

# Space Syntax and Pervasive Systems

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**Abstract** In this paper we describe our novel use of space syntax for the design and development of pervasive systems. Pervasive systems are computer systems that are designed to be “invisible” to users because they are designed to blend in with their environment and become part of the fabric of everyday life. Pervasive systems consist of fixed, mobile and embedded components, each of which may entail interactive capabilities and intelligence. Due to their close relationship with the build environment, pervasive systems are an ideal domain for adopting a space syntax methodology. The contribution of this paper is two-fold. First, we present an adaptation of the space syntax methodology aimed at researchers and designers of space and pervasive systems. By developing an adaptation of the space syntax methodology we intend for space syntax to be added the arsenal of tools and theories that researchers use to understand and design pervasive systems. To exemplify how this can be achieved, we present three case studies that demonstrate crucial ways in which space syntax analysis can aid the design of pervasive systems. The case studies presented here show how space syntax can be used in the development of pervasive system as an application development tool, as an exploratory tool, and as a modelling tool.

**Keywords** Space Syntax, Pervasive and Ubiquitous Computing, Observation, Methodology, Applications.

## 1 Introduction

The relationship between computers and space is a topic that has persisted throughout the various advances in computer science, as early as when the first Multi User Dungeons (MUDs) were developed (Muramatsu and Ackerman 1998). With the advent of personal computers, researchers began considering the relationship between physical space and “digital space” (Dix 2000; Dix 2003) and examined how to optimise this relationship and convey it to users. Advances in

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graphics enabled the development of virtual reality systems, in turn sparking a wave of interest in “virtual space” and its potential for replacing real space (e.g. Shiode and Kanoshima 1999). The popularity of the Internet, the World Wide Web, and “online” systems gave rise to research on cyberspace (e.g. Spinello 2000), interaction space (O’Neill et al. 1999), and social space (Harrison and Dourish 1996). All such work suggests that computer systems generate various types of space that as designers we must understand, manipulate and optimise.

Interestingly, while some theories consider digital and virtual space as potential alternatives to physical spaces, today we see that physical space is more important than ever before. With urbanisation levels reaching more than 50% for the first time in history (United Nations 2007), visions suggesting the end of cities and the rise of cyber cities seem more and more out of touch. As Stephen Graham suggests, “We are not experiencing some wholesale, discrete break with the urban past ushered in by the ‘impacts’ of new technology. Rather, we are experiencing a complex and infinitely diverse range of transformations where new and old practices and media technologies become mutually linked and fused in an ongoing blizzard of change” (Graham 2005, pp 96).

Urban space has become more relevant than ever, especially in light of pervasive systems operating at the urban scale. As the field of pervasive systems matures, the models, theories, and tools used in our research evolve. Hence, as computers move away from the desktop and into our cities and our lives, we need new theories and tools to help us understand the relationship between urban space and our systems. Urban space is now the infrastructure on top of which our pervasive systems operate (Dourish and Bell 2007).

In an attempt to systematically incorporate this infrastructure in our systems, we here present our novel adaptation of space syntax (SS) and its use in the design and development of pervasive systems. To acquaint the reader with SS’s concepts and methodology, we first describe SS and present its main ideas from the perspective of pervasive systems. We then present three case studies demonstrating our novel application and extension of SS in the course of designing pervasive systems.

Our main contributions are, first, the adaptation and operationalisation of SS for use in pervasive computing, and second the use of SS to develop pervasive systems.

## **2 Space Syntax**

Space syntax, much like pervasive computing, is a relatively young and multidisciplinary domain. The central concept behind SS is that the configuration of space, rather than space itself, is the driving force behind how cities operate. Architectural and urban design, both in their formal and spatial aspects, are seen as configurations in that the way the parts are put together to form the whole is more important than any of the parts taken in isolation. The first major publication on SS

came in 1984 where Hillier and Hanson set out a theory of space as an aspect of social life (Hillier and Hanson 1984). In his second major publication Hillier (1996) brought together an array of configuration analysis techniques and applied them to issues of architectural and urban theory. What sets SS apart from other architectural theories is that SS aims to explain how cities are, rather than how cities ought to be. The basic motivation of SS is the realisation that in addition to functioning as bodily protection, buildings operate socially in two ways: they constitute the social organisation of everyday life, and they represent social organisation.

The initial research finding that motivated the development of SS is that, *ceteris paribus*, movement in cities is generated by the configuration of the cities' streets. This fundamental relationship underlies many aspects of cities including the distribution of land use and the spatial patterning of crime. SS research has shown that ineffective configuration in cities or housing estates can cause social segregation and antisocial behaviour. Such examples have given rise to the notion of good, or bad, syntax. To better illustrate this point, Hillier provides an analogy between architecture and language.

“Language is often naively conceptualised as a set of words and meanings, set out in a dictionary, and syntactic rules by which they may be combined into meaningful sentences, set out in grammars. This is not what language is, and the laws that govern language are not of this kind. This can be seen from the simple fact that if we take the words of the dictionary and combine them in grammatically correct sentences, virtually all are utterly meaningless and do not count as legitimate sentences.” (Hillier 1996, pp 7).

Similarly, successful architecture is not just about simply constructing streets and connecting buildings, and neighbourhoods; it is about how we connect the different parts of a city, neighbourhood or building.

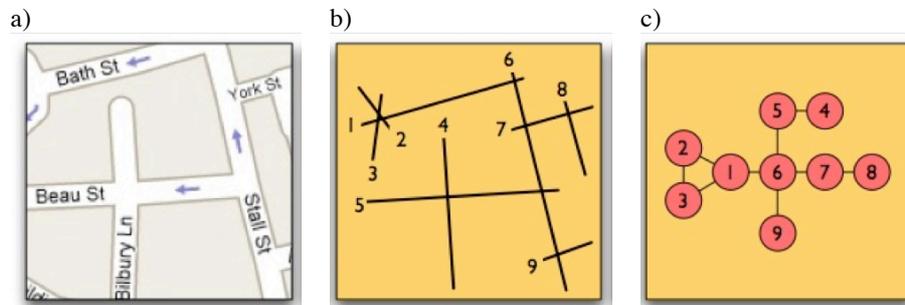
## ***2.1 Operationalisation***

We note that while SS covers a multitude of topics, including vision, isovists, and indoor space, here we focus on the application of SS to urban space. While cities are extremely rich in many respects, SS focuses on a single property: spatial configuration. All claims, findings, and understandings of SS derive from the analysis of spatial configuration. While SS is applied to both indoor and outdoor spaces, here we focus on the outdoor and urban use of SS.

### **2.1.1 Axial maps**

The fundamental premise of SS is that every city can be represented as an “axial map”. A city's axial map can be derived by simply drawing the set of least and longest straight lines (axial lines) such that all open spaces have an axial line passing through them. The next step in the analysis is to transform the axial map into a

graph. This transformation is a unique aspect of SS as it results in graphs that, at first, seem counter-intuitive (Figure 1).



**Fig. 1** a) map of city, b) axial map, c) graph representation.

An axial map is transformed into a graph by representing each axial line as a node, and linking the nodes (i.e. axes) that intersect in the axial map. This graph representation is the edge-vertex dual of how we intuitively represent maps: street intersections as nodes and streets as edges. SS uses the opposite: streets become nodes, and intersections become links.

It is worth highlighting the fact that in SS analysis streets become nodes. Each street, irrespective of its width, length, and location, is represented as a single node in the graph. This is an extremely powerful representation, because it enables researchers to identify concrete metrics for each street in a city. This is achieved by carrying out analysis of the graph, and deriving numerous metrics for each node (i.e. street).

### 2.1.2 Metrics

A city graph can be analysed in terms of its properties such as the integration of nodes. In SS, integration describes the deepness or shallowness of a node in relation to the other nodes in the graph. To arrive at a highly integrated street, pedestrians require on average fewer changes of direction (assuming a change of direction means changing streets). On the other hand, less integrated streets are relatively isolated from other streets, and require more changes of directions to get to them. Typical examples of highly integrated streets are high streets, while cul-de-sacs and alleyways are usually less integrated.

Readers may realise that the metric of integration is identical to the concept of distance in traditional graph analysis. In fact, SS utilises many traditional graph metrics, but has developed its own jargon when referring to them. Additionally, SS researchers have developed new metrics. In Table 1 we show the most popular

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metrics used by SS, their conventional name (if one exists), and their definition and description.

space syntax	Graph theory	Description / Definition
Integration	Closeness	The mean distance between an axis and all other axes of the system.
Connectivity	Degree	The connectivity of axis <i>i</i> is the number of axes that it intersects.
Choice	Betweenness	The number of times axis <i>i</i> is used when calculating the shortest paths between all pairs of axes in a system.
Control	-	The degree to which axis <i>i</i> controls “access” from and to the axis it intersects.
Global metric	-	A metric for an individual axis, calculated using the whole system.
Local metric	-	A metric for an individual axis, calculated using the axis’ neighborhood (e.g. axes up to three intersections away).
Intelligibility	-	The correlation between axes’ connectivity and global integration
Synergy	-	The correlation between axes’ local and global integration.
PageRank	PageRank	The popularity of an axis <i>i</i> as determined by the number of popular axes intersecting axis <i>i</i> (recursive)

**Table 1** Table basic space syntax metrics. For each metric we give the corresponding graph theory terminology (if it exists), along with a definition and description of the metric.

Connectivity is a metric used to describe the number of streets that any particular street intersects. (Note that in terms of SS, streets and axes are identical, since all metrics are calculated based on the axial map representation shown in Figure 1b).

Control is a metric that describes the extent to which an axis, or street, controls access to and from streets that it intersects. For instance, a street *i* connected to multiple cul-de-sacs has high control, as anyone wishing to go to the cul-de-sacs must use street *i*.

Similarly, choice is a metric that describes the importance of a node in the context of a greater system. An axis *i* with high choice indicates that many shortest paths between pairs of axis use axis *i*. In other words, axis *i* is utilised by many pedestrians wishing to follow the shortest path to their destination.

The metrics we describe here may be applied globally or locally. Global metrics consider the whole system when calculating a property of an axis, while local

metrics consider only the immediate neighbourhood of an axis. For instance, global integration describes the mean distance between an axis and all other axes of the system. Local integration, on the other hand, describes the mean distance between an axis and its immediate neighbourhood. Thus, local integration of “radius 3” considers an axis neighbourhood up to three intersections away.

Calculating the correlation of one metric with another generates a number of metrics. For instance, a city’s intelligibility is the correlation between axes’ connectivity and global integration. In other words, intelligibility is a measure of how well we can predict an axis’ global integration given its connectivity, and vice versa. Practically, intelligible urban grids offer a good correlation between what pedestrians can see, and what they cannot see.

A similar metric is synergy, which describes the correlation between axes’ local and global integration. This metric considers how well we can understand a neighbourhood given an understanding of a city, and vice versa.

More recently, the PageRank algorithm (originally used by Google search) has been shown to provide a very good correlation with pedestrian movement (Jiang 2008; Jiang et al. 2008). It provides a means for relatively ranking the importance of an axis  $i$  by considering the importance of the axes pointing to  $i$ .

## ***2.2 Data collection and observation***

An integral part of SS involves data collection, either through observation or analysis of publicly available data sources. While axial maps and graphs offer concrete metrics, it is only through observation and further data collection that one may understand how a city operates on an aggregate level.

In the course of their work, some researchers may be interested in the economic aspects of the city, while others might focus, for example, on the flow of pedestrians. It is through data collection and observation that SS can make claims about such aspects of a city. Using correlation, SS analyses observational data in relation to the structural properties of streets described in the previous section. We now give examples of the most popular data sources utilised by SS, and then describe the techniques used to gather empirical data.

### **2.2.1 Data sources**

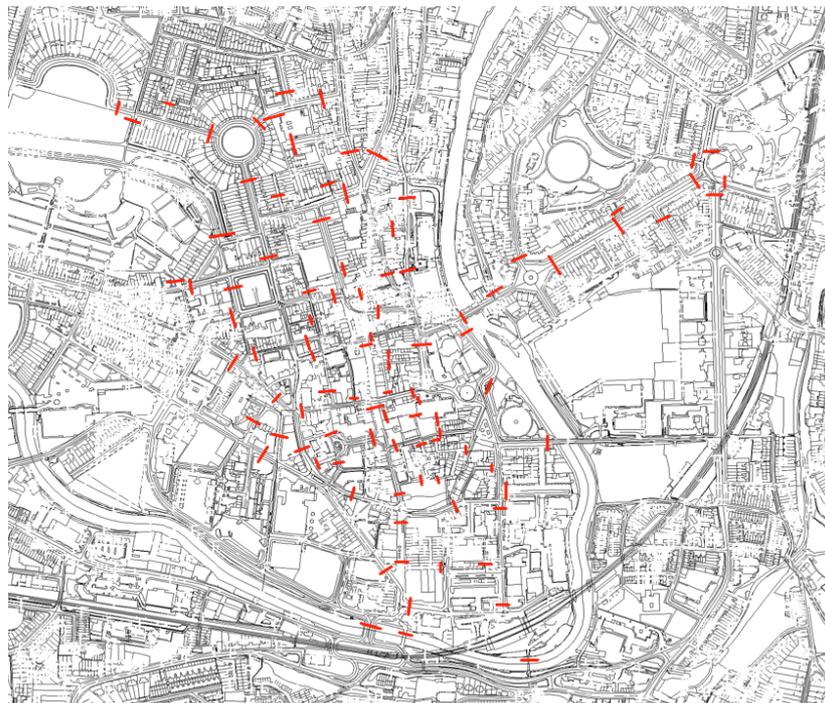
There is a virtually endless list of data sources that SS can utilise, provided that they are appropriately geo-tagged. This means that the data must be attributable to specific streets in a city. Examples of such data include statistics on crime, land use, land use change, movement & flows, economic growth, safety, social status, work habits, shopping behaviour, quality of life, demographics, prostitution, and human encounter. All these data sources can be utilised by SS, if they are fine-

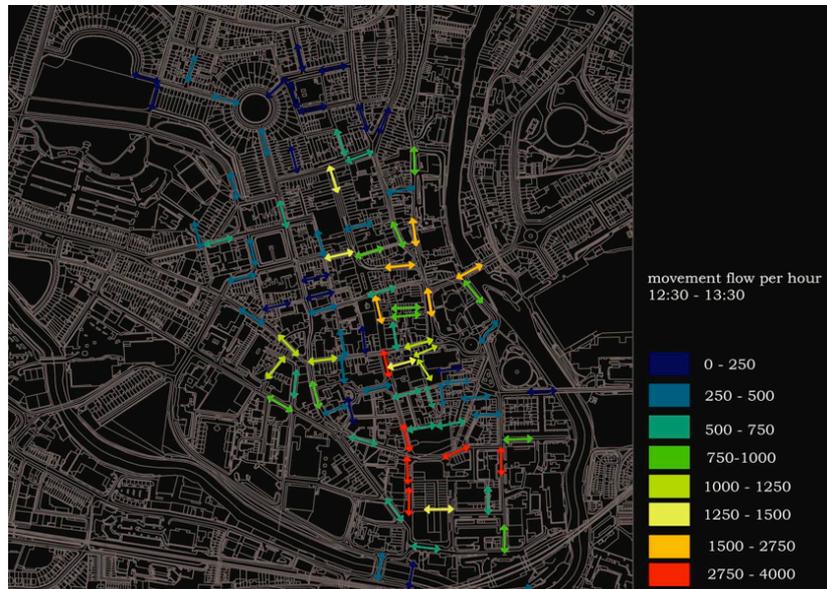
grained enough to enable researchers to attribute this data to specific streets of a city.

In addition to utilising existing datasets, SS employs three primary observational techniques, which enable researchers to gather data on people's use of cities. These techniques are gatecounts, static snapshots, and trails.

### 2.2.2 Gatecounts

Gatecounts are used to establish the actual flows of people throughout the city over the course of a day. A gate is a conceptual line across a street, and gatecounts entail counting the number of people crossing that line. Using this technique the observer stands on the street and counts the number of people crossing the gate in either direction. A typical two-day observation (complemented by a one-day pilot) will involve about 100 gates throughout the city, as shown in Figure 2a (taken from one of our own studies). Here we counted the number of people crossing each gate, and to do so we deployed multiple observers. Our 12 observers took five-minute samples from each gate in five cycles throughout the day, from 8:30 a.m. to 4:00 p.m. over two days.





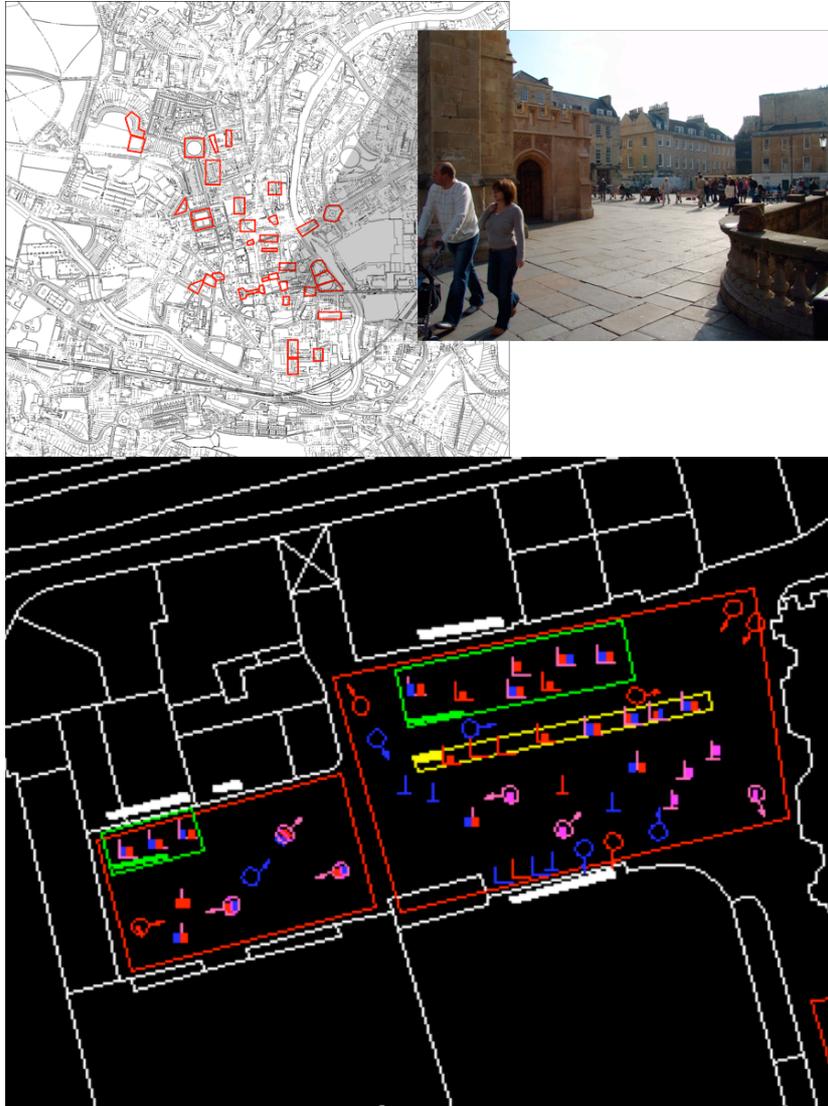
**Fig. 2** Gatecounts. In the top, a map of the city marked with the location of the gates. At the bottom, the observed flows of pedestrians, colour-coded from red (high flow) to blue (low flow).

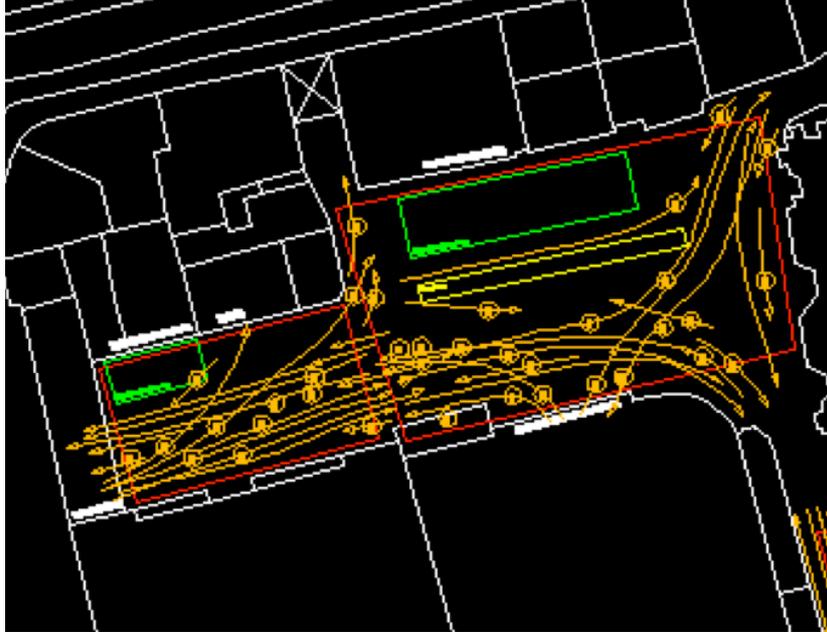
In Figure 2b we see a colour-coded graph of the observed flows of people, ranging from high flows of 2750-4000 people per hour (red) to low flows of 250 people per hour or less (blue). This enables us to correlate between the (SS) predicted and actual flows of people across the city. In this manner we are able to identify the general trend of the city, as well as some outliers - i.e. streets that are over-performing or under-performing (in terms of pedestrian flows) in relation to their integration.

### 2.2.3 Static snapshots

The next SS observation method we consider is static snapshots, in which various open spaces of the city are considered in detail (Figure 3). The method can be used for recording both stationary and moving activities, and is useful when a direct comparison is being made between the two types of space use. A strength of this method is that it makes the patterns of space use in an urban area apparent. For each open space under consideration, the observers record the movements in and out of the space, as well as the type of activity taking place in the space.

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**Fig. 3** Static snapshots. The top shows a map of a city, with multiple “convex spaces” identified. The middle and bottom shows the static and mobile activity as recorded in one such space.

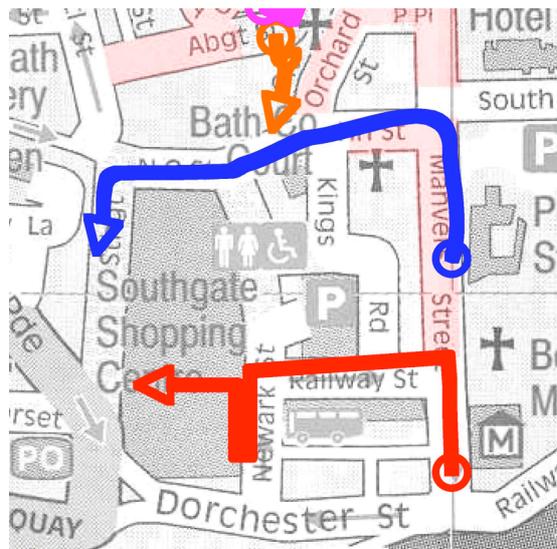
In Figure 3 we present a sample observation of people’s movement within a particular city. The top of Figure 3 shows the map of a city, with marked “convex spaces” where observation is to take place. For one such space we show our observation of static (middle of Figure 3) and moving activities (bottom of Figure 3). Here, we identify the entry and exit points that people used throughout the day. This gives us an understanding of how people perceive a particular space, and how it is utilised. For example, we may observe that a seating area in a park is actually not used for seating but for playing by children. A common observation is use of certain spaces by people making calls on the mobile phone or using their laptops. In Figure 3 we see our observations of people’s activities in this space. We differentiated between instances of males, females, children, or groups of people. For each instance we recorded if they were standing or sitting, and also commented on their behaviour and activities.

#### 2.2.4 Trails

A third method used for understanding the urban landscape is called trails, or people following. This involves tracing the movement of a specific person or group for a fixed time period (e.g. three minutes as shown in Figure 4). This is an increasingly important technique for observing movement that disperses from a spe-

cific “movement distributor” – for example, a train station or a shopping mall. It can be used to investigate three specific issues:

- The pattern of movement from a specific location,
- The relationship of a route to other routes in the area, and
- The average distance people walk from the specific location (this can help determine the pedestrian catchment area of architectural spaces such as a retail facility or public square).



**Fig. 4** Trails. A set of 3-minute trails are shown here, indicated by a beginning (circle) and end (triangle).

Trails give us a sense of how people use the city in different ways. A mother pushing a pram will follow different routes compared to a young student or a tourist. In Figure 4 the two large trails at the bottom show two people walking at a fast pace who decided to take alternative routes for similar beginning and destination points. We also see at the top of Figure 4 two slow-paced pedestrians originating from the same location but going to different destinations. As part of this method, observed trails are augmented by comments that the observer can attach to a trail. Typically, trails are collected by “people following” or manual observation, but GPS trails can also be used.

### ***2.3 Empirical results***

SS researchers have explored various aspects of space and cities in terms of axial maps. Aspects such as pedestrian flow, space use density, crime, cognitive maps,

and intelligibility, have been considered in relation to SS. Here we provide a brief overview of their results.

The correlation between pedestrian movement and spatial integration has been elaborated in (Hillier and Hanson 1984), while further studies have identified this correlation in relation to a large sample of cities and towns (Hillier et al. 1987), galleries (Hillier 1996; Peponis et al. 2004), office buildings and workspaces (Sailer and Penn 2007; Peponis et al. 1997), and even research laboratories (Hillier et al. 1985). While the observational evidence provides strong correlations, causality has not been determined to date. The recent identification of PageRank as a metric that correlates extremely well with pedestrian movement may provide some insight into a possible causality (Jiang 2008; Jiang et al. 2008)

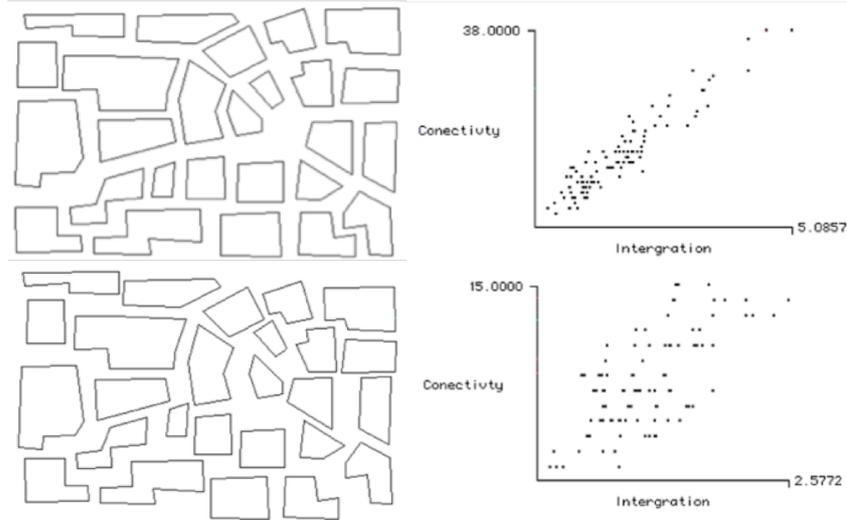
In an attempt to understand the effect of space on cognition, the authors in (Kim and Penn 2004) analysed people's cognitive maps using SS. Their results suggest that the image of spatial configuration maintained in cognitive maps is highly associated with that of the physical built environment. The strong correlation between sketch maps and purely configurational measures of spatial patterns suggest that configurational and relational properties of spatial patterns are perhaps more important for the purposes of navigation than is precise local information.

A further aspect of the relationship between space and movement is highlighted by the differences between weakly and strongly programmed spaces. Strong programmes exist when activity follows a strict pattern, while weak programs describe an "all-play-all" environment. Thus, while courts and schools are strongly programmed, research labs and shopping malls are weakly programmed. The study reported in (Hillier 1996) suggests that as the program becomes weaker, the distribution of space use and movement is defined less by the program and more by the structure of the layout itself. In other words, weakly programmed spaces exhibit a strong correlation between integration and density of space use.

Similarly, the relationship between space and crime has been reported in a number of papers (e.g. Hillier and Sahbaz 2005; Hillier and Shu 2000). The findings suggest a relationship between spatial morphology and various types of crime, such as street robbery and residential burglary. The researchers note that conventional approaches to preventing crime, such as the creation of cul-de-sacs, may in fact be reinforcing crime.

A fundamental difficulty in understanding space is that it is generally impossible to intervene in a systematic way. Because it is extremely difficult to modify aspects of cities and observe the effects, SS research utilises modelling experiments to observe the effect of spatial configuration. In such studies, virtual spaces are generated, analysed and modified. For instance, in a study reported in (Hillier 1996) the layout of a hypothetical deformed grid is shown to have a high correlation between integration and connectivity. The building blocks are then slightly shuffled, resulting in a weak correlation (Figure 5). This marginal reshuffling is shown to result in an unintelligent design, where what pedestrians can see from any location on the grid is not a good guide to what they cannot see.

While difficult to generalise from such artificial experiments, researchers have found universal properties of cities. In a recent study, 36 cities in 14 countries were analysed in terms of axial maps (Carvalho and Penn 2004). The authors show that the cities form two main clusters when considering the distribution of axial length, irrespective of the size of cities. Their results point to an underlying self-similar morphological property of cities, suggesting that cities are fractal in nature.



**Fig. 5** The top figure shows an “intelligible” urban layout, where integration and connectivity are highly correlated. The bottom figure shows the effect of a slight misplacement of the buildings, resulting in an unintelligible layout (Hillier 1996).

Some of the topics that SS-related research has recently begun to address relate to incorporating geometric and metric measures in the analysis of cities (Hillier et al 2007), measuring spatial capital (Marcus 2007), understanding presence, co-presence and encounter (Hanson and Zako 2007; Kostakos and O’Neill 2007), preserving and rehabilitating space, settlements and cities (Amorim et al. 2007; Greene and Mora 2007; Karimi et al. 2007), designing spaces for improved evacuation (Choi et al. 2007), transportation (Kisimoto et al. 2007), and quality of life (Ribeiro and Holanda 2007), considering the relationship between space and prostitution (Hadjichristos 2007), and extending SS to three-dimensional analyses (Wang et al. 2007). Further work has considered automated ways of generating axial maps (Peponis et al. 1998). Most of these topics are in early development, but provide a good indication of the issues SS researchers are interested in further exploring.

## 2.4 Criticism

The simplicity of SS, and its apparent ability to attribute complex phenomena to just spatial configuration, has induced a lot of criticism. A point of debate is whether or not SS is a theory. It is the view of the authors that SS is not a theory in the traditional scientific sense, as it cannot predict phenomena *a priori*. However, SS does provide invaluable tools to explore and understand real world phenomena, and, more importantly, to generate hypotheses.

A stream of criticism addressed at detailed aspects of SS was published in (Ratti 2004), where it was suggested that the same spatial configuration can result in more than one mapping, that SS cannot deal with regular grids, that SS ignores building height, discards metric information and land use information, and finally that axial maps are arbitrary.

A rejoinder to this criticism (Hillier and Penn 2004) addresses each of the above points in detail. The authors claim that minor changes in the built environment can give rise to alternative mappings from apparently similar configurations, but point out that, syntactically, those changes are important. Additionally, they provide morphological and behavioural evidence to support their claim. On the issue of SS's inability to deal with regular grids, the authors respond by claiming that, in practice, such grids do not occur, and therefore SS is applicable. In respect to SS's disregard for building height, metric information, and land use information, the authors explain that these are considered in their analysis, rather than in the axial map. In response to the criticism of axial maps being arbitrary, the authors provide statistics evidence from 28 major cities to suggest that axial lines are significant elements of cities, and that the errors associated with tracing them are not statistically significant.

## 3 Pervasive systems and space syntax

So far we have described the components of SS analysis. We identified axial and graph analysis as the basis of SS analysis, and pointed out that a number of metrics have been developed to describe and understand cities. We also highlighted data collection and analysis as important steps in SS analysis. We now summarise how SS integrates all these aspects in a workflow, and provide a sample "outline" of how to carry out SS analysis.

The steps involved in SS analysis may be summarised as:

1. Generate an axial map of a city
2. Gather data (observation or data sources)
3. Identify correlations between data and SS metrics
4. (Optional) Evaluate alternative designs

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The first two steps are a straightforward application of the processes we described in the previous sections: generating axial maps, and gathering data. Step three is in many ways the crucial step of SS analysis. Given a dataset on, say, crime, SS researchers try to correlate any of the multitude of metrics they have developed with instances of crime.

To illustrate our example of crime, consider a dataset that describes the number of burglaries that took place on every street of a city over a five year period. Thus, some streets may have zero burglaries, others one or two, while other streets may have fifty or more. Such data may be correlated with any SS metric that can characterise streets, such as integration, connectivity or choice. Thus, we are able to plot a graph where one axis describes the number of burglaries, while the other axis describes connectivity, integration, or any other SS metric. Each plotted point in such a graph represents a street. Overall, crime and any SS metric may display a strong correlation that may be described by a mathematical function.

Given the identification of a strong correlation, in step four we are able to evaluate alternative designs. For instance, let us assume a strong correlation between crime and integration. We can then explore the effect on crime if we introduce a new bridge, close a street, or replace a building block with a park. To evaluate such alternatives, we alter the axial map to reflect the proposed changes and assuming the correlation between crime and integration holds, observe how crime is distributed based on the newly calculated integration values for each street.

To incorporate SS in the design of pervasive systems, we have modified the four steps described above by incorporating our own systems in the procedure. The result is the following iterative sequence:

1. Generate an axial map of a city
2. Gather geo-data about the **pervasive system** (logs, usability, etc.)
3. Identify correlations between data and SS metrics.
4. (Optional) Evaluate alternative designs of the **pervasive system**

Our procedure describes a meaningful way of analysing data characterising our systems, and correlating them with the urban morphology of the environment in which our system is deployed. For instance, usability data can be captured about a system at various locations across a city, and then correlated with SS metrics just as crime data can be correlated with SS metrics. Furthermore, these correlations can provide a rationale for evaluating alternative designs and changes to our systems.

This modified procedure is a concise summary of how we have integrated SS in the design of our systems. We now describe in detail three case studies in which we used SS in our research.

## 4 Case studies

In this section we describe three case studies where we used SS in the course of research and development. These case studies demonstrate the role of SS as a simple application module, as an explanatory tool, and as a modelling tool.

### *4.1 Space syntax and application development*

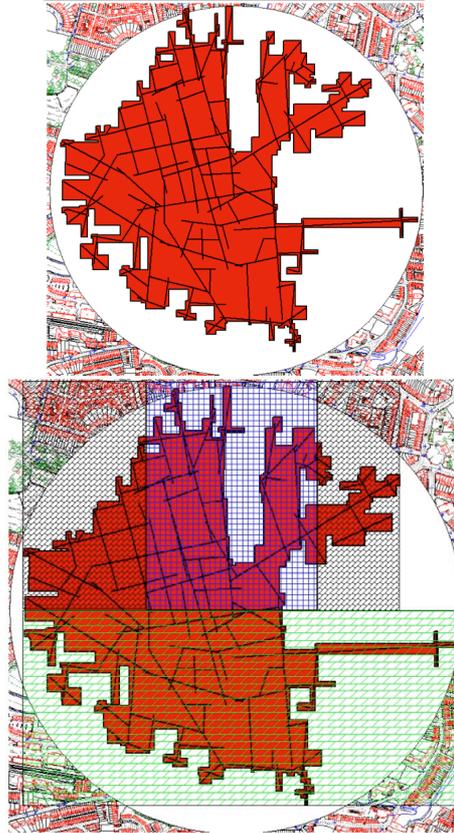
In this case study we consider the redesign of a pedestrian way-finding application (Collomosse et al. 2006). The concept behind this application is that users can utilise their mobile phones' camera to take a picture that may be analysed in order to correctly identify a user's location and orientation. This would be useful for phones that do not have GPS, or where GPS reception is poor. Our analysis is made possible by a server database that holds geo-tagged images of a city. The application originally worked by uploading a photograph to the server, which searched through the database for a close match. The server had a virtual map of the city, and many photographs attached to specific locations in this map. Finding a match for the uploaded image meant identifying the user's location and orientation. However, the search through such a database of images is linear, and therefore expensive.

In our redesign, we suggest that the search can be optimised if we have some knowledge of the user's location. For instance, we can assume that users may have GPS that can be used to detect location, but this may not always function accurately within a city with tall buildings and narrow streets. Another source of location information may be proximity technologies, such as WiFi triangulation or Bluetooth beacons. Given such information, an obvious optimisation to the search process is to use the last known co-ordinates of a user's location in order to narrow down the search through the database. Thus, knowing that ten minutes ago the user was at location  $x$ , the search through the database may be limited to the streets within a radius of 1 km from location  $x$  (depending on user's average speed).

In Figure 6 (top) we show this optimisation in the form of a white circle enclosing all the streets to be searched during a particular query. A further optimisation is to focus on the paths that have a total distance of up to 1 km, such that only a portion of the white circle is searched. These are shown as dark axes highlighted with red.

In the bottom of Figure 6 we show how SS was used to further optimise the database search. Our intention was to identify an optimum ordering of the axes to be searched in the database. Since SS can give us a list of axes order by the likelihood of where a user might be, a sequential comparison between a user's submitted image and the images associated with the highlighted axes is more likely to

find a match sooner rather than later. Overall, therefore, the search effort is reduced.



**Fig. 6** Space syntax optimisation of searching through a database of geo-tagged images. Assuming a pedestrian was heading north, we identify the streets on which they may have moved to after  $x$  minutes, and further identify three zones based on the pedestrian's last known trajectory.

Our SS optimisation was done through a series of iterations, each time measuring any obtained performance gains. Initially we ordered the axes using a radius- $x$  SS metric, i.e. we considered a neighbourhood of diameter  $x$  segments around the user's last known location and ordered all of them with various SS metrics. However, this approach did not present significant performance gains.

After a series of iterations, we settled on the following solution. First, the radius- $x$  axes are segmented in three zones (Figure 6, bottom) based on the user's last known trajectory. Here, our assumption was that users are more likely to maintain their last known trajectory, rather than change it, as suggested by SS. Therefore we create three zones:

- zone A: assume the user kept his last known trajectory (blue, square-patterned grid in Figure 6b).

- zone B: assume the user deviated slightly from his last known trajectory, either to the left or to the right (black, zigzag-patterned grid in Figure 6b)
- zone C: assume the user greatly deviated from his last known trajectory (green, tile-patterned grid in the lower-half of Figure 6b).

Within every zone we rank each axis based on its local integration. The result is that rather than searching through the whole set of radius-x axes in an arbitrary order, the axes are ordered first based on the user's last known trajectory, and then based on each axis' local integration (as defined in Table 1).

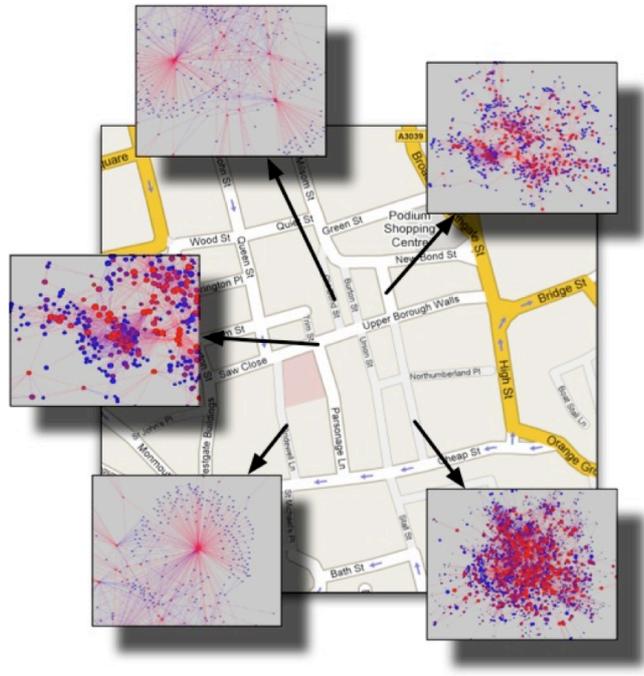
Our optimisation reduced the search time by 75% on average (Mason 2007). The most successful aspect of our optimisation was zone ordering. Our further refinement of axes ordering based on local integration was successful, but to a smaller extent. This was in part due to the fact that the zones themselves were too small for any further ordering to have a considerable effect.

## ***4.2 Space syntax as an explanatory tool***

In recent years, a considerable amount of research has focused on collecting mobility traces using networks of WiFi or Bluetooth scanners (Chaintreau et al. 2006; Crowded 2007). Such traces describe the presence of people at different locations and different times. Earlier work (O'Neill et al. 2006) has reported on a collection methodology, which involves augmenting the SS gatecount and static snapshot methods by employing a network of Bluetooth scanners.

Further work (Kostakos and O'Neill 2007) explains how mobility traces may be translated to sociographs describing users' encounters across a city and over time. Effectively, each user gets represented as a node in a sociograph, and then link together nodes (i.e. users) that have encountered each other at some point in time. Doing so allows us to represent the dataset of each scanning location, as well as of all scanning locations, as a sociograph. This has yielded some interesting results, including the identification of underlying equations describing the degree, betweenness, and closeness of the derived sociographs.

In Figure 7 we see a visualisation of the process: for various scanning locations across the city, a number of sociographs are derived over time. While merging all scanning locations may generate a complete sociograph, for our purposes here we choose to differentiate between each scanning location. Here, we show what each individual scanner can "see".



**Fig. 7** Visualisation of sociographs obtained from various locations in a city.

An observation we have made from the comparison of sociographs from different scanning locations is that they are similar, yet distinct (Kostakos and O’Neill 2007). While visually it is difficult to accurately compare sociographs, we are able to compare them by plotting their various properties (such as degree distribution). In our research we have found that the sociographs are similar enough to make us hypothesise the existence of an underlying principle, yet distinct enough such that each location gives rise to unique sociograph properties.

Our long-term research is focused on identifying the reasons for those small, yet distinctive differences in the sociograph properties. We do so by applying our modified SS procedure described earlier. Currently, our hypothesis is that spatial configuration has an effect on the observed sociographs. Much like researching the relationship between crime and spatial configuration, we are currently researching the relationship between spatial configuration and urban encounters as represented by sociographs. The understanding of this relationship can be a great help in the *a priori* design, as well as deployment of pervasive systems in cities.

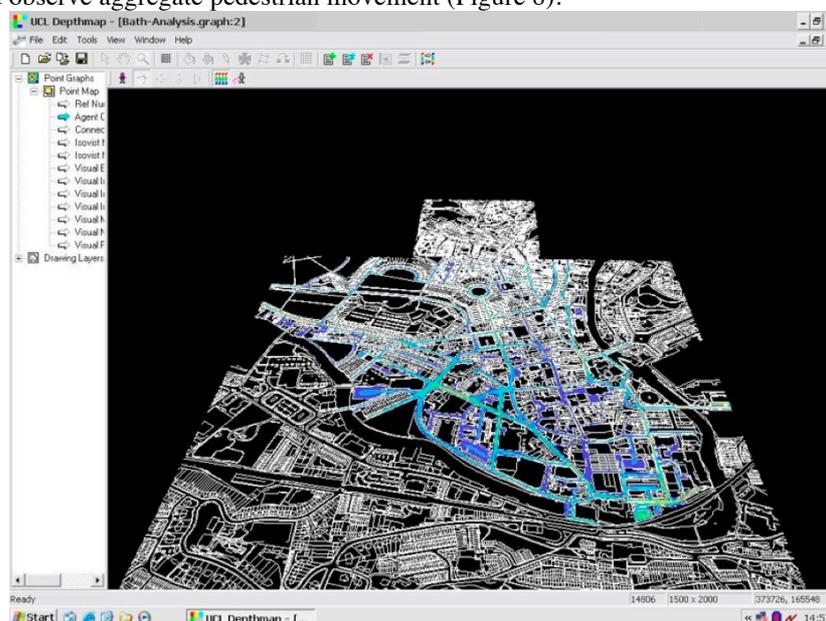
Our results suggest that spatial integration is correlated with sociograph density. However, there are many more relationships to be examined, since spatial layout and sociographs each have numerous properties, resulting in an exponential number of potential correlations to be examined. Hence, a key contribution of our work lies in developing a systematic way of identifying and examining these relationships.

Currently, however, the main obstacle in such a line of research is that many samples are required to derive strong correlations. In our case each sample corresponds to a scanning location: in Figure 7, for example, we show five such samples. In order to derive meaningful statistics, one requires a large number of scanning sites, which will operate over long periods of time. This can be quite expensive in terms of both computational and human resources. A way of overcoming this limitation is by using modelling and simulation, as we describe next.

### 4.3 Space syntax as a modelling tool

As a direct result of observing people's movement in space, the authors in (Turner and Penn 2002) have developed an agent simulation of pedestrian movement. Drawing on Gibson's ecological theory of perception (Gibson 1979), they developed a vision-based mental model of the world, based on the concept of axial lines, which drives agent behaviour. Their approach is distinct in the sense that their system employs an exosomatic visual architecture, thus their agents may be programmed with movement rules originating from Gibson's principle of affordance. By doing so, they make space, rather than agent intelligence, the primary causality of movement.

The resulting aggregate movement patterns of agents closely match those of humans. Based on these results, they have published a free simulation environment, called Depthmap (Turner 2001), which enables users to load city maps and observe aggregate pedestrian movement (Figure 8).



**Fig. 8** A map of the city of Bath with virtual pedestrians. Within this simulation we are able to establish virtual scanners that collect synthetic mobility traces.

In our research we have extended Depthmap in order to generate synthetic mobility traces. As we noted in the previous case study, it is really difficult and expensive to carry out longitudinal Bluetooth or WiFi scans at multiple locations in a city. To address this problem, we have focused our efforts on carrying out Bluetooth scans within Depthmap.

By loading a map of the city of Bath inside Depthmap, we are able to establish virtual scanners in the exact locations where we carried out our real-world Bluetooth scans. At the moment, we are tweaking the Depthmap simulation rules so that the sociograph properties of the virtual scans match those of the real-world scans. Once we derive simulated data that match our empirical data, we will then extend the network of our virtual scanners within Depthmap. This will give us enough data to enable us to look for correlations between sociograph properties and spatial properties, as described in the previous section. Effectively, this approach will enable us to systematically identify the effect of spatial morphology on encounter and ultimately social behaviour. Moreover, these may be used to help us understand how to best integrate our systems in the fabric of everyday life.

## 5 Conclusion and ongoing work

In this paper we describe our novel use of space syntax (SS) in the design and development of pervasive systems. Our two novel contributions are our modification of the SS methodology, and our use of SS in building three distinct systems.

SS has a number of strengths that we find useful in our research. First, it helps us understand how space is, as opposed to how it ought to be. Additionally, the understanding and metrics derived from SS are in a form readily understood by computers. As such, SS can easily be used to design and augment pervasive applications. We demonstrate this in our case studies, where we used SS to simply augment and improve an existing application, as an explanatory tool, and as a modelling tool.

Our ongoing work, hinted throughout the case studies, involves the development of an urban space simulation environment. Such an environment will enable us to quickly test pervasive applications that draw on people's mobility and sociality.

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