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Measurement of congestion and intrinsic risk in pedestrian crowds

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ABSTRACT

In this study, we present a method to quantify the amount of congestion and the intrinsic risk in pedestrian crowds. Levels of congestion are estimated based on the velocity vector field obtained from the analysis of video recordings of moving crowds. By using data collected during supervised experiments, we show that the so-called "congestion level" allows to define a threshold for congestion under safe conditions and to measure the smoothness of pedestrian flows. The proposed approach has been compared with alternative quantities such as density, flow or the "crowd pressure" showing a more universal and consistent description of crowd motion. Later, the "crowd danger" of different pedestrian streams has been computed confirming that multi-directional motion is more dangerous than unidirectional one for equal levels of density. From a more practical perspective, the congestion level allowed to get a complete picture of the region in front of bottlenecks and to identify the formation of organized structures also under constant density and flow conditions. In addition, since only velocities are used in the computational process of the congestion level, it is more suitable for applications involving computer vision and emerging technologies, since density is usually difficult to obtain in very crowded situations. The congestion level and the crowd danger may help in the design of pedestrian facilities by simplifying interpretation of results from simulation and efficiently identify hotspots or design flaws. Finally, crowd control may benefit from the methods presented by potentially allowing a clear identification of dangerous locations during mass events.

1. Introduction

The technological improvements of the last centuries have led to a trend toward urbanization which has rapidly spread on a global scale. The "2014 World Urbanization Prospects" by the United Nations (Desa et al., 2014) noted that globally a larger population already lives in urban areas compared to rural areas. The proportion of urban population was as little as 30% in 1950, but it is projected to reach 66% by 2050. At the same time, the population influx from rural areas is making modern cities more crowded and the tendency seems not to change in the near future.

Quality of life in urban centers is strongly influenced by the way those crowds are managed and controlled. On the macroscopic scale, policy making and urban planning are the most effective instruments. Their goal is to create a pleasant environment avoiding to concentrate large amount of population in a restricted area and allowing a homogeneous distribution of transportation infrastructures over space and time. In this regard, architecture and design also have an influence by acting on the perception of the surrounding

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environment. However, even by carefully planning urban spaces to homogeneously spread the population over a large area, there are often physical limitations constraining the growth of cities and their centers will always attract a larger population compared to external neighborhoods. This translates into the requirement to manage flows of people on the microscopic scale (i.e. inside buildings or in restricted areas). Transportation hubs and places designed to host large events will always need to deal with huge crowds and their management and control on the microscopic scale is important for safety and comfort reasons.

While crowd accidents are not very frequent, their seriousness can be devastating. Some examples are the Love Parade accident in Germany in 2010 (21 people killed and more than 500 injured) (Helbing and Mukerji, 2012), the Khmer water festival in Cambodia the same year (347 death and 755 injured) (Hsu and Burkle, 2012) and more recently the stampede which generated during the 2015 annual Hajj pilgrimage in Saudi Arabia (figures on fatalities vary depending on the source, but it is believed that about thousand people died (BBC, 2015)). The relative rarity of crowd accidents creates several issues related to their research and consequent prevention. Since occurrence is still mostly unpredictable, data regarding those accidents are very scarce and fragmented. In addition, since accidents occurred in different parts of the world and in very different contexts, it is quite difficult to gain relevant information from witnesses who were present during those events. This makes in turn difficult to train personnel overlooking the crowd, since experienced people who witnessed previous accidents may never have the opportunity to use their knowledge for future occasions. Finally, an additional issue making difficult the prevention of crowd accidents is that, in general, there is no single cause and their occurrence is a correlation of several factors which are hard to identify beforehand.

A solution which is being used to allow a better management of facilities involving large crowds is to use simulation models and identify potentially dangerous locations. Several simulation models have been developed to reproduce pedestrian crowds (a review is given in Zheng et al. (2009) and Wa¸s et al. (2015)) and although it is still difficult to predict motion on the strategic and tactical level (Schadschneider et al., 2009), a certain degree of maturity has been reached for the microscopic (or operational) level. To allow a more efficient control of crowds, it is now possible to combine on-site real time measurements with simulation models to predict changes in the near future (Mitsubishi, 2016; Matyus et al., 2016). Although applications in this regard are still limited, a growing interest has been shown toward this particular solution.

But still, there is a fundamental problem which is not solved even by the use of computer simulations: evaluation/interpretation of crowd motion and composition. As it will be discussed in detail later, density has been typically used to judge criticality of pedestrian crowds. Most of the classifications used for human crowds are based on density (and/or flow) and they usually depend on the principles of the fundamental diagram. However, evaluation based on density presents two important shortcomings: (i) it is not universal (this aspect will be discussed also later) and (ii) it is inaccurate in relation with information gained from sensing technology.

Classical crowd sensing methods (based on computer vision and distance sensors) are rapidly improving, with their accuracy constantly increasing and hardware requirements being reduced by more efficient algorithms (Alahi et al., 2014). But there are still several limitations, especially when it comes to the estimation of density (Johansson et al., 2008; Daamen et al., 2016; Kok et al., 2016). At low densities, there are different alternatives to methods based on cameras, such as WiFi and Bluetooth scanners (Abedi et al., 2015), GPS (Sekimoto et al., 2016) and inertial sensors (Kazuya et al., 2013) which allow to get an overall image of what is occurring on a large scale. However, when dangerous dense crowds are to be analyzed, then computer vision is probably the only option which can provide relevant information. Density estimation is particularly difficult for dense crowds, but on the other side the particular conditions make it is easier to estimate velocities (Junior et al., 2010). When crowds move like a continuum, optical flow can be applied with good accuracy allowing to obtain a velocity vector field of the moving crowd (Zhang et al., 2012b).

For the reasons above, it is important to develop a universal measure able to evaluate congestion and/or intrinsic risk of pedestrian crowds mostly based on the analysis of their motion by means of velocity. Such a measure would allow to use more efficiently information gained from cameras and would also help evaluating results from computer simulation. To conclude, the development of a measure estimating the amount of congestion and the intrinsic risk (or potential danger) in pedestrian crowds is vital from both a management and a control perspective and would help designing better pedestrian spaces and preventing accidents in the future.

This paper aims to define such quantities, which we will call “congestion level” and “crowd danger”. Details on the calculation algorithm and calibration/validation through controlled experiments are presented and discussed in this manuscript. In particular, we will show how the method proposed here allows to detect the formation of organized structures in a condition where the analysis based on the fundamental diagram would fail.

2. Definition of congestion level and crowd danger

2.1. Previous attempts to estimate congestion and intrinsic risk of pedestrian crowds

Although density has been traditionally used to estimate the level of congestion in human crowds, it is known that it is not the only relevant property making a particular crowd more congested (or dangerous) than another one (Helbing and Mukerji, 2012; Dambalmath et al., 2016). A crowd density above 5–6 persons m^{-2} (from now on simply shortened as m^{-2}) is generally considered as the threshold above which caution is required and prompt actions are necessary to avoid accidents (Helbing and Mukerji, 2012; Tertoolen et al., 2012,). Typical simulation models are also intended to deal with crowds up to a maximum of about 6 m^{-2} (according to the definition provided by Weidmann (1993) for the typical size of human body). Densities measured during crowd accidents are usually in the range of 10 m^{-2} (Nicholson and Roebuck, 1995; Lee and Hughes, 2005; Zhen et al., 2008), with some authors reporting