Modeling metastable dynamics of dyads from large-scale data

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Abstract Understanding of social groups behavior is crucial in pedestrian dynamics. In this study, we analyze and model the movement of dyads using millions of real-world trajectory at a train platform in Eindhoven The Netherlands. We identify key external parameters influencing dyad configurations and develop a data-driven differential modeling approach based on these parameters. The proposed model is validated by comparing simulated and empirical data on key statistical properties.

Keywords Pedestrian dynamics, groups, metastable dyads, real-life data, stochastic modeling

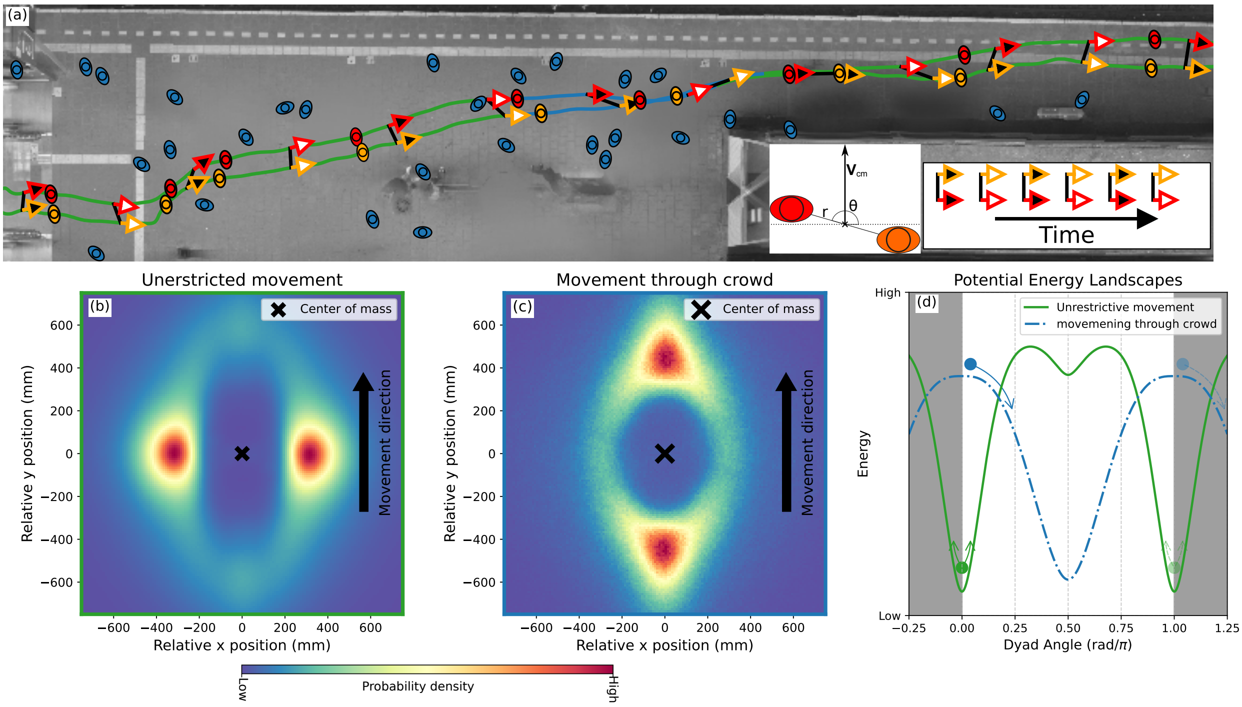

Figure 1: **(a)** Example of a dyad trajectory walking on the platform of Eindhoven Central Station. Arrows identify points in the trajectory happening simultaneously. In the initial and final part of the trajectories (green segments) the dyad traverses relatively empty areas, while in the middle part (blue segment) the dyad navigates through a denser crowd. The dyad formation along these segments conforms with the probability density functions respectively depicted in heatmaps **(b)** and **(c)**. In which the preferred walking direction is perpendicular and parallel to the walking direction respectively. **(d)** illustrates changes in the energy landscape as the dyad traverses the platform, driving a transition from a perpendicular to a parallel configuration.

In built environments, pedestrians often navigate as part of social groups. Understanding their behavior is essential for developing accurate predictive crowd simulations and represents a fundamental challenge in this field. Social group dynamics have been extensively studied in controlled laboratory settings or with small-scale annotated real-world data [1, 2, 5]. While dyads (social groups of two) prefer to walk side by side (perpendicular to the walking direction) [2], this behavior is mostly observed in low-density conditions, often relying on hand annotated data. A model incorporating basic assumptions about dyad social dynamics can effectively predict this configuration [4]. Recent advances in automated

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vision allow for large-scale collection of pedestrian trajectories in real-world settings. This enables high resolution statistical analysis into the preferred configuration of dyads, outside of low-density conditions.

In this study, we identify and parameterize how external parameters influence preferred dyad configuration as they navigate through a wide variety of crowds scenarios in a real-world setting (a train platform at Eindhoven Central Station) An example trajectory is shown in Fig. 1a. We automatically identify more than three million dyads dyads by building on top of the graph-based method by Pouw at al. [3] in a wide variety of crowd scenarios.

We show that the preferred dyad configuration is driven by two key external parameters: the density of the surouding crowd (ρ) and the relative velocity ($\mathbf{v_r}$) between the dyad and this crowd. As reported in Fig. 1b, in low-density situations, the preferred configuration is perpendicular to the movement direction, while when navigating through stationary dense crowds (Fig. 1c), the preferred configuration is parallel, indicating that the system exhibits meta-stable behavior.

In the reference frame of the dyad center (parallel to the dyad velocity), any dyad configuration can be described by an angle, θ, and a distance, r, between the dyad pair (cf. Fig. 1a). We model the switching behavior between these two preferred configuration and the parallel configuration with a Langevin-like equation,

$$\ddot{\theta} = -\frac{\partial U\left(\theta, r, \rho, \mathbf{v_r}\right)}{\partial \theta} - \gamma\dot{\theta} + \eta(t), \tag{1}$$

where $U\left(\theta, \rho, \mathbf{v_r}\right)$ is a potential function, γ is a damping coefficient and $\eta(t)$ represents stochastic noise. To utilize this model we make the key assumptions that there is a Gibbs-like relation between probability $P(\theta, \rho, \mathbf{v_r})$ of the dyad being in configuration (θ, r) and the potential, which results in

$$U\left(\theta, \rho, \mathbf{v_r}\right) \propto -\log\left(P(\theta, \rho, \mathbf{v_r})\right). \tag{2}$$

We validate our modeling approach by comparing empirical observations of dyad pairs with simulated trajectories considering a wide range of observables including conditioned probability distributions on θ as function of time and autocorrelation functions (cf. Fig. 2).

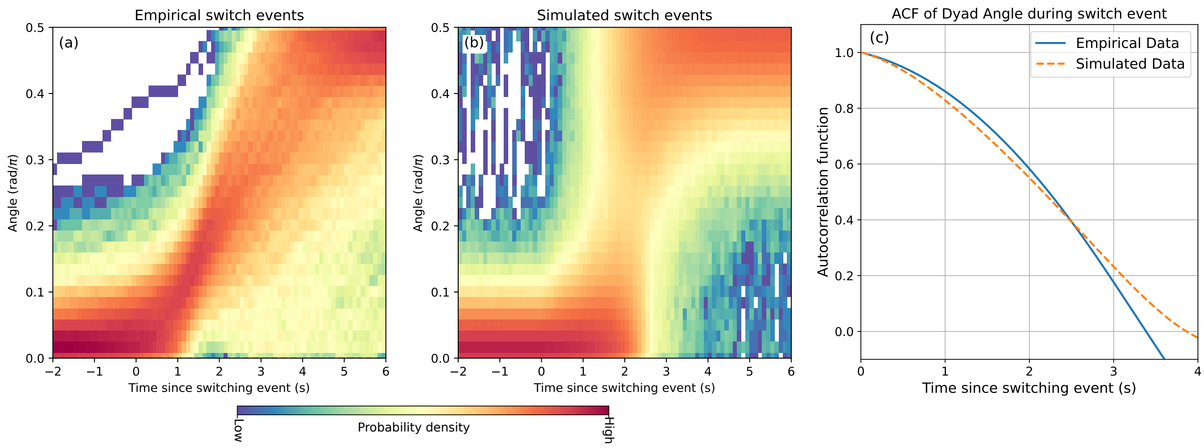

Figure 2: Transition dynamics of dyad pairs from a horizontal to a vertical configuration. **(a)** Probability distribution of switch events derived from empirical data. **(b)** Corresponding probability distribution obtained from simulated trajectories. **(c)** Autocorrelation function (ACF) for both the empirical and simulated trajectories for $\theta(t)$.

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