the path between observer and target are recorded (e.g. A, B, C) and the intercepts at the FOI are calculated for the top (lines At, Bt, Ct) and base (lines Ab, Bb, Cb) of each vegetated region, defining the TC subzones. Vegetated regions whose projection falls completely within the NS zone are removed, and any baselines which fall in the NS zone are redefined using the angle to the top of the NS zone.

(e) The vegetated zones are considered in order, furthest from the observer first. To simplify the process an average ray path is used to describe the impact of each vegetated region in each TC subzone (e.g. lines Ax and Ay in detailed view). The permeability values from each cell are applied to the ray to calculate its coverage.

Figure 9. Line of sight model – projected vegetation zones (A, B, C) onto FOI.
index, by multiplying the current coverage index by the permeability value, such that a ray experiences an exponential decay. The formula may be written as coverage index = \(100(p_1p_2 \ldots p_n)\), where \(p\) is the decimal permeability rate in the range 0–1, which determines the likelihood of the ray passing through that cell (see Figure 6 for more details).

(f) The TC zones are assigned an appropriate coverage index value that corresponds to the presence of vegetation along the LoS. For example, the zone between Ct and Cb is assigned the coverage index calculated from ray Cx, the region between Bt and Bb is assigned by Bx, whereas Ax and Ay are used to assign the remaining A zones. Any regions not assigned a value are known as inter-canopy (IC) zones and treated as visible through clear atmosphere (same as AC and UC).

(g) The coverage indexes (Ax, Ay, Bx, Cx) are applied to the column zone areas and summed to give a single façade area visible value for the TC zone.

(h) Any rays which encounter trunk zones will be terminated.

(i) Any rays which have a coverage index of below 1% are terminated and the zone is considered as not visible. As rays fade exponentially, this is useful for improving performance for rays which are tending towards 0%.

(j) The process is repeated for all target columns within an FOI to give a single visible façade area. A perceived area is also calculated which considers the observer’s viewing angle and distance (see Section 2.2). For interior target cells within a FOI (i.e. not on the FOI boundary), a large proportion of the zoning will be NS, as the majority of the column is blocked by exterior cells.

To describe the vegetation impact across the FOI façade, a new visibility metric is introduced, which divides the FOI into thirds. The zone definitions are created without considering the visibility of the structure but instead use the extreme FOI target points which create the widest angle from the current location. This is so as the visibility results, which are summarised according to these zones, may include the percentages for area visible, visibility through vegetation and hidden from view, as shown in Figure 10. The output quantifies the extent and pattern to which an FOI is blocked from the current view and may be used by LBSs to build natural egocentric descriptions, such as ‘the gallery is visible in front of you, although partially hidden by vegetation on the right side’.

The next section demonstrates the use of the modified visibility model in a vegetated urban area through a number of trials, which illustrate how the adaptations improve the modelled results and are able to accommodate seasonal variation, views under bridges and also a demonstration of how the new metric may be used to describe a scene.

![Figure 10. Summarising visibility across an FOI in thirds by viewing angle.](image-url)
4. Examples of visibility modelling with vegetation

4.1. Differences between visibility modelling with and without vegetation map

The first example demonstrates the difference in the visible region when the observation location is sighted under vegetation. The visibility of nearby objects can be massively over- or underreported when only a DSM is used, as depicted earlier in Figure 2. Typically, views are either extended as if the user was positioned at tree top height or very limited by nearby undulating canopy. Figure 11 shows an example where the horizon is drawn for an observer standing under a tree. In the case without the vegetation model the results are irregular, displaying almost no view at the first location and a wide view for a point 1 m further north. In reality, the views are almost identical as shown by the model that includes the vegetation information. The model that includes the vegetation information is therefore more stable and similar to real-world experiences.

The new model also permits calculation of visibility UC cover. The visibility of each target is divided into component parts to describe how much is clearly visible and visible through vegetation. LoSs passing under the canopy are considered as clearly visible and the coverage index decays at the atmospheric rate. Figure 12 shows the modelled visibility of a landmark at three locations, the latter two both including views under the canopy layer. The Façade Area Visible metric is an indication of how much of the building is visible, whereas the Perceived Area metric factors in viewing angle and distance. Prior to the inclusion of the vegetation map, the FOI was not considered visible from the vegetated area (Figure 12iii).

4.2. Taking account of seasonal vegetation changes

As outlined in Section 3.2, the model accommodates a simplified approach to cater with seasonal vegetation changes. Each cell in the vegetation map is encoded with a Boolean value to reflect whether it responds to change between seasons. UC results are not affected

Figure 11. The horizon as modelled with and without a vegetation map, from a location under a tree.
by seasonal variation, nor are Evergreens and tree trunks which exhibit the same visual properties throughout the year. The cells which are affected by season are automatically assigned a standard single minimal visual permeability rate for the winter mode, allowing the rays to pass through to a greater extent, simulating the lack of winter foliage.

This is a highly simplified approach to seasonal change, as trees drop leaves at different times of the year and to varying degrees. Although the model could be easily modified to store a seasonal change date and fade between winter and summer permeability values, it is not yet practical to collect such data for large city areas. Therefore, this example only models a basic switch between the extreme summer and winter foliage densities.

The modelling of visibility for three FOIs was carried out in both winter and summertime, as shown in Figure 13. The Area column describes the total building facade visible, irrespective of viewing distance or viewing angle. The Perceived Area Total column is calculated by factoring the Area visible with the viewing distance, viewing angle and LoS ray coverage index. A more detailed explanation of the differences between metrics may be found in Bartie et al. (2010). The Clear and Through Vegetation columns show the division of Perceived Area into the component parts, for those rays passing through vegetation and those only decaying at atmospheric rates. A number of observations can be made from the
results. The Perceived Area Visible Through Vegetation increases dramatically in wintertime as expected with minimal foliage to block the LoS rays which pass through the vegetated zones. Building B experiences no change between summer and winter as the only parts visible from this location are behind Building C and above the tree line. The perceived Clear Area does not change between summertime and wintertime for any of the buildings, as the view above and underneath the canopy are not affected by the seasons. Building A shows less change between seasons than Building C, because the northwest wall (left side of photograph) is clearly visible all year around, and not hidden behind vegetation. Building C experiences the most dramatic change between summer and winter, with the largest increase in area visible through vegetation.

It is also noticeable that the results for Building C tend to underreport the impact of vegetation. As the photograph in Figure 13 shows, Building C was mostly hidden from view in summertime with only a small proportion of the building visible UC. The calculated area difference between summer and winter indicates a doubling in the visible building area, whereas the photographic evidence suggests the change should be greater. Upon further investigation it appears that the LiDAR data set failed to capture the complete canopy shape for the large tree in front of Building C. Full waveform LiDAR (Reitberger et al. 2006) and improved data capture technologies will assist in the future, as more detailed tree profiles will be available to the model.

### 4.3. Modelling visibility under bridges and overpasses

Aerial LiDAR surveys only capture information in the LoS, therefore clearance heights under bridges and overpasses are not available. However, with minor coding alterations a
special case may be included into the visibility model to accommodate LoS passing under such objects. To do this, the tree trunk model was adapted such that the canopy height stores the value of clearance above the DTM, allowing the LoS to pass under the DSM elevation at the atmospheric decay rate. A fifth permeability class is used to denote the cell as a special case so the model does not consider the LoSs passing through these cells as having encountered vegetation. An example of this is shown in Figure 14, whereby the majority of the building would have previously been considered out of sight.

The procedure to update a map region is fairly simple, requiring only the cells under marked bridges and walkways to be assigned the special permeability class. The clearance heights can be set to a generic value for vehicles or pedestrians appropriately, or refined through a ground survey.

4.4. Reporting the vegetation distribution across a feature

The vegetation distribution in front of an FOI may be described by dividing the maximum field of view for the FOI, regardless of its current visibility, into thirds. The interception heights (Figure 9) are used to summarise the percentage clearly visible and that visible through vegetation, into the three zones. The ray coverage index is not applied to the result, as the metric is intended to provide a quantitative description of the vegetation’s impact on the view across the FOI façade from a given location irrespective of vegetation type or density. Figure 15 illustrates this with an example where the right side of the FOI is mostly hidden by vegetation, the central third is slightly hidden behind vegetation and the left side is totally clear. Any views under the vegetation canopy are classed as clearly visible.

5. Conclusions and future work

The introduction of LiDAR-sourced DSMs has permitted urban visibility modelling to move from isovist (Tandy 1967, Benedikt 1979) to viewshed methods (Tandy 1967, Lynch 1976), permitting the visual exposure model (Llobera 2003) to be applied in urban environments. However, the model is subject to errors which result from the representation of vegetation in LiDAR-sourced DSMs, and therefore a number of modifications are required so that LoSs
may be modelled through vegetated zones. Although vegetation has been considered in visibility models before (Dean 1997, Llobera 2007, Liu et al. 2008) consideration has not been given previously to how the visual exposure model may be adapted to accommodate supplementary information on vegetation density and distribution.

This article implements an urban visual exposure model with a number of modifications and novelties. The impact of vegetation on the view of landmarks is incorporated by considering raster tree models, which provide canopy base height, tree density and seasonal variation information on a cell-by-cell basis. In addition both a DSM and DTM are used such that the observer may always be placed at ground level and not incorrectly at tree top height when walking underneath trees. Furthermore, the LoS is permitted to pass partially through, and clearly under, the canopy layer. A new visual exposure metric is proposed and demonstrated which describes the distribution of vegetation in front of FOIs from an egocentric viewpoint. This is useful for building narrative descriptions for a feature and may be used by LBSs to describe scenes to a user or identify targets by the presence of foreground vegetation.

The model has a number of limitations associated with collection and storage of the permeability values. The image-based thresholding technique is time-consuming and defines average permeability values for vegetated regions possibly missing significant density variations. The model is also limited to a single set of attributes, which describes the canopy vertically above each cell. This could be improved by defining many attribute sets over different vertical ranges or using voxel data structures, thereby accommodating multiple canopy layers and improving the fidelity of the model. However, the biggest difficulty is in collecting the detailed tree foliage densities, trunk and branch locations. Ground-based LiDAR surveys for city regions could be used to capture more accurate tree models (Omasa et al. 2008), and it may also be possible to distinguish different tree types in urban settings using full waveform LiDAR (Reitberger et al. 2006) and thereby automatically determine deciduous trees.
The model may be run in any urban environment where the spatial information layers are available; however, there is a considerable computational impact on the simulation performance when introducing vegetation into the visual exposure model. Previously, many LoSs were terminated prior to reaching their designated targets, as they encounter visual blockades where trees exist in the DSM. As a result of the supplied vegetation layer, these rays are now modelled through the vegetation to their designated targets, dramatically increasing the number of computation steps required per ray. Furthermore, the number of lookups is tripled from a single DSM to the DSM, DTM and vegetation layer adding computational overhead. For near real-time applications, the model may be parallelised across multiple processors (Teng 1993, De Floriani et al. 1994) or the results cached for rapid retrieval.

It is rather difficult to empirically test the model’s output quantitatively, but this should form the basis of future work, perhaps by conducting user trials which compare the model’s output with observers’ opinions.

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