



A qualitative model for describing the arrangement of visible cityscape objects from an egocentric viewpoint



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ARTICLE INFO

Article history:

Received 3 April 2012

Received in revised form 6 November 2012

Accepted 17 November 2012

Keywords:

Egocentric projective spatial model

Qualitative model

Visual exposure modelling

ABSTRACT

A qualitative model is presented here, which is suitable for describing the relationships between the visible parts of buildings as seen by a street observer. It is intended for use in a Location Based Service (LBS) whereby users access geo-referenced digital datasets on location. Typically such applications filter data according to keywords and two-dimensional spatial reasoning, such as finding all hotels within 500 m. However, a LBS which in addition is able to reason from the user's egocentric viewpoint has the benefit of being able to refer to the arrangement of features in a more natural way, which is particularly useful for dialogue based systems. This research presents a user centred qualitative model which combines and extends previously published projective and topological models. The proposed extensions improve the fidelity of the model by subdividing projective space into finer addressable units, and through their combination the model is able to summarise relationships between complex objects in 3D space, making it suitable for use in queries. The model is demonstrated in a LBS able to establish the visibility of nominated landmarks in a cityscape by using high resolution digital elevation models, which can then support the user who may request information based on the locations of other landmarks (e.g. What's the building on the left of the train station?), or listen to descriptions of landmarks in relation to known features (e.g. the bus stop is in front of the post office). The framework is shown to be able to reason about objects typically in the field of view, and to be suitable for use in spatial queries.

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1. Introduction

There is no doubt that Location Based Services (LBSs) are becoming more commonplace with the increase in geo-referenced data (Jiang & Yao, 2006) and location aware devices using Global Navigation Satellite Systems (e.g. GPS) and network based positioning (LaMarca et al., 2005; Skyhook, 2008). LBSs are designed for use by non-experts and require supportive and 'calming' interfaces to ensure ease of use in difficult environments (Weiser & Brown, 1996). Much of the spatial theory employed by these applications is hidden from the user, such as the ability to use two-dimensional spatial reasoning (in R^2) to determine which features are within defined zones (e.g. finding all hotels within a city boundary). System usability is very important for the success of LBS applications, and great efforts are made to reduce the seam between the application and the user by closely modelling the user's viewpoint (Ishii, Arita, & Kobayashi, 1993; Ishii, Kobayashi, & Arita, 1994). For example, way-finding applications use the direction of

travel to determine the frame of reference by which turning instructions are relevant to the user.

While 2D topology is sufficient to impart navigational instructions, the egocentric view which LBS user's experience is 3D (Meng, 2005; Reichenbacher, 2005). Communication typically involves turning the relationships between 3D objects into qualitative abstractions (Cohn & Hazarika, 2001), often incomplete or inaccurate yet sufficient to convey in linguistic terms the spatial relations between objects (Jackendoff, 1992; Jiang & Yao, 2006). Language defines space according to an axial structure (Munnich, Landau, & Doshier, 2001), yet in comparison to the number of nouns available only a few spatial terms exist to describe the relationships between objects (Jackendoff, 1992). According to Freeman (1975) there are only 13 primitive spatial relationships, as shown in Table 1. Primitive relations form the minimum set of descriptors which may be combined to form more complex spatial descriptions, usually limited to a combination of two primitives (Gapp, 1995). For example in the English language there is no single term for "left of and above", instead two primitive terms are used in conjunction.

Egenhofer and Kuhn (1998) suggest retooling is required for spatial applications beyond the desktop, supporting qualitative queries (Yao & Thill, 2006) and reasoning from a number of

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Table 1
Egocentric primitives spatial relations – Freeman (1975).

Left of	Above	In front of	Inside	Near	Beside	Touching	Between
Right of	Below	Behind	Outside	Far			

different frames of references. This closer integration would lead the way to applications able to filter and describe spatial relationships in a more natural way, such as “take the *first left* and you’ll see the supermarket *behind* the park”. Such descriptions draw on knowledge of the user’s location and direction to determine the appropriate terminology, as well as an ability to determine what is in the user’s field of view, and reason what is ‘*behind*’ another feature from that viewpoint. The ultimate goal would be for an LBS to pass the ‘spatial Turing test’ (Winter & Wu, 2008), whereby its instructions are indistinguishable from those generated by a human. A key element currently missing from published research is a model which unites the output from visibility results within a framework of projective relations enabling the description of object positions in relation to other objects in view (e.g. landmark buildings) as seen from the observer’s viewpoint.

The research presented fills this void by combining visual exposure modelling with projective reasoning models to determine which parts of Features of Interest (FOI) are visible to a LBS user, summarising the relationships between FOIs using a projective reasoning model, such that qualitative descriptions are possible. The projective relationship model presented combines a number of existing projective reasoning models (Billen & Clementini, 2006), extended through the adoption of Allen’s (1983) interval definitions to increase the range of descriptions. The results are summarised as a tree structure providing a framework to describe the relationships between FOI bodies, and may be serialised making it suitable for storing and querying. The paper begins with a summary of the existing spatial reasoning models (Section 2), before introducing the extensions used for the new combined model in Section 3. The model is tested within a virtual city guide LBS which uses visibility modelling to calculate the visual exposure of FOIs as outlined in Section 4. The paper concludes in Section 5 with suggestions for how spatial reasoning may be used in conjunction with other techniques to more closely model the user’s view for use in LBS.

2. Spatial reasoning review

There are a number of formal models for spatial reasoning, which in Geographic Information Science are usually based on two-dimensional datasets. The most notable definitions describe the topological relationships between features, such as the 9 intersection model (Egenhofer, 1991; Egenhofer & Franzosa, 1995; Egenhofer & Herring, 1990), Region Connection Calculus (Cohn, 1997; Cohn & Hazarika, 2001) and the Calculus Based Method (Clementini & Di Felice, 1997, 1995; Clementini, Felice, & Hernández, 1997). The Dimensionally Extended 9 intersection model (9DE-IM) (Clementini & Di Felice, 1995) differentiates between the type of intersection (point, line, and polygon), and is particularly useful for querying spatial data, leading to its adoption as a standard (OGC, 2006). This model is based on topological space, and therefore coordinate independent, resulting in identical descriptions for both scenarios depicted in Fig. 1.

Besides topology, egocentric qualitative modelling should consider the user’s viewpoint (Fogliaroni, Wallgrün, Clementini, Tarquini, & Wolter, 2009; Hernández, 1991; Tarquini, De Felice, Fogliaroni, & Clementini, 2007); however, while topological relations have been researched in three-dimensional space (Borrmann & Rank, 2009) only limited research exists on 3D projective rela-

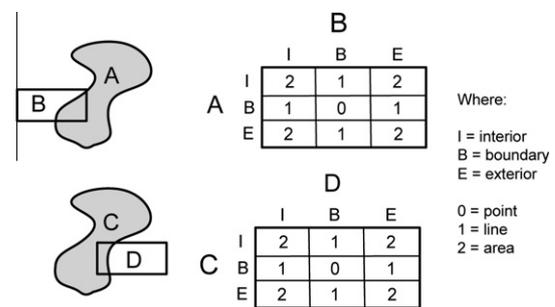


Fig. 1. Example of 9DE-IM – region overlap.

tionships (Billen & Clementini, 2006). Projective spatial modelling considers the relations between objects with respect to a frame of reference, and is therefore suitable for use in LBS. Consider the following examples:

Example a: The bus stop is *in front* of the post office.

Example b: Is that the post office *north* of the Church?

Example c: What’s the name of the street *left* of the school?

These examples demonstrate the three types of frames of reference by which spatial relationships are usually defined, which are the *intrinsic*, *absolute*, and *relative* frames (Majid, Bowerman, Kita, Haun, & Levinson, 2004). The intrinsic frame of reference is defined by a nominated feature, from which the spatial modelling is carried out. The functionality of a feature, as in the main building entrance, may be used to determine *front* from *back* (Levinson, 2003). For example “the bus stop is *in front* of the post office” (Example a) uses the post office to define the frame of reference from which the spatial relationship “*in front*” then has a meaning. Absolute references (Example b) are defined according to an external framework such as a map grid (e.g. North), while relative references (Example c) are able to describe relationships as seen by an observer’s point of view.

Following another categorisation, frames of reference are divided into two types, *allocentric* and *egocentric*, depending on whether the origin of the frame of reference is placed outside or inside the observer, respectively (Klatzky, 1998).

The absolute frame of reference does not consider the observer’s orientation, and therefore requires the user to deduce the relative direction themselves. The intrinsic view may be significant in some cases, especially when directions are given with respect to specific landmarks. The relative (and egocentric) frame of reference, being a projected view of space from the viewpoint of an observer, is the most relevant to LBS applications and is a ternary comparison between the primary object, a reference object, and the observer (Hernández, 1991).

2.1. Projective spatial qualitative modelling

The primitives of Table 1 may in part be determined using the 5-intersection model (Clementini & Billen, 2006), which is a model for ternary projective relationships. The model is formed on the basis of collinearity of three points, which is the most primitive invariant in projective space. The traditional definition of geometric collinearity only covers points. Its definition is a set of points

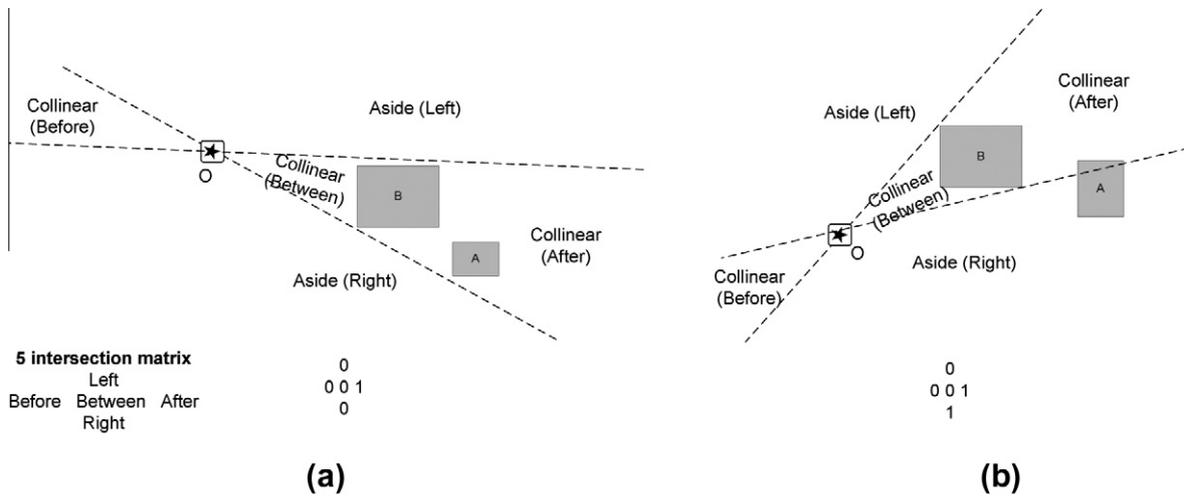


Fig. 2. Collinear and aside zones for one point and two regions.

which fall on a common line, and for a set of three points may be written as $coll(p1, p2, p3)$. The relationship is symmetrical, meaning that the order of points may be changed while maintaining collinearity, so $coll(p2, p1, p3)$ would also hold true.

In the 5-intersection model, collinearity has been extended to consider regions such that it may be used to build a qualitative model of space. There are a number of definitions for collinear regions, but for the purposes of egocentric qualitative modelling the $collinear_2$ definition (Billen & Clementini, 2005), as used by the 5-intersection model, is most appropriate. Its definition is that all of the points ($p1$) within the primary feature (A) must be collinear with a point ($p2$) of the observer (O) and a point ($p3$) in the reference object (B). For clarity the definition is rewritten here using O to define the LBS user (i.e. the observer), B as a reference object, and A as the primary object,

$$coll_2(A, O, B) = \nabla p1 \in A[\exists p2 \in O[\exists p3 \in B[coll(p1, p2, p3)]]]$$

This may be explained by considering the 2D case in Fig. 2a, whereby region A is considered collinear with the view from O to B (referred to from now on as OB). The reference frame is built around O and B using external and internal tangents to define the collinear and aside acceptance zones. Fig. 2b shows a similar situation except only part of region A is collinear with OB, and is therefore considered partially collinear, and partially aside. The appropriate 5-intersection matrix results for each example are also shown in Fig. 2.

Coplanar space may be refined into between, before, and after through considering the order of regions in the direction of OB. The Aside relations may be refined into Left and Right in R^2 space, thereby creating the 5-intersection matrix (Clementini & Billen, 2006). The link between the 5-intersection model and directional relations expressed in various frames of reference has been recently discussed in Clementini (2011).

The model is suited to describe the projected relations for FOI 2D boundaries, but does not consider the 3D aspects of features and therefore additional modelling is required in the form of a quaternary relational model.

2.2. Quaternary relational model in R^3

The quaternary projective relation model in R^3 (Billen & Clementini, 2006), uses three reference objects to define a plane from which the relation of a fourth (primary) object may be determined. The plane divides 3D space into two half-spaces, referred to as HS^{+ve} and HS^{-ve} , which correspond to *above* and *below*.

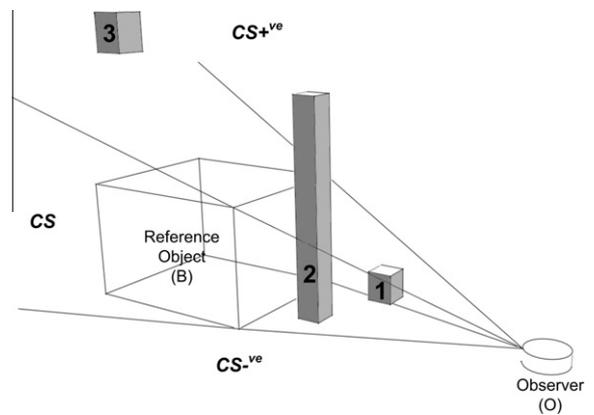


Fig. 3. Defining coplanar, above and below for 3D bodies using a quaternary model.

However, this does not provide a definition to reason for 3D bodies, and it is therefore necessary to define a coplanarity subspace as presented in Fig. 3. By defining two planes, one between the observer and the base of the reference object, the second to the top of it, a volume is created which can be used to describe 3D bodies. Anything occupying the space between planes is in Coplanar Subspace (CS) (e.g. 1 and part of 2), while anything above the subspace is in CS^{+ve} (e.g. 3 and part of 2); in this example, there is nothing in CS^{-ve} .

3. A combined model, with extensions

While the quaternary model in R^3 is able to define coplanarity relations among 3D bodies, it is not able to define relationships such as Left and Right. Therefore for the purposes of describing FOI positions to a LBS user it is beneficial to merge it with the 5-intersection model. In addition we propose a number of extensions to increase the fidelity of the output and to use the intrinsic frame of reference, centred on the observer, to describe the space behind the observer which is considered to be out of view. The combined model is intended for use by LBSs which have access to a 3D city model, or 2.5D surface model, and the user's orientation from the position trajectory or a magnetometer. It is able to describe complex relations between objects, be mapped to Freeman's primitives, and may be used in spatial projective queries. Fig. 4 shows how the acceptance zones around the observer are defined according to this approach.

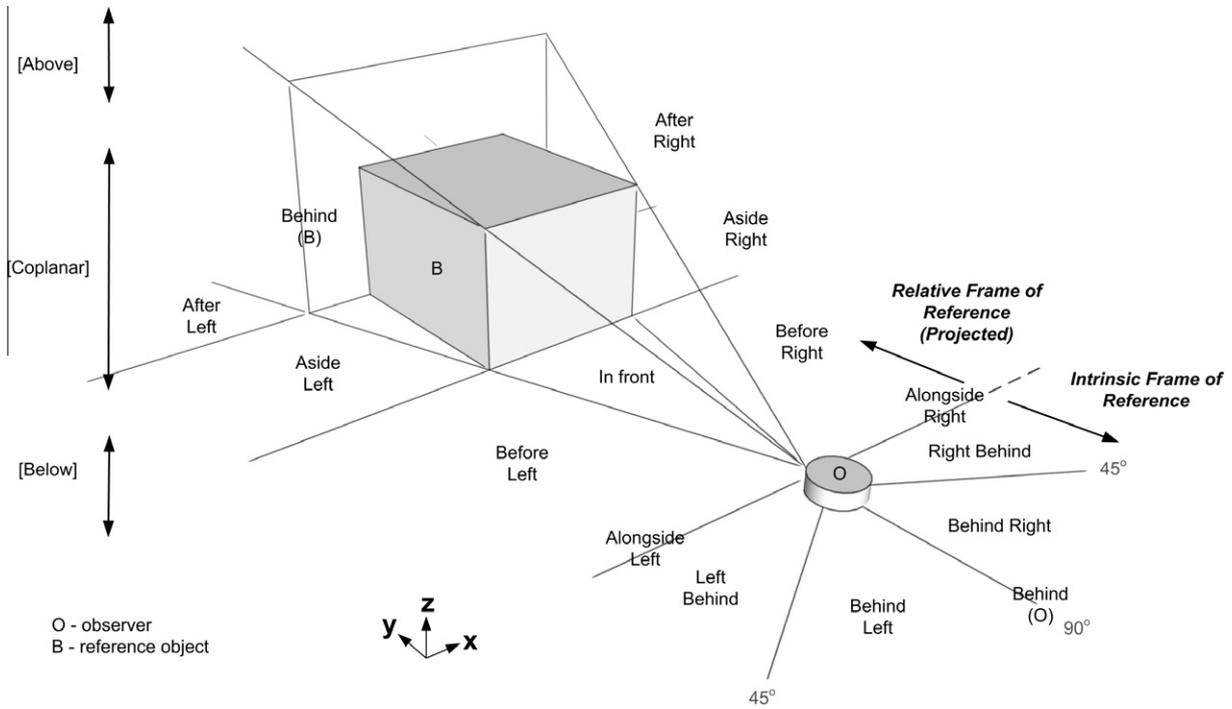


Fig. 4. Acceptance zones for the combined model.

The combined model uses an intrinsic frame of reference when the reference object is behind the observer. The position is described using terms such as ‘the bank is *behind* you and to your *right*’, or ‘the bank is on your *right* just *behind* you’ with the word order being based on the magnitude of the angle. In these cases the observer (O) is referenced (*you/your*) which is considered more appropriate than reporting the primary object (A) to be *before* the original reference object (B) as returned from the 5-intersection model, even though it is behind the observer. For any regions which extend across the border from *behind* to *in front* of the observer the term *alongside* may be added to the relation, such that *alongside right* and *alongside left* are used.

In all other cases the primary region is reasoned in relation to the reference object, and its position described using the 5-intersection model. The vertical elements (*above*, *coplanar*, and

below) are reasoned using a quaternary relational model in R^3 for the same reference object, giving a total of 26 ($3^3 - 1$) addressable projected zones.

To improve the model’s granularity while conforming to projective geometry invariant restrictions, a number of model extensions are proposed. Currently the 5-intersection model is unable to differentiate between the *Before Left*, *Aside Left*, and *After Left* regions marked in Fig. 4, instead describing the result as *Left*. In fact all of the primary regions (A1,A2,A3,A4) in Fig. 5 are indistinguishable from the results of the 5-intersection model. However, if the primary and reference objects are projected onto a line between O and the focal point on B (i.e. where the observer is looking), then a 1D collinear set is available for further analysis (Fig. 5). This set is used to order the primary regions from *before* to *after* the reference object, using only relative orders and no numeric

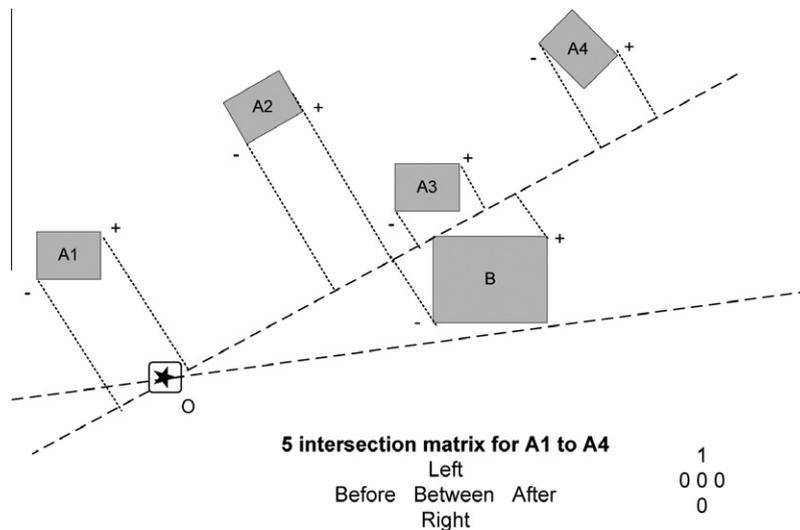


Fig. 5. Extending the 5-intersection model for regions.

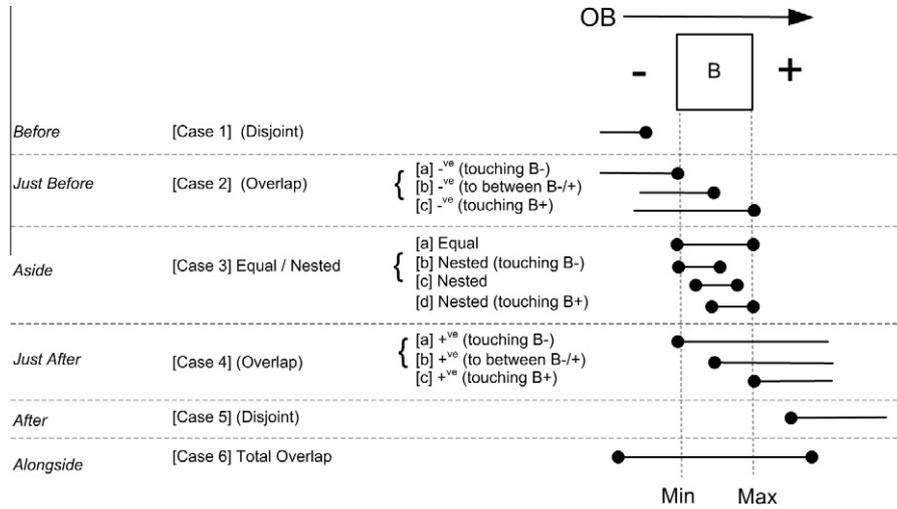


Fig. 6. Relations in 1D using overlap and disjoint refinement (based on Allen (1983)).

measurements. By considering the most extreme points for each region (shown as - and + in Fig. 5), it is possible to define a set of distinct outcomes thereby increasing model granularity. The next section describes the implementation of this extension for the combined model considering the case for each axis independently, beginning with an improvement in modelling the fidelity for depth (Y-axis).

3.1. Graded cases for Y axis

The 5-intersection model only describes concepts of depth (Y-axis), using the terms *In front* and *Behind*, for collinear space. Here we propose that *aside* space may also be subdivided through consideration of other models.

Allen's (1983) concepts of temporal relationships may be applied to one dimensional space to describe the relationship between two objects (Güsgen, 1989). A region may be defined in 1D space using its extreme points, those that appear first and last on the axis being considered. Therefore by using the extreme points from both the primary region (A) and reference object (B) 13 identifiable relationship cases may be defined conforming to Allen's 13 temporal relationships. Fig. 6 shows the definitions for the Y-axis which fall into six main classes describing the depth of space from the observer as *before*, *just before*, *nested*, *just after*, *after*, and *alongside*.

From this the positions of the primary objects in Fig. 5 may be described as follows: A1 is *before* and *left* of B, A2 is *just before* and *left*, A3 is *beside* B on the *left*, and A4 is *after* B on the *left*. More specifically these may be referred to as A1 is *Case1*, A2 is *Case2a*, A3 is *Case3c*, and A4 is *Case5* as described in Fig. 6.

Although collinear space has existing definitions for *in front* and *behind* an additional definition of *nested in front* and *nested behind* space may be introduced, which arises when the convex hulls overlap. For example in Fig. 7 the primary object is partly left (1) and partly collinear (2,3). The collinear space may be divided into that which is completely behind (2) the reference object (B), and that which is nested (3). To assist with clarity a differentiation in terminology is made between *before* and *in front*, and *after* and *behind*, for *aside* and *collinear* space respectively.

3.2. Graded cases for X axis

A similar refinement may be made to the X-axis such that objects to the left and right may be defined more specifically. In

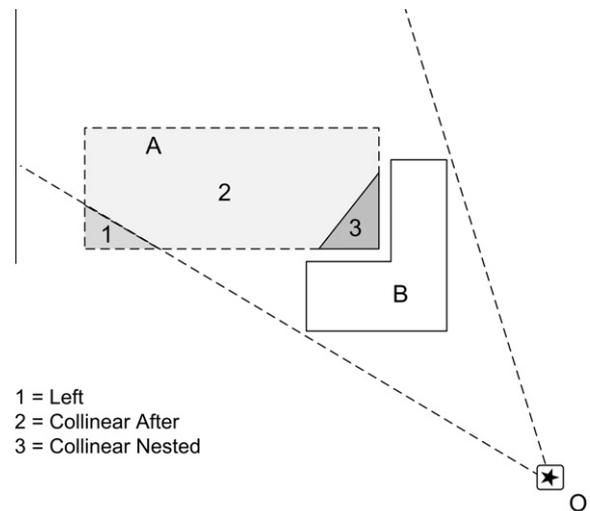


Fig. 7. Collinear nested space.

projective geometry angles may not be used as part of a definition as they are not preserved throughout transformation, however, collinearity is invariant. The existing definition for collinear regions (coll2) may be extended to describe the thirteen cases (Fig. 6) by considering the extreme points from each region. These are the furthest left and furthest right points for a region, denoted using $+ve$ and $-ve$ suffixes. The six main X-axis cases are shown in Fig. 8a, and a number of graded examples are shown in Fig. 8b, where A is the primary object and B the reference object. This approach permits the use of terminology such as *immediately right*, *in front just right*, *in front right*, and *totally in front*.

The full set of thirteen cases for the X-axis may be defined using tests of collinearity between the extreme points and the regions as shown in Table 2. For example Case 1 states that to be true all points (x) from Region A should be left of the zone formed between the observer (point y) and an interior point (z) of convex hull in region B. Case 2b is true when the positive extreme point (x_{+ve}) from region A and the observer (point y) and a point z from the convex hull formed from the interior points of region B should be collinear, and the negative extreme point (x_{-ve}) from A is on the left side of OB. By adopting these extensions a graded approach to the X-axis definitions can be introduced into the model's definitions.

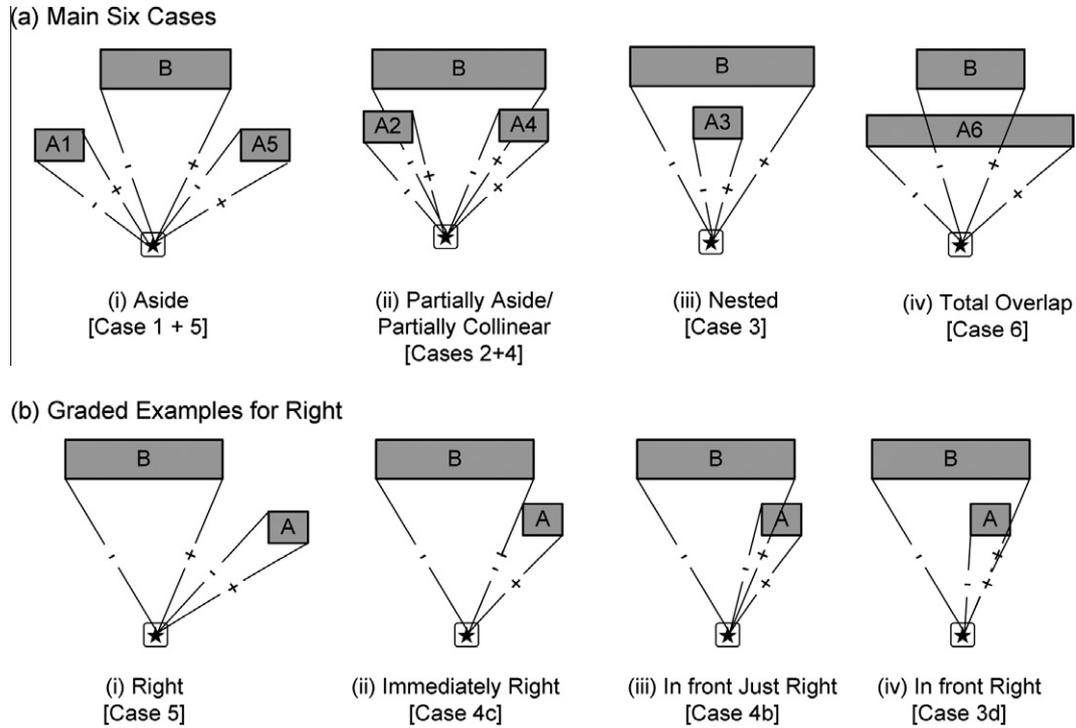


Fig. 8. Testing for collinear and aside cases where B is the reference object, A is the primary.

Table 2
Determining X-axis case based on collinearity for visible regions and extreme points.

Case1 (A, O, B)	$\forall x \in A [\exists y \in O [\exists z \in CH(B^\circ) [ls(x, y, z)]]]$
Case2a (A, O, B)	$coll(x_{+ve}, y, z_{-ve}) \wedge x_{-ve} \in A [\exists y \in (O) [\exists z \in CH(B^\circ) [ls(x_{-ve}, y, z)]]]$
Case2b (A, O, B)	$x_{+ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [coll(x_{+ve}, y, z)]]] \wedge x_{-ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [ls(x_{-ve}, y, z)]]]$
Case2c (A, O, B)	$coll(x_{+ve}, y, z_{+ve}) \wedge x_{-ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [ls(x_{-ve}, y, z)]]]$
Case3a (A, O, B)	$coll(x_{-ve}, y, z_{-ve}) \wedge coll(x_{+ve}, y, z_{+ve})$
Case3b (A, O, B)	$coll(x_{-ve}, y, z_{-ve}) \wedge x_{+ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [coll(x_{-ve}, y, z)]]]$
Case3c (A, O, B)	$\forall x \in A [\exists y \in O [\exists z \in CH(B^\circ) [coll(x, y, z)]]] \wedge \neg coll(x_{-ve}, y, z_{-ve}) \wedge \neg coll(x_{+ve}, y, z_{+ve})$
Case3d (A, O, B)	$coll(x_{+ve}, y, z_{+ve}) \wedge x_{-ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [coll(x_{-ve}, y, z)]]]$
Case4a (A, O, B)	$coll(x_{-ve}, y, z_{-ve}) \wedge x_{+ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [rs(x_{+ve}, y, z)]]]$
Case4b (A, O, B)	$x_{-ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [coll(x_{-ve}, y, z)]]] \wedge x_{+ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [rs(x_{+ve}, y, z)]]]$
Case4c (A, O, B)	$coll(x_{-ve}, y, z_{+ve}) \wedge x_{+ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [rs(x_{+ve}, y, z)]]]$
Case5 (A, O, B)	$\forall x \in A [\exists y \in O [\exists z \in CH(B^\circ) [rs(x, y, z)]]]$
Case6 (A, O, B)	$x_{-ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [ls(x_{-ve}, y, z)]]] \wedge x_{+ve} \in A [\exists y \in O [\exists z \in CH(B^\circ) [rs(x_{+ve}, y, z)]]]$

Coll = collinear LS = left side RS = right side CH = convex hull x, y, z are points in regions AOB respectively. Extreme points are denoted by suffix -ve or +ve.

3.3. Graded cases for Z-axis

Previously, the concept of quaternary relationships for determining above and below in R^3 was raised in Fig. 3. An example for a more complex primary body is given in Fig. 9, whereby a number of planes are created between the observer and reference object. The primary object (A) being considered as a set of individ-

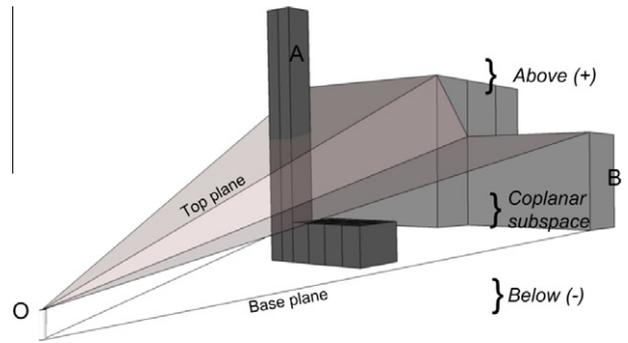


Fig. 9. Spatial qualitative modelling for the Z-axis.

ual columns for which the appropriate Z-axis case may be determined, with the overall classification accounting for the range of cases encountered. In Fig. 9 the primary feature (A) would be classed as Case 4a, signifying it occupies the coplanar subspace and extends into CS^{+ve} .

The methods described in Sections 3.1, 3.2, 3.3 are used to reason between a primary and reference object in 3D, with results being stored in a tree form as described in the next section.

3.4. Qualitative modelling – tree form

The qualitative modelling results for each axis may be stored according to the thirteen cases (shown in Fig. 6) using a ternary system. These are shown in Fig. 10 whereby 'F' indicates an empty set, '0' indicates extreme points of primary and reference objects are collocated on an axis, and '1' indicates a line passes through the region.

The order of modelling is as follows: examine the X axis to determine left, collinear, and right sections of the primary object. Each section is then processed to determine the Y axis sub-parts

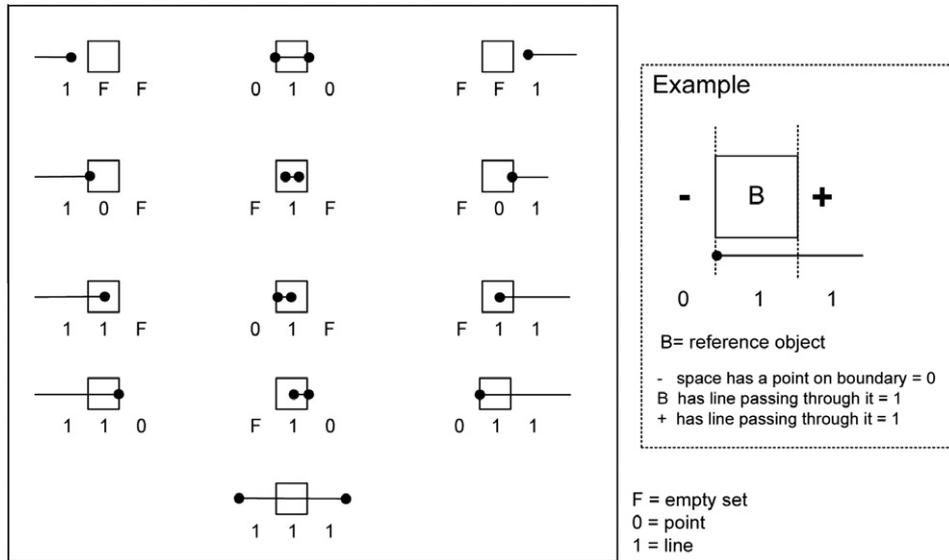


Fig. 10. Qualitative refinements.

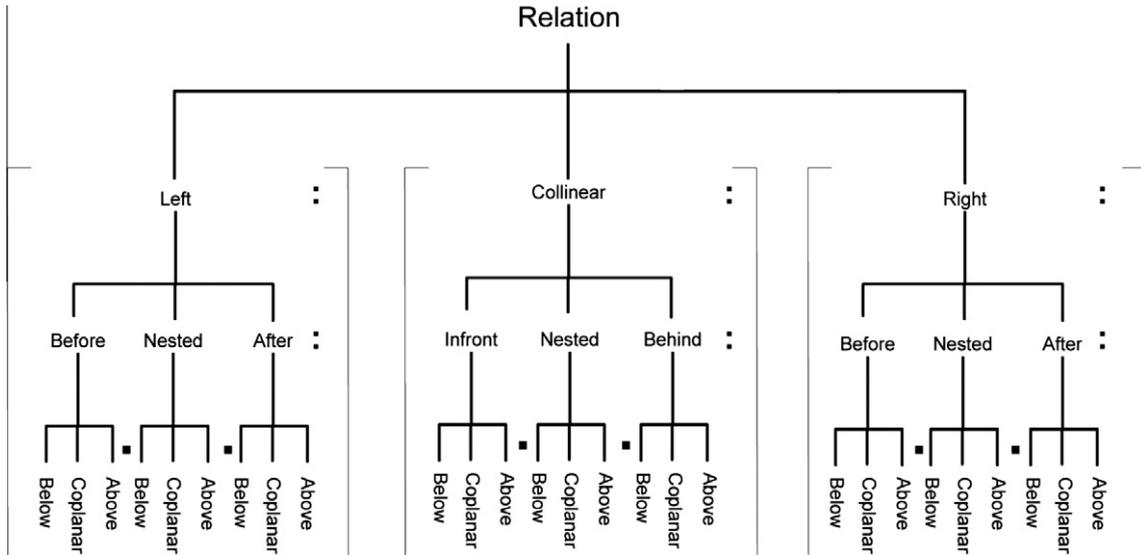


Fig. 11. Structure of the implemented qualitative modelling tree.

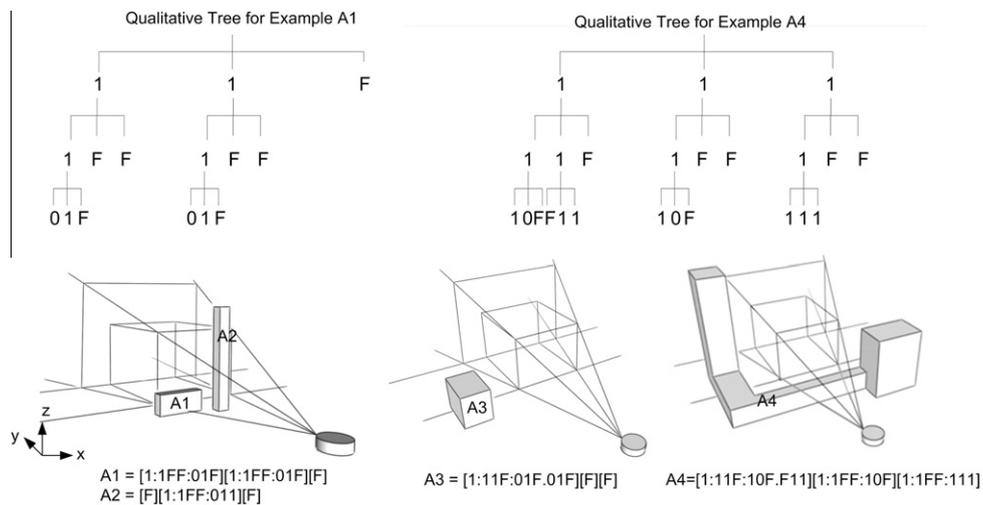


Fig. 12. Examples of model output for objects in 3D space.

Table 3
Implementation of Freeman's primitives.

Primitive relation	Graded extensions	Search criteria examples
Left of	Left	[1:?:*][F][F]
	Immediately left	[1:?:*][0:?:*][F]
	Just Left	[1:?:*][1:?:*][F]
Right of	Right	[F][F] [1:?:*]
	Immediately right	[F][0:?:*][1:?:*]
	Just right	[F][1:?:*][1:?:*]
In front of	In front of	[F][1:1FF:~][F] [F][1:1OF:~][F]
	In front left	[1:1FF:~][0:1FF:~][F] [1:1OF:~][0:1OF:~][F]
		In front right
	In front just left	[1:1FF:~][1:1FF:~][F] [1:1OF:~][1:1OF:~][F]
	In front just right	[F][1:1FF:~][1:1FF:~] [F][1:1OF:~][1:1OF:~]
	Behind B (reference object)	Behind
Behind left		[1:FF1:~][0:FF1:~][F] [1:F01:~][0:F01:~][F]
Behind right		[F][0:FF1:~][1:FF1:~] [F][0:F01:~][1:F01:~]
Behind just left		[1:FF1:~][1:FF1:~][F] [1:F01:~][1:F01:~][F]
Behind just right		[F][1:FF1:~][1:FF1:~] [F][1:F01:~][1:F01:~]
Behind O (observer)		Relative position calculated in metric space and graded into seven zones
Above	Above	[*?:FF1]
	Immediately above	[*?:F01]
	Just above	[*?:F11]
Below	Below	[*?:1FF]
	Immediately below	[*?:1OF]
	Just below	[*?:11F]
Beside	Beside left (holds for AOB and BOA)	[1:F1F:~][F][F]
	Beside right (holds for AOB and BOA)	[F][F] [1:F1F:~]
Touching	Use DE-9IM as topological relationships hold in projective space	
Between	Quaternary projective relations between bodies in R^2 between (AOBC)	
Near/far	Metric space model	
Inside/outside	Use DE-9IM topological model (e.g. the stream is inside the park)	

which are then defined against the Z axis, forming a tree as displayed in Fig. 11, which may be serialised. Here the tree is serialised by depth with a decimal point placed between each branch and a colon between each layer to improve reading ease. Square brackets added to sub-parts of the tree assist when searching for specific patterns in the abbreviated serialised form, as becomes evident later in the paper. Values from lower branches are only included if a True condition is met, removing excessive False nodes from the serialised result. This single string is able to describe all possible projective relationships a solid primary object may have with a solid reference object in 3D space. A number of examples for simple and complex shapes are shown in Fig. 12.

The serialised value may be used to describe projective relationships between the visible aspects of two objects in 3D space, suited to the egocentric modelling required for LBS. Where specific criteria are not required a wildcard (*) may be used denoting any sequence may be substituted into that portion of the serialised key, a question mark (?) where any single character (F,0,1) may be used, or the letter T when a True value (0 or 1) is required. For example the search term [1:F1F:~][F][F] would match any primary object which is *Beside Left* of the reference object, while items *Above* the reference object could be found using the search criteria [*?:F?1], and those *Below* using [*?:1?F]. Combinations such as *Beside Left* and *Above* would be found using [1:F1F:F?1][F][F].

3.5. Implementation of Freeman's primitives for 3D LBS

The model presented combines existing theory with a number of extensions for the purpose of qualitative modelling for LBS in

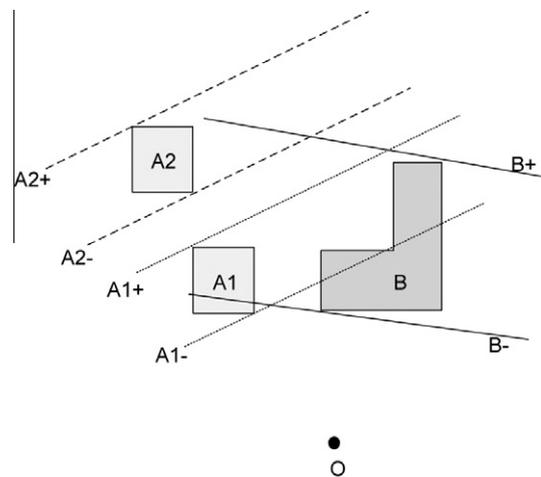


Fig. 13. Beside relation defined using a reciprocal test.

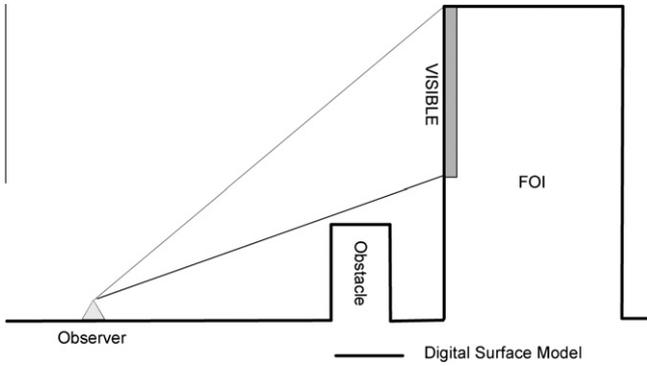


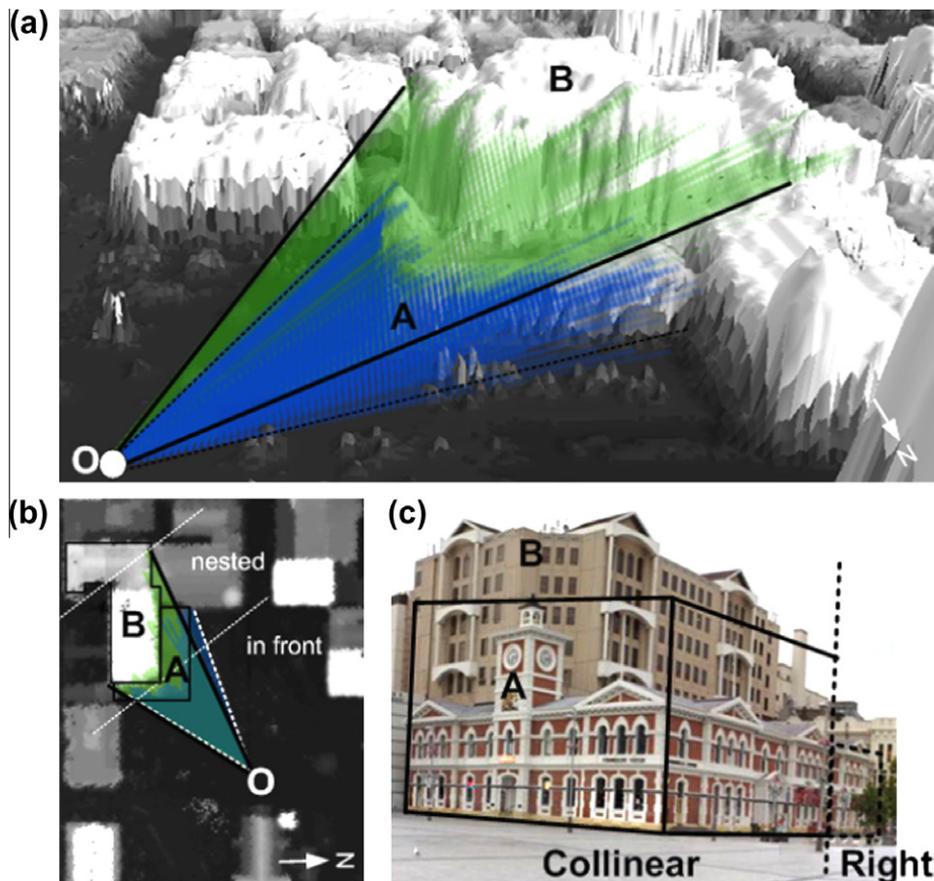
Fig. 14. Visual exposure modelling for a Feature of Interest (FOI).

3D, and is based on projective invariants. The model is able to describe complex relationships beyond those used in language, and therefore it is useful to map the outputs to Freeman’s Primitives. As shown in Table 3 this is possible for the majority of cases with the exception of the definitions of *Near* and *Far* which require a definition using metric space. Other terms such as *Inside* and

Outside, and *Touching* may reference the DE-9IM, as topological relationships hold in projective space.

Near and *Far* are fuzzy distance descriptions and therefore more suited to metric based models. There is no exact boundary, and a reference scale is critical in determining the relationship (Peuquet, 2002). For example two buildings may be described as near each other while two cups on a table may not be. To overcome this scale issue Abella and Kender (1993) define the *Near* relationship to be when the bounding boxes of objects have non-empty intersections. *Far* is defined as when the distance between bounding boxes is greater than the larger of the bounding box’s longest axis. According to this definition, and other related work (Duckham & Worboys, 2001), two objects may be neither near nor far from each other.

The term *Beside* may be defined as the zone of nested space in the *Y*-axis and aside space in the *X*-axis, correlating to the *aside* region in Fig. 4. However, the term implies a finite zone near the reference object and not an open set as currently defined. To limit the region’s extent the *Near* relationship may be included in the definition, using metric space as outlined above. However, an alternative approach would be to limit the zone’s extent by checking the reciprocal relations of AOB and BOA as follows. If a part of region A falls within the *Aside* relation of B, and part of region B falls within the



Relationship (AOB) is:
 $[F][1:11F:11F.11F][1:F1F:1FF]$

A is COLLINEAR and RIGHT of B
 The collinear section is IN FRONT + NESTED, and BELOW + COPLANAR
 The right section is NESTED and BELOW

Fig. 15. Real world trial – case Study 1 (a) perspective view of visibility model on LiDAR sourced DSM showing LoSs (b) plan view of LoSs (c) photograph from viewing location.

Aside zone of A, then the two regions may be considered to be *Beside* each other. For example in Fig. 13 the *Aside* zone for the reference object is denoted by the B– and B+ lines, which includes both primary objects A1 and A2. The *Aside* zone for A1 includes B, and therefore these two objects are considered to be *Beside* each other, whereas A2 is not considered to be *Beside* B. This method accommodates the scale of the objects such that the definition is suitable for small or large objects (e.g. buildings or mountains).

Table 3 shows examples from the serialised tree, where a wild-card (*) implies any result combination may be substituted for that part of the tree, and T indicates a true value (0 or 1) is required.

The next section demonstrates the model’s use in a real world scenario, whereby it is able to define and determine FOIs which are visible to a LBS user.

4. Application of combined qualitative model to LBS

4.1. Visibility analysis

The model’s implementation requires an ability to calculate what is in the user’s field of view. This may be done using visibility modelling which in turn requires a Light Detecting and Ranging (LiDAR) sourced digital surface model (DSM) to provide data on the city’s profile, including buildings, vegetation, and topography (Omasa, Hosoi, Uenishi, Shimizu, & Akiyama, 2008; Palmer & Shan, 2002; Rottensteiner & Briese, 2002). The visual exposure of each FOI is calculated by considering the lines of sight between the observer and each raster cell within the FOI boundary, considered as a target. The model returns results for each of these targets denoting the

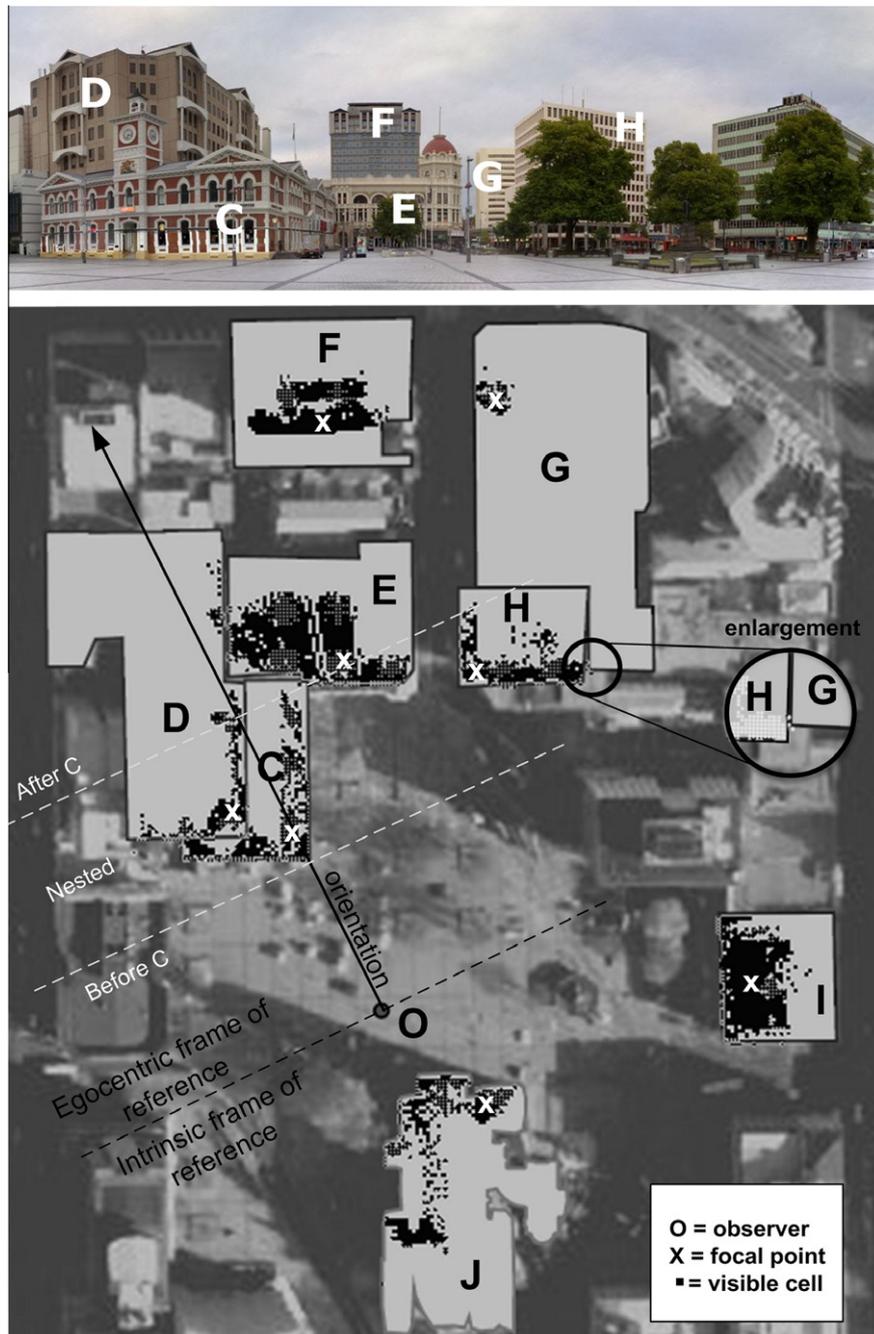


Fig. 16. Projective relations – map showing visibility of buildings from point O. Notations for the example where C is the reference object are also added.

extents visible as vertical columns (Fig. 14) so that various visual exposure summaries may be calculated per FOI, including the total façade area visible. These results may be used to determine, for example, if the entire façade of a church is visible or just the top part of the spire. As the observer moves so the model is re-run giving a dynamic account of the parts of FOIs visible, which can then be summarised using the projective model outlined in this paper. A more detailed account of the visibility model implemented may be found in Bartie, Reitsma, Kingham, and Mills (2010).

The visibility analysis is the most costly phase of the implementation after which the results may be processed in different combinations according to the selected reference and primary objects for qualitative modelling. Many thousands of projective scenarios may be queried very rapidly (i.e. sub-second) to populate various qualitative trees, supporting dynamic interrogation of relationships between visible city objects.

4.2. Case Study 1

A dataset for the city of Christchurch, New Zealand was used to trial the combined qualitative model. A DSM at 1 m resolution was used to carry out the visual exposure modelling for selected FOIs, the results of which quantify the vertical visible extent of the cells within the defined FOI boundary.

Fig. 15 shows the result from the trial, with the model's description of the relationship between the primary building (A) and the reference object (B). The rays cast by the visibility model are shown

from a perspective view in Fig. 15a, with blue lines indicating the rays from the observer to FOI A, and green lines show the rays to FOI B. A plan view of the situation is shown in Fig. 15b, and a photograph with the denoted sections in Fig. 15c. The results describe which parts of the FOIs are visible to the observer, and define the bodies which are used in the modelling process. The tree is completed by first considering the X-axis definitions (i.e. A is collinear, and right of B), then each section is further refined until the tree is populate at all levels (Fig. 11).

A further set of trials were then undertaken to study a more complete set of relations between FOIs.

4.3. Case Study 2

For this trial the relationships between a number of FOIs were studied from a single location in Christchurch (NZ), the corresponding photograph and mapped visibility results from which are included in Fig. 16. A complete set of modelling was performed between FOIs C to J, from an observation point in Cathedral Square, with each FOI being used as the reference object. For reasons of space the results in Table 4 are abbreviated, showing a complete set of results when C was the reference object, and a summary of the more interesting results from other trials.

4.3.1. Analysis of results

For the majority of cases the model's output is fairly self-explanatory, however, a number of results require further

Table 4
Egocentric qualitative modelling results when looking towards focal point on each reference object.

Reference object (B)	Primary object (A)	Serialised relation	Explanation
C	D	[1:F1F:F11][1:F11:F11.F11][F]	x: Left + collinear y: Nested, nested + behind z: Coplanar + above, coplanar + above
	E	[F][1:FF1.FF1][1:F11:F1F]	x: Collinear + right y: Behind, nested + after z: Above, coplanar
	F	[F][F][1:FF1:F11]	x: Right Y: After z: Coplanar + above
	G	[F][F][1:F11:F1F.F1F]	x: Right y: Nested + after z: Coplanar
	H	[F][F][1:F11:F11.F11]	x: Right y: Nested + after z: Coplanar + above
	I	Intrinsic	Intrinsic: right + behind
E	J	Intrinsic	Intrinsic: behind
	C	[1:1FF:F11][1:1FF.F11][F]	x: Left + collinear y: Before, in front z: Coplanar + above
F	G	[F][F][1:11F:11F.11F]	x: Right y: Before + nested z: Below + coplanar
G	F	[1:F1F:F11][F][F]	x: Left y: Nested z: Coplanar + above
H	C	[1:1FF:F1F][F][F]	x: Left y: Before z: Coplanar
I	J	[F][F][1:1FF:F11]	x: Right y: Before z: Coplanar + above
J	I	[1:11F:F1F.F1F] [F][F]	x: Left y: Before + nested z: Coplanar

investigation. The relationship between regions is not symmetrical, as demonstrated by $r(\text{COE})$ and $r(\text{EOC})$. The X-axis relationship is mirrored, with E appearing *right of and collinear* with C, and C appearing *left of and collinear* with E. However, E is *nested and after* C, while C is simply *in front* of E. Part of the explanation can be seen in Fig. 5, whereby A3 is *nested* with B, but B would be considered *behind, nested and in front* of A3. However, the other factor is that the depth perception is calculated by using a single focal point, and as this moves between reference objects so the descriptions of depth change.

A further phenomenon of reciprocal projective relationships may be noted in the Y-axis where $r(\text{IOJ})$ and $r(\text{JOI})$ both report the other to be in the *before* zone. This can be explained with a simple example of two objects on a table, as shown in Fig. 17. The plan view (Fig. 17b) shows that the metric distance OA is greater than OB, as shown by the arc C of radius OB. However, from a projective point of view the relationship is that A is *aside and before* B which agrees with the egocentric view shown in Fig. 17a.

When A is considered as the reference object then B is considered *aside and before* A, demonstrating one of the differences when modelling in projective space rather than metric space.

The FOI pairs C–D, D–E, D–H, E–H and F–G are considered to be *Beside* each other according to the reciprocal definition outlined in Section 3.5, as demonstrated in Table 4 with results F–G and G–F sharing a mutual Y-axis nested relationship. The pairing of D and H is perhaps questionable, but the large size and depth of building D accounts for why the model produces this result.

The FOI pairs C–D, D–E, D–H, E–H and F–G are considered to be *Beside* each other according to the reciprocal definition outlined in Section 3.5, as demonstrated in Table 4 with results F–G and G–F sharing a mutual Y-axis nested relationship. The pairing of D and H is perhaps questionable, but the large size and depth of building D accounts for why the model produced this result.

The result from such qualitative modelling may be used to form sentences which describe to a user the position of a FOI in relation to one already known, particularly useful for speech based interfaces. It is also possible to define a spatial query which returns all the regions which satisfy a particular projective relationship, as demonstrated in the last case study.

4.4. Case Study 3 – spatial queries

The model may be used within spatial queries to determine which FOIs take part in a specified projective relation. A question mark (?) may be substituted for any single value (F,0,1), and an asterisk (*) for any result combination. For example referring to Fig. 16, a search for the FOIs *behind* ($[*][1:F?1:*][*]$) the reference object E, gives a single result of F, while the more general search for those *after* ($[?:F?1:*]$) gives the results D, E, F and G. A similar distinction may be made between the FOIs which are *right* of E ($[*][*][1:?:*]$) yielding results G and H, and those on the *right* which extend *after* E ($[*][*][1:F?1:*]$), returning only G. The FOIs on the *left* may be divided into those *coplanar and extending above* ($[1:?:?T1][*][F]$), and those *totally above* ($[1:?:FF1][*][F]$) giving results C and D respectively.

The model may also be used to find the locations where a specific projective relation between two FOIs exists, such as finding where E appears to completely overlap (X-axis Case6) the reference object F. This is done using the search criteria $[1:?:*][1:?:*][1:?:*]$ and gives the result mapped in white in Fig. 18.

As FOI E has a tower on the right side (as seen in Fig. 16) a further study was carried out to determine the locations from where this tower would appear to extend *above* FOI F. The query used was $[*][*][1:?:?1]$ which keeps only those locations that have a *right* side component above F. The matching locations are shown in Fig. 18 as black triangles. This kind of analysis, involving the

relationships between FOIs, lends itself to tourist guide LBS applications which would be able to instruct a user to move to certain locations to obtain particular views of the city. It may also have uses in town planning, urban design or for photographers looking for a given arrangement of entities.

4.5. Model evaluation

The model presented combines the output from a visibility engine with models of projective space, offering greater qualitative descriptive capability than previously possible. The number of acceptance zones created allows for parts of primary objects to be described individually and therefore more subtly than by using existing models, such as the 5-intersection model (Clementini & Billen, 2006). For example in Case Study 1 the primary object has two distinct relationships with the referring object, a collinear part and the part to the right. Each of these parts is described separately; one being coplanar/below while the other is below. By comparison existing models only deal with whole objects and would describe the primary object as being coplanar/below. Another example in Case Study 2 with the reference set as C and the primary as F, is where existing models would describe the relationship as to the right, while this model would describe the primary as after /right. This addition is made possible through the introduction of Allen's (1983) interval definitions.

The combined model is able to encapsulate complex relationships between objects in projective space in a tree form, allowing for rapid storage and retrieval. There is a growing demand for this capability in speech based LBS applications (Bartie & Mackaness,

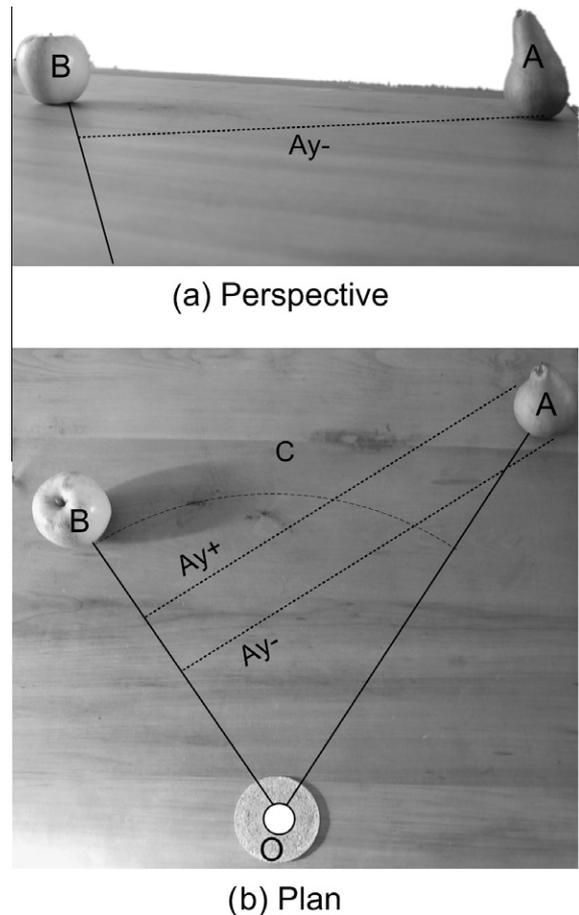


Fig. 17. Y-axis model – how two objects can share a reciprocal in front relationship.

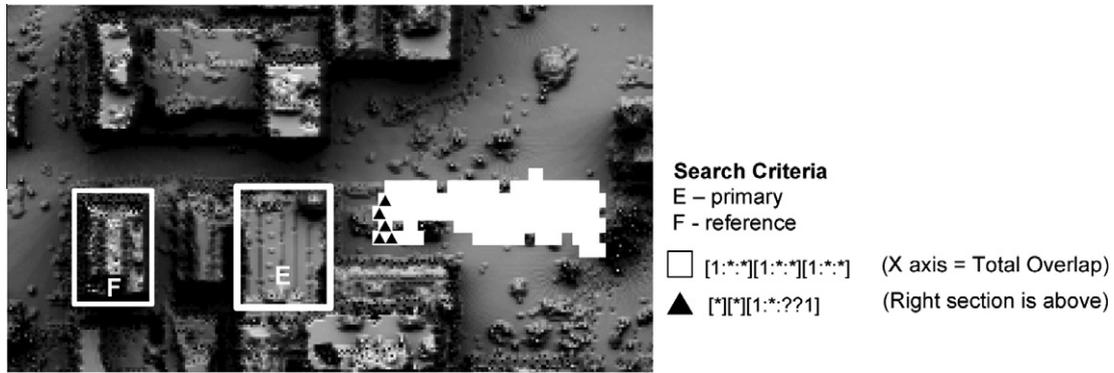


Fig. 18. Querying the tree to determine locations matching specified qualities.

2006), which use Natural Language Generation and Natural Language Parsing. One of the challenges with such applications is to reduce the user's cognitive load by more closely modelling their view, and adopting human-like descriptions.

5. Conclusion and future work

The focus of this research has been to establish a combined qualitative model for use in LBS which may be serialised into a single descriptor able to convey complex relationships between reference and primary objects in 3D from a specified observation point. The combined model uses a number of existing projective models which were extended by adapting Allen's (1983) temporal model to improve the fidelity of relation definitions.

A number of case studies were used to demonstrate how a high resolution LiDAR based DSM could be used in conjunction with a visual exposure model to establish which parts of FOIs were in view, from which the projective qualitative model was able to describe the relationship between the FOIs as seen from the observer's frame of reference. Such modelling would be useful in dialogue based systems, allowing the user to construct questions about unknown features by describing their relationship to known ones.

The model may be used to describe the relationship between objects, to search for buildings which match a given relationship criteria, or to find locations where a particular relationship exists between objects. The model may be used in combination with existing spatial and attribute searches, such as to find the names of all buildings of historical significance in view to the right and behind the train station.

Further work should consider the issue of primary object fragmentation, which is a concern when a more distant low primary building extends either side of the taller closer reference object. In this case the model describes the relationship as an overlap situation (Case6), however, the corresponding details from the collinear section are missing as they are out of sight.

There would be benefit in considering how composite qualities may be formed by combining a series of trials, such as describing C and D as right of B, then modelling the relationship between C and D to determine which is closer. There may also be benefit in including fuzzy classification methods which consider the proportions of buildings within each zone so that the most dominant classification is used first when describing the relationship. Furthermore projective qualitative modelling may be combined with other datasets, such as topography and building geometry, to generate more complete descriptions, such as "the bank is the tall building on the right of the hill". As an example the model has been used to form the basis for recognising the relation "opposite" (Bartie, Reitsma, Clementini, & Kingham, 2011).

There are a range of dialogue based LBS applications which could benefit from modelling the qualities of projective relationships, allowing for greater interaction between digital city models and language to support the user. It is also expected that the transition of relations, for a moving observer, would form the basis of future research in an LBS context.

Cognitive models of space are qualitative (Hernández, 1991), and the most successful qualitative model will be match a user's cognitive model. Future research should evaluate this model for use in a number of different urban tasks, to establish the suitability of the model in real world LBS context.

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