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Space–use analysis through computer vision

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ABSTRACT

Buildings are complex dynamic systems composed of sub-systems and components in continuous interaction with human behavior. Occupancy and movement data are crucial to deepen the understanding of the built environment performance. Observation data is paramount in space–use studies. However, there is a lack of automatic observation techniques, which enable the continuous and systematic recording of the mobility behavior, the producing of non-arbitrary registries, the gathering of big data and the emergence of patterns. This study is divided into two companion, although autonomous, papers. The first paper [M. Kuipers, A. Tomé, T. Pinheiro, M. Nunes, T. Heitor, Building Space–Use Analysis System — a Multi Location/Multi Sensor Platform, Automation in Construction 47 (2014) 10–23] describe the video-based analysis system and give account of preliminary use patterns obtained by data fusion of video plus RFID inputs; the present paper expand the obtained results and focus on investigating analytical procedures aimed at the study of the functional condition of architectural artifacts, and promotion of a better understanding with the spatial conditions, based on computer vision based tracking. Computer vision allows the simultaneous recording of the user and the spatial container and a full description of the movement behavior. The proposed method for the analysis of the space–use interactions is evaluated in two main atriums of a university department building. It allows to: a) represent, describe and quantify occupancy/co-presence patterns and movement/navigation patterns; and b) establish correlations between the occupancy/movement patterns and the morphological properties of space. Several mobility indexes and its mapping are obtained, such as the number of users, time occupancy, average speed, and users' encounters. The results show how space–use data can be interfaced with spatial analysis tools to arrive at an understanding of the relationship between space–use and building design.

1. Introduction

Built environments can be conceptualized as layered and interconnected systems that integrate spatial, physical, technical and social components tightly coupled. The conceptualization of buildings as nonlinear and dynamic systems, composed of interacting elements, embedded into feed-forward and feedback loops of interactions, enshrines, definitely, the notion of the occupant not only as an integral component of the built systems [1] but also as its node. In fact, complexity arises from the individual actions and choices of the occupants, at each moment, which are variable and difficult to predict. Occupants are not passive components of the built environment but its mind force [2] according to whom the other systems react. Furthermore, along the buildings life cycle, the occupants' needs may vary broadly, which contribute to increase the need to understand the factors that influence and regulate the dynamics of uses.

Accordingly, enquire the occupant behavior, arises as a crucial effort to improve the built systems performance, contributing to respond intelligently to the changing needs of the end-users [3], and simultaneously ensure their welfare and the sustainability of the built environment. Such target is particularly relevant contemporarily, with built environments evolving towards to more complex systems considering information flows, non-deterministic occupant behavior, and the integration of diverse problem-solving procedures — approaches that seek the adjustment of the performance of the built environments to the users' needs through the learning about their behaviors [4–6].

1.1. Movement and space topology: a vertex to decode the functional performance of the built environment

The first choices made in the preliminary stages of the architectural design process are about spatial organization, i.e. how the individual spaces and corresponding uses as a response to function, are distributed in a plan – physical form – and how they are linked both internally and

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externally to the surrounding environment. According to this view, the spatial form, or organization maybe considered the primeval system that support the other systems (technical systems included) once they are defined in later design stages and, dependently, of the spatial organization.

As consequence of the preliminary design options, the spatial form coins the way occupants will interact with each other and with the building itself. In other words, spatial form conditions the spreading of uses and location of the activities through the spatial system. Space–use analysis studies, carried on under space syntax perspective, considers that spatial systems are shaped by a kind of social logic which is responsible by its organization [7]. It is worthwhile to note the convergence between the syntactic model, which considers that the spatial form tends to be organized similarly to how the social group that inhabits it is organized, and the conceptualization of Lu et al. [1,4] stressing the embedding of the occupants as an intrinsic feature to the building system and proposing an application of the chaos theory to the building design.

Hillier and Tzortzi [8] argue that space is not a mere support or container of the human activities, but an intrinsic factor of these and of their patterns of behavior. The authors consider that human activities have a kind of "natural geometry" (e.g. people move according straight lines; interaction assumes, essentially, convex shapes), and because of that people tend to organize space according to ways that reflect this. In turn, space configuration, i.e. the sequences and choices offer by the spatial form, in a more or less intelligible way, determines the way of human activities processes and the way people move. Movement, therefore, is a basic condition of human existence, and the understanding of the effects of different layouts on how people move should be a basis to describe the spatial layouts in terms of its potential of functionalities and uses. According Hillier and Penn [9] "buildings are fundamentally about movement, and how it is generated and controlled."

Wayfinding research also stresses the importance of space configuration in the way people explore and learn about an environment. Configuration becomes particularly significant in the case of non-familiar users with the spatial context. Research based evidence suggests that floor plan layout has the greatest influence on way-finding performance [10–12]. According to O'Neill [13], an objective component of floor plan layout is concerned with the topological connections (paths) between choice points, i.e. locations where two or more paths diverge and people can make decisions about the route to choose. Such network of connecting paths and choice points constitute an important environment feature once topological information is available, which is the first information to be acquired during exploration tasks.

Kaplan and Kaplan [14] also stressed that topological information is a natural by-product of the learning process about the environment as one goes through the different places, and Passini and Arthur et al. [15,16] emphasize that people can reach their destination without a previous comprehensive knowledge of the environment, since the perceived spatial organization serves as a framework for constructing a cognitive map and for integrating information that will be obtained once inside.

Space syntax methods have also been adopted to investigate navigation decisions and their relationships with plan morphology. Haq and Zimring [17] suggest that people's understanding of the environment evolves from topological (local knowledge) to spatial knowledge (global knowledge), as users became more familiar with the environment. Peponis et al. [12] proposed the concept of a "search structure", which links the idea of path in an environment [18–20] and the understanding of the global configuration of a building. Paths are the key concept in way-finding performance i.e. the process of determining and following a path, between an origin and a destination. According to the authors, the "search structure", resulting from the interaction between the properties of spatial layout and the users' navigation behaviors, produces specific patterns of exploration.

The extensive literature review listed in [21], can be expanded with other significant studies that have recently contributed to deepen correlations between spatial configuration and observed movement of users, e.g., [22–26]. In those studies, the main aspect of interest about user behavior is movement. Movement expresses the traces of users' actions in space. It reveals users preferences or rejections, their social interactions, their appropriation modes of space, and ways of the processing of activities along the spatial systems. In fact the study of movement is a nodal point in the space–use research.

1.2. Observation: the vexata quaestio of space–use research

Space–use research aims at analyzing of concrete and contingent nature of the relation between built space and its use. However, by virtue of their contingent nature, such facts can only be established through observation. Through studying these facts, the conditional factors that shape them can be revealed, and the question of whether these conditional factors are governed by rules can be established. Space–use observation makes it possible to translate the buildings systems interactions into patterns of structure and behavior. This is a first step to understand the interdependencies between the space shape and the spread of users' navigation behavior through spatial systems. For such reasons, direct observation is paramount in space–use studies.

However, in spite of the understanding of movement be a crucial topic, two problems arise: 1) movement has been understood only partially and not globally, making it unsuitable to achieve a comprehensive knowledge about the functional performance of the built environment; 2) the current observation methods are not adequate to a broad and deep study of the spatial movements. It must be stressed that an extensive understanding of the users' navigation behaviors is dependent of the development of suitable observation methods based on automatic procedures.

Lahr [27] argues that observation must be exact and comprehensive, that 'it should perceive everything that exists, and nothing more than what exists, never confusing the objective verification of facts with our more or less subjective interpretation of them'. There should also be a stipulation for observation to be permanent and continuous in order for all phases of observed actions to be studied, as well as the sequence in which they occur. Such requirements are not reachable by means of human observers methods, still predominantly used [28], in spite of the wide range of technological means available (an extensive literature review is listed in the previous paper about this topic [21]), as well as the widespread and embedding of pervasive systems in the daily life. These circumstances open many opportunities to acquire large amounts of data about users' spatial behaviors [29].

Despite the recent technological developments the detailed observation of the pedestrian behavior is still a very complex issue [28]. Detailed observation is crucial to the space–use analysis research because it allows visualizing the complete sequence, or spatial narrative, about the user traces and not only frames of that movement. Usually, researchers are not concerned with the understanding of such detailed sequences but only with certain moments of it. In the previous paper [21] several works are referenced, which illustrates these approaches. For what concerns the deepening of the study of relations between built space and its uses, the acquisition of such fragments of behavior is rather limited.

For that purpose, one needs not only to visualize complete sequences of movement but, also, to visualize them into the spatial context where they occur. Much less attention is given to investigations of observation systems of environments in use especially featured to such space–use analysis aims. In the scope of space–use analysis, and syntactic research in particular, movement has been understood in a rather fragmentary mode – normally, as rates of people counting in certain points of spatial context (i.e. imaginary gates) [30] – i.e. always in a subsidiary way of the syntactic model, and never as a research