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Human Mobility Patterns: A Source of Geospatial Knowledge

Mónica Wachowicz, Antonio Vázquez-Hoehne, Daniela Ballari,
Daniel Orellana-Vintimilla, and Ayar Rodríguez-de-Castro

The study and analysis of human mobility patterns and their relationship with the environment can provide us with a better understanding of certain aspects of human behaviour. New, ubiquitous and non-intrusive devices have made it easier to place sensors in mobile phones, Personal Digital Assistants (PDAs) or even clothing, providing us with relatively low cost means of gathering highly detailed data on the movement of people and the environments in which they move. However, new spatio-temporal models and geovisualization techniques need to be developed to handle the large volumes of data generated by these technologies, and to detect, analyse and visualize mobility patterns so as to understand the interplay between human mobility and the environment, while at the same time maintaining the individuals' right to privacy. The findings from such studies will help to lay the foundations for more sustainable human mobility.

Keywords: Geovisualization, Human Mobility Patterns, Spatio-Temporal Modelling.

1 Introduction

One of the most important challenges facing the science of geographical information is the creation of new models that accurately assimilate space and time. Current Geographic Information System (GIS) models are generally based on the paradigm of the "static map" inherited from traditional cartography and geography, but these models are unsuitable for representing the dynamism that exists in the real world.

From natural disasters and epidemics to geo-marketing and new Location-Based Services (LBS), interest in understanding the links between the environment and people's behaviour has led to a need to broaden concepts, examine trends and generate new knowledge about population mobility. For example, mobility patterns in emergency situations can be very different from normal situations, so experts in risk management are interested in identifying and

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Figure 1: GLONASS Is Being Developed in Russia. <http://www.sistema.com/>.

understanding these patterns to design better evacuation plans and safer infrastructures. In another context, mobility analysis can be used to develop systems that provide information to the user that is relevant to their activities. For example, in a museum, you could receive information on your PDA about the works that interest you: the system will analyse your mobility pattern to see which works you find interesting (those you stop to look at) and which works you do not (those you pass by without stopping). In this way, the system will analyse user preferences and may suggest other works; the curators of the museum can also analyse the patterns of many people and improve the layout of permanent exhibition spaces and the planning of temporary exhibitions.

The popularization of mobile technology and ever-present computers will lead to a wide range of applications based on data captured by sensors embedded in everyday devices. These sensors, apart from recording the location and movement of people, can also capture data from the environment such as temperature, lighting conditions, humidity, noise, etc., thus providing information that may be useful in monitoring environmental effects (e.g. pollution caused by traffic) in a much more detailed fashion compared to what has been possible so far.

In this context, at the Mercator Research Group of the Polytechnic University of Madrid, led by professors Monica Wachowicz and Antonio Vázquez, of the School of Engineers in Topography, Geodesy and Cartography, the development of theories, techniques and automated systems are investigated for the creation of a "mobility information infrastructure" to provide tools for managing, consulting and analysing information on population mobility and to work out the patterns that will, in due course, enable us to understand the behaviour of individuals in the environment.

The aim behind this infrastructure is the development of a multidimensional model of positioning data adapted to OnLine Analytical Processing (OLAP) which allows users to carry out the classical operations of analysis and information retrieval in spatial and temporal dimensions. Examples of these operations include recovering specific data from summarized information (drill-down) or vice versa, when synthesized information is generated from specific data (roll-up). In this way, through statistical operations, information of great interest on population mobility can be obtained. For example, an analysis of mobility patterns can show the different types of interactions between people at the individual level and in groups or between people and their environment.

The main technologies used for capturing mobility data are GPS and mobile multi-sensor systems. The techniques used to analyse the stored data include spatio-temporal *modelling* and *geovisualization*. These techniques provide excellent opportunities for analysing large amounts of data and generating useful and opportune information on population mobility.

2 Technologies to Capture the Movement

Satellite navigation systems such as the Global Navigation Satellite System (GLONASS, see Figure 1), Global Positioning System (GPS, see Figure 2) and Galileo (in development) are playing an increasingly important role. These systems allow us to locate an object or *feature* through a series of tracking devices that move on the Earth's surface. Recently, these systems have begun to be incorporated into mobile technology such as mobile multi-sensor networks (or Mobile Sensor Webs), mobile phones, PDAs and so on.

The best-known devices are personal tracking devices, which gather data on the geographical positions they have been to. By downloading the data from such a device onto a computer, it is possible to generate the trajectory that the device has taken. At present, GPS tracking is also possible in real time via digital cellular networks or via satellite. Examples of these would include devices incorporated into a wristwatch, a small GPS tracking device, a medical control device or a mobile phone.

It is also possible to continually track any vehicle with a GPS receiver and a transmitter module for sending data. A current example is the SPOT Satellite messenger, a device that receives GPS location data and transmits it back to the satellite. The SPOT device incorporates an emergency "911" button which, when pressed, notifies via satellite the GEOS International Emergency Response Centre every five minutes until it is cancelled. In turn, the GEOS alerts the local emergency services, such as the Coast Guard or Police De-

Figure 2: The GPS System is Currently Operated by the United States Department of Defence. <http://www.defenselink.mil/>.

partment, and provides them with the exact location of the device.

However, the mobile multi-sensor networks, such as wireless sensor networks (WSN), have emerged as the ideal technology for capturing the movement of people and their environment. A WSN network consists of a large number of integrated sensor nodes (Figure 3) deployed in a certain area, working together via a wireless network. These sensors are typically small in size and are able to detect various single-event phenomena (temperature, light, sound, humidity, etc.), gather and process data and then transmit that data to the users. Compared to other sensor networks, the advantages are that the nodes are small, very lightweight, use less energy and have the capacity to self-adapt to the intervention of people, the environment and the current status of the nodes. Although there are still limitations in terms of energy and computing resources in the sensor nodes of a mobile network, it is more than possible that this technology will prove to be an important source of information in the coming years and will revolutionize the present methods of data capture and processing [1]. Some of the changes brought about by WSN technology include the high resolution of both spatial and temporal data and the fact that the data is captured not only pervasively and non-intrusively, but also proactively and opportunistically [2]:

- *Capturing high spatial and temporal resolution data:* The vast amount of data that has been gathered in recent years and continues to be gathered cannot be displayed or analysed by manual techniques. Instead, we need to develop new tools to manage, analyse, add, merge, and understand this data in real time (or close to real time) and in a distributed manner. The role of semantics in the management of spatial and temporal data is essential, so that data from various heterogeneous sources can be integrated, analysed and visualized [3].
- *Pervasive and non-intrusive data capture:* The sensor nodes and devices that carry them (mobile phones, clothing, PDAs, etc.) can be transported by people in a non-intrusive way. Thus, the people and their movements become the focus of the capture and display of information from sensors [4].
- *Proactive and opportunistic data capture:* The capture of the information is no longer a passive exercise, but can be carried out proactively, with more precise and intelligent objectives being established. For example, sensors on bicycles can be configured to capture information only when the bicycle is moving. In fire detection systems, the data capture system is activated in the event of a suspected fire. However, when the sensor is carried by a person, the data on the area covered, the events detected and the human interactions involved are collected opportunistically in the sense that the system can have no control over where people go, nor over the area in which they move [4].

The role of georeferencing, as a link between mobile sensors (individuals) and the environment, as well as the idea of a network structure composed of different nodes, means that we need to pay special attention to the spatio-temporal models.

3 Spatio-Temporal Models

Spatio-temporal models are needed to create a framework that makes the information generated by mobile multi-sensor networks available in such a way that the information plays the main role, measuring what we are really interested in. These models ensure *universality*, which depends on the interpretation of the user, and *meaning*, covering simultaneously both multi-sensor mobile networks as well as knowledge about the specific domain of the problem.

For decades, spatio-temporal modelling has been based on using the paradigm of *simplicity*. While recognising its complexity, the real world seemed straightforward enough to produce models that simplified and gathered the essence of things via specific observations that would end up being used to construct conditional scenarios such as "*What would happen if ...?*" in order to help our understanding and to structure debate [5] [6]. In fact, this paradigm has gradually become less convincing as it was recognized that the scientific investigations accumulated through spatio-temporal modelling (designed to get precise answers to social, environmental and economic problems) were ambiguous. Batty and Torrens concluded that "*both macro and micro*

Figure 3: Wireless Multi-Sensor Nodes are Starting to Integrate GPS Technology which Enables Geolocation of the Nodes and their Data.

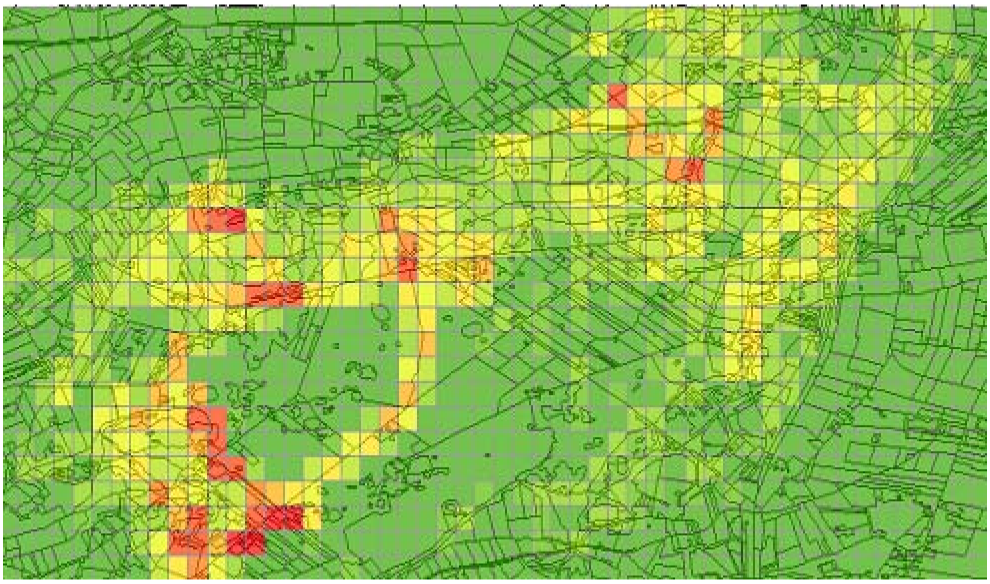

Figure 4: The Red Areas Indicate Sites of Major Attractions in the Dwingelderveld National Park (the Netherlands).

events, from predictions of the stock market and the general performance of the economy to more local issues such as demographic change and traffic movements in cities seem beyond our understanding as well as control, in that extraneous events now seem to dominate their behaviour. Although this may always have been the case, the models that were fashioned a generation or more ago now seem wholly inadequate" [7].

Our research is therefore based on the premise that spatio-temporal models are still *necessary*, since they are required for all sensory observations and are of universal application, but they are also *infinite*, because space and time are not (nor can they be) objects (or features) in themselves, as they have no borders or limits. The differences in the way an environment is observed or measured with mobile multi-sensors will generate a continuous stream of images of that environment on a continuous time line, which will vary among individuals and will depend on a particular purpose. The multidimensionality of space-time is a field of research that is far more complex than first imagined.

Our spatio-temporal model is based on the notion of multidimensionality using three progressive spatio-temporal dimensions corresponding to three levels of spatio-temporal knowledge: the sensory level, the symbolic level and the cognitive level. Firstly, at the **sensory level**, understanding the environment is not separate from what you see (or what the sensors detect) and can be understood by focusing on specific sensory data that becomes the key to modelling something different (e.g. an accident, a storm or uncontrolled urban sprawl). Secondly, at the **symbolic level**, the environment is perceived through the interpretation of symbolic representations that do not necessarily have a direct link to sensory perception, as would be the case with mobile multi-sensors. Thirdly, the **cognitive level**, a purely conceptual level, deals with human spatial cognition and the capacity of knowledge in an explicit spatio-temporal context. In our research, the challenge is to learn how the next generation of spatio-temporal models will be linked to these three levels of spatio-temporal knowledge or how these levels are linked to each other.

For example, at the symbolic level, we are attempting to conceptualize space in terms of its use, distinguishing between *available space* (which exists physically), *possible space* (in which people can move), *tangible space* (the space actually used in the movement) and *potential space* (the projected area between the origin and destination, taking into account the limitations of speed and time). To study the tangible space, we used a hot spot analysis. This technique allows us to classify and categorize every part of a study area in terms of whether they are near or actually part of particular areas with different intensities of use. The intensity of use is measured by the degree of concentration of points representing the position of individuals over a certain period of time. Thus, a place where large numbers of people are recorded is a "*busy site*" and may be interpreted as an "*attractor*" of movement (Figure 4).

Our spatio-temporal model was formalized using the Web Ontology Language (OWL), which arose as a standard from the Semantic Web and is now recommended by the World Wide Web Consortium (W3C) [8]. An interesting feature of OWL is that it is based on a family of languages known as Description Logic (DL), which provides an inference system based on well-founded semantics [9]. The two basic components of DL are the Terminological Box (TBox), consisting of *concepts* and *roles* (properties) and the Assertional Box (ABox), consisting of particular instances. The *concepts* are used to describe the common properties of a class of individuals and the *roles* are binary relations between these concepts. The *assertions* indicate an individual's membership to a particular class. In addition, a number of language constructs such as *intersection*, *union* and *role quantification* can be used to define new concepts and functions. The main reasoning tasks in the model are, first, classification, satisfiability and subsumption (calculation of a concept based on hierarchy), and secondly, the control of the example (verifying that a particular instance is an example of a concept).

OWL currently has three sub-languages (also called "species"); these are, in increasing order of expressiveness: OWL Lite, syntactically the simplest version, which can define simple hierarchies and constraints; OWL DL, which provides the maximum expressiveness corresponding to description logic; and, finally, OWL Full, which provides the maximum expressiveness as well as the syntactic freedom of Resource Description Framework (RDF), but without guaranteeing the computational processing of all the concepts. In our spatio-temporal model, we use OWL DL to formalize the mobility semantics and for automated reasoning tasks.

4 Geovisualization

Geographic visualization (geovisualization) emerged from the foundations of diverse fields such as cartography, geographic information systems, image analysis and spatial data analysis, with strong links to research into the scientific visualization of information and exploratory data analysis in statistics. Geovisualization also plays an important role as an intermediary between the user and the computer, improving interaction between the two and making data exploration easier. Visual approaches to data exploration often employ sophisticated graphic techniques to uncover structures in data. A typical method consists of four main stages: exploration, confirmation, synthesis and presentation. In this case, the aim of representing the data visually is to help recognize archetypes and generate hypotheses rather than simply present a result. Visual representations can help to build knowledge; these representations may be *propositional* (proposing something for consideration), *analogical* (describing something for comparison) or *procedural* (defining an action or set of actions required to do something).

Figure 5: Location of Sites Showing Pauses in Movement During an Urban Game Using Mobile Technology (Amsterdam).

Most of these methods are grouped into three categories that reflect the theories of human categorization, knowledge schemes and cartographic semiology. These are *feature identification*, *feature comparison*, and *feature interpretation*. In this model, the features can be individual ones or they may be archetypes of features. In this case, they may vary in size and particularity, as well as the extent to which they reflect the state of things, i.e. they may be static within a time frame in question, or they may exist because of a certain action or process (e.g. local average minimum levels in a two dimensional grid of sea level pressure values compared to the detection of a cyclone).

Feature identification puts the emphasis on what is observed (at an abstract level) rather than what the data represents. It focuses on examining the data distribution in all its dimensions in an attempt to distinguish different features, patterns, anomalies, points of interest, etc. Geovisualization methods are particularly useful for observing identities and abstract patterns including concentration, sequencing, different glyphs, changes from one space to another, animations through space and time, spatio-temporal cubes and multiple images or "small multiples".

Feature comparison looks at multiple features or archetypes. The goal is "*to enhance the likelihood that an analyst will see not only features, but relationships among features*" [10], with possible links to one or more of the relevant dimensions. Location is the most obvious dimension, therefore the tools to monitor spatial phenomena are particularly important and the comparison might also be based on the outward appearance, the degree of clustering of archetypes, the temporal correspondence or any other attribute. Geovisualization methods that facilitate the comparison of features include point clouds, parallel coordinate plots, small multiples, overlapping layers and varied colour schemes.

Finally, the main goal of **feature interpretation** is to help make connections between abstract representations of data, metadata, the analyst's prior knowledge and other sources of knowledge external to the data set that is being explored (e.g. digital libraries). Through these connections, the behaviour of features and the relationships between them may in turn correspond to the behaviour of such relationships among phenomena in the real world. Geovisualization methods that facilitate the interpretation of spatio-temporal features include all the above mentioned methods in combination with information visualization methods such as knowledge construction with visualizations tools, verbal information, etc. Examples of these include conical trees

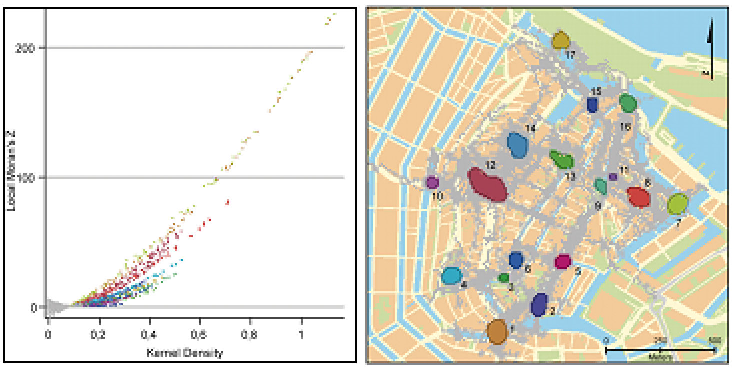

Figure 6: The Application of Spatial Statistics Allows us to Identify "Points of Interest" that Structure the Development of the Movement.

[11], spider diagrams [12] and the spatialization of information [13].

The aim of our research is to develop an iterative process in which the high level (conceptual) questions lead to specific consultations (system); the responses to these will then be examined by users looking for interesting patterns in human mobility, in a way that can lead them to suggest new questions. This kind of exploration involves the challenge of providing the analyst with rapid, incremental and reversible operations that stimulate a continuous visual reaction. It also requires a graphical user interface to reorganize the data on the fly, to juxtapose the features according to various criteria and to display the relationships between the properties of different features, bearing in mind that a feature may be physical (e.g. traffic flow) or abstract (e.g. access to a place), or it may even be an event (e.g. pollution occurring within a certain time and space). To achieve our goal, we looked into a process management system that brings various methods and their associated tools together into a single exploratory environment in order to facilitate a scientific understanding of very large data sets.

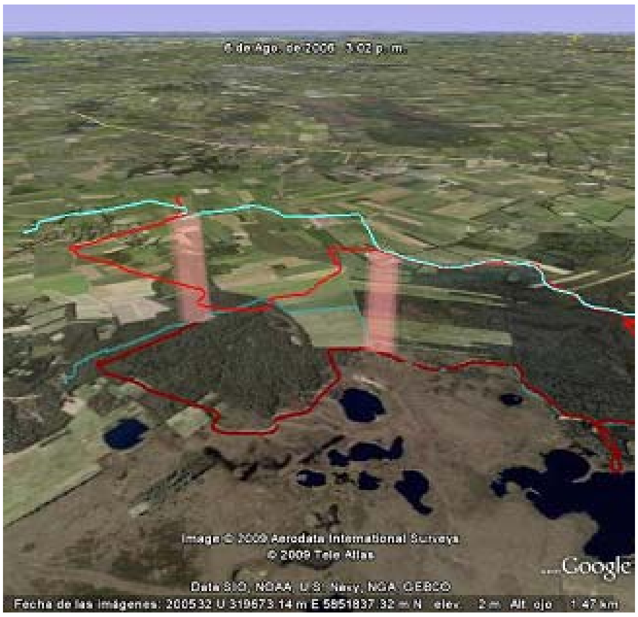

Figure 7: The Spatio-Temporal Representation of Motion Allows Us to Detect Movement Patterns that Demonstrate the Different Types of Interactions Among Individuals.

5 Results

A number of experiments were carried out in which data was gathered on the movement of thousands of people in several locations in Europe. This has enabled us to develop a methodology based on the synergy between different disciplines such as transportation, information technology, urban planning, geomatics and cartography.

Starting with a series of apparently random motion vectors, we took on the challenge of building models, images and animations that could help to understand the flow of movement related to daily activities such as shopping, getting to work or walking in a park.

Pauses in movement (e.g. stopping at traffic lights or because of traffic accidents) is another interesting concept: detecting, deducing and predicting the locations of concentration of such "stops", i.e. places where the movement tends to be suspended, may provide a basis for making decisions for more sustainable urban mobility (see Figures 5, 6 and 7).

6 Privacy Issues

Protecting privacy is a fundamental question, since the data sources usually contain sensitive personal information from which the behaviour patterns and habits of citizens could be inferred. Positioning data contains sensitive information about the mobility of people and therefore must conform to data protection laws. National and European regulations on privacy issues require that any use of personal data must be authorized by the individuals concerned (known also as "data subjects") by means of explicit informed consent. On the other hand, the regulations also stipulate that it is possible to use positioning data without restrictions if such data has become "anonymous". The first case covers positioning data from volunteers, i.e. those who consciously engaged in an experiment. The second relies on developing anonymity-preserving algorithms which guarantee the privacy of individuals.

The results of this research show that it is possible to gather, store and analyse large amounts of data and produce models of human flow paths in cities. Projects like this are leading us to a better understanding of the movement of people, which will allow us to lay the foundations for more sustainable mobility and a healthier environment in the cities of the new century.

7 Key Findings

"*A mobile device linking the real and virtual worlds could change your perception of your surroundings.*" (The Economist, May 2003).

We would highlight three main findings from our research in the last few years:

1. Monitoring will consist of data-gathering models led by events that incorporate observations from multi-sensor mobile networks in real time gathered at the request of users. Most monitoring processes will dispense with the post-processing phase, which is currently very time consuming because raw data (e.g. from orbiting satellites and in-situ observations) is gathered in such volume and diversity that it varies from place to place and from one moment to the next. Therefore, event-led data-gathering models are needed to provide integrated information about the behaviour of human movements and the ability to produce spatio-temporal maps of an environmental phenomenon.

2. Tracking objectives and *monitoring* the behaviour of people, goods and data will create new cultural, social and virtual scenarios that will require the development of a *continuous representation of geographic space* projected onto a spatio-temporal model, including events, activities and processes capable of getting contextual information from any place. However, it is important to note that any representation in a continuous space inevitably raises the question of realism. The GIS paradigm representing an environment using different layers will no longer be applicable.

3. There will be impact on and implications for privacy, in the sense of keeping sensitive data safe from explicit discovery (e.g. publication of a person's identity) or implicit discovery (providing non-sensitive data from which sensitive information may be inferred). There is a common consensus on the need for social acceptance of data gathering of this sort. This should be achieved by gaining public support for the resulting solutions, services and applications in areas such as transport, sustainability, spatial development and environmental awareness.

8 Application Areas

Various types of mobile applications, such as those developed from LBS, have been developed to meet many of society's needs relating to economic development, social experience and culture. For example, LBS can currently provide tourists with devices that show them their location, find addresses and routes, and retrieve information about their immediate environment. They can also read and leave comments on interactive maps [14]. It is also possible to compile a travel diary from the location of a tourist over a certain time period. Some systems are also capable of suggesting interesting places to visit, or can display enriched information in an augmented reality environment. There are also applications of LBS for transport, trade and process management.

The results of this research may be applied in environmental studies to understand the mobility patterns of dynamic entities, ranging from hurricanes and tornadoes to mice [15] and aircraft [16]. Specialized sensors can be designed to provide information about the movement of the entity and the environment in which it is located, including data on levels of light, pollution, proximity, noise, etc., in order to put together a dynamic view of the environment and the interactions between its components.

Other application areas include security monitoring operations using sensors equipped with various devices (e.g. photography, video, GPS trackers, etc.). The MITRE Corporation recently described a project that develops a strategy for the identification and tracking of vehicles by security agents, with the subsequent objective of finding patterns in airline accidents in order to identify what are known as "precursors" of dangerous situations in the air.

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