Evolving laws of human cooperative behaviour*

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In this study, we improve Lévy walk model, and make it suitable for simulating the collective behaviours of humans. Here we show how rescuers find missing persons by collective cooperative search in a natural background. In the search process, the search strategy represents an optimal algorithm which is used to maximize the success rates for finding missing persons. We simulate the rescuer's movement pattern, and find some basic laws governing the rescuer's cooperative search. For example, the probability that each rescuer finds missing persons shows a power law distribution.

Keywords: cooperation, random walk, natural disaster

PACC: 0175

1. Introduction

In the world, great natural disasters often occur, from earthquakes and [1] floods[2] to hurricanes[3] etc. Along with the great disaster, a large-scale cooperative search for missing persons is inevitable. Despite many centuries having passed, our understanding of how to regulate the collective cooperative search behaviour is still inadequate.

Natural disasters are a violent killer for humans.[4−6] In order to reduce the disaster casualties, governments, communities or civilian groups usually organize an army or volunteers to search for missing persons in the disaster area. Since the natural environment has been destroyed by disaster, rescuers do not know what the new environment is. Moreover, missing persons distribute randomly on the disaster area, whose exact locations are not known as a priority. Under such a condition, the success of the search for rescuers usually relies on the large-scale cooperation. In the cooperative search process, rescuers need to find missing persons with a shorter search time. In other words, rescuers need to use an optimal search strategy to maximize the success rates.

Lévy walk is a type of random walk which involves a two-species reaction–diffusion process.[7−10] This special walk has a scale-invariant property, whose trajectory is a fractal pattern.[11,12] As a simple model of the diffusion processes, it is interesting since it could be a mechanism of transport and search.[13−15] Here we improve the Lévy walk model, and use it to simulate the collective cooperative movements of walkers. Our aim is to investigate some basic laws for the cooperative behaviours of walkers. Since human collective cooperative behaviour is similar to that observed in other nature fields,[16,17] our results may help to explain various phenomena in these fields. The paper is organized as follows. In Section 2, we outline the improved Lévy walk model. The numerical computation results are presented in Section 3. Finally, conclusions of this approach are presented.

2. The improved Lévy walk model

A Lévy walk is defined as that at each time step i the walker moves a length l_i chosen from a probability distribution $P(l_i)$ with a power-law tail: $P(l_i) \sim l_i^{-\mu}$ with $1 < \mu \leq 3$, where μ is the power-law exponent. Recent studies show that Lévy-like behaviour approximately describes human trajectories.[18−20] The distance distribution of human movement seems to be consistent with the results of Lévy statistics.

In the proposed method, we use the Lévy random number generator to return an integer value between 1 and a specified maximum value. Using such a generator, an integer array is generated, where each element takes a value between 1 and the specified maximum value. The proportion of each taken value is equal to the probability of that value arising from the power function $P(l_i)$.

Based on the Lévy walk, we propose an improved walk model which is suitable for describing collective movements of walkers. Within such a crowd, walkers

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cooperate by exchanging information with each other. According to the exchanged information, each walker selects a position as his/her next position. The next position has a larger distance from the positions that other walkers locate currently. At each time step, each walker moves from his/her current position to his/her next position. The movement distance is randomly selected from the integer array that generated by the Lévy random number generator.

The simulated system constitutes $N_{\rm r}$ rescuers and $N_{\rm t}$ missing persons. $N_{\rm r}$ rescuers depart from a randomly selected position. They search in different directions. If the positions of rescuers exceed the preset dimensions, they return from top/bottom or left/right to departure area. In the search process, rescuers receive information regarding the positions of other rescuers. Rescuers can see missing persons within a perceptual region of radius $R_{\rm s}$.

3. Numerical computations

We use the above improved Lévy walk model to simulate the movement trajectories of rescuers. The missing persons are randomly distributed in a 2D assumed landscape. The power-law exponent μ for Lévy walk takes an optimal value of $\mu = 2$. The specified maximum value of random generator is 15. Rescuers constituting a crowd depart from the centre of the landscape. $N_{\rm f}$ is the number of the missing persons who are found. In simulations, $R_{\rm s}$ is set to be $R_{\rm s} = 4$.

Figure 1 shows the search efficiency of rescuers by cooperation for $N_{\rm t} = 20$. Figure 1(a) shows the $N_{\rm f}$ as a function of the search time T. Here ten rescuers search in an assumed landscape of size 200×200. In Fig. 1(a), it is obvious that most of the missing persons are found within early search time. At the time $T = 3841$, all missing persons are found. Further, we measure the success rate $R_{\rm c}$ which is the average number of missing persons who are found per distance movement by all rescuers. The measurement results are shown in Fig. 1(b). In Fig. 1(b), $R_{\rm c}$ has larger values around $T = 600$. The success rate $R_{\rm c}$ is strongly related to the distribution of missing persons. In our simulations, the distribution probabilities at different sites are uniform.

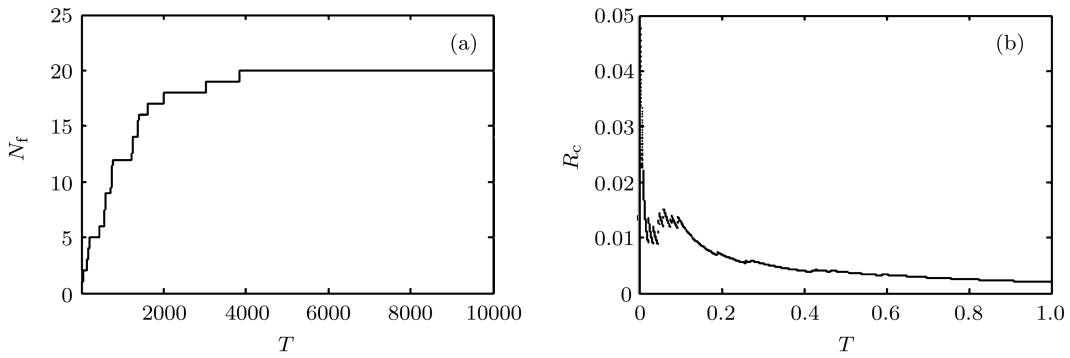


Fig. 1. (a) The total number of the missing persons who are found at different time. (b) The success rate of rescuers varies with the search time T.

In the process of disaster relief, if the time that missing persons are found in is too long, the survival probability of the missing persons is small. Rescuers need to find more missing persons within a finite search time. The number of rescuers has an important impact on search efficiency. We introduce a parameter ζ which is defined as $\zeta = N_{\rm f}/N_{\rm r}$. ζ represents the probability that each rescuer successfully finds missing persons. The distribution properties of ζ is plotted in Fig. 2 for $N_{\rm t} = 20$ and $T = 1000$. Figure 2(a) shows how ζ varies with $N_{\rm r}$. Here the values of ζ are obtained by averaging a number of measurements. From Fig. 2(a), we can infer that the data shows a power law distribution $\zeta \propto N_{\rm r}^{-\gamma}$. We plot $\ln\zeta$ against $\ln N_{\rm r}$ in Fig. 2(b), and then obtain the exponent $\gamma \approx -0.85$. The results suggest that as the number of rescuers is small, rescuers find missing persons with higher probability. However, it is possible that as ζ is large, $N_{\rm f}$ is small.

If we change the values of the parameter $N_{\rm t}$ and T, the function relationship between $\ln\zeta$ and $\ln N_{\rm r}$ possibly become nonlinear, such as $N_{\rm t}$ is larger and T is

smaller. The measurement results are shown in Fig. 3. Here N_t and T are set to be $N_t = 40$ and $T = 400$ respectively. From Fig. 3, we clearly see that the data can be divided into two parts. As N_r is smaller, the exponent γ is larger than –1 ($\gamma = -0.47$), and as N_r is larger, the exponent γ is equal to -1. In addition, when the search time T is large enough, all missing persons will be found. In this case, the exponent γ is $\gamma = -1$.

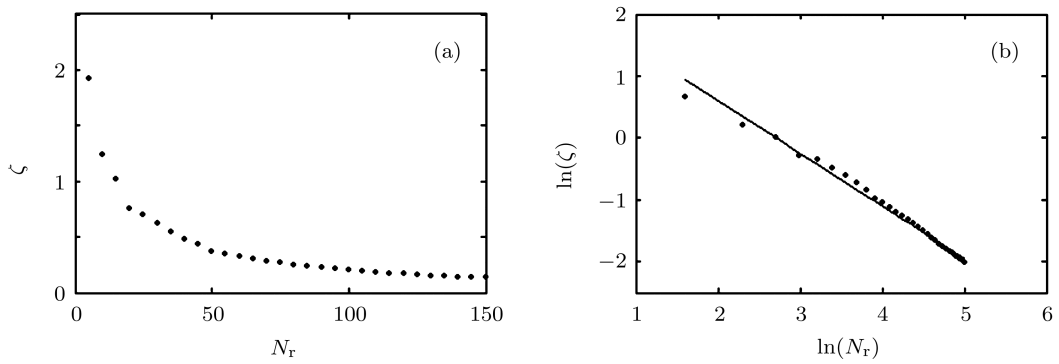


Fig. 2. (a) The probability property of success search. (b) A plot of lnζ vs. lnN_r.

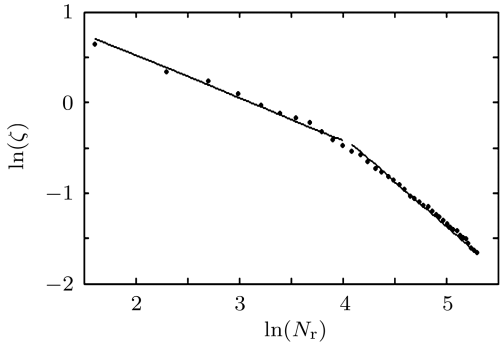


Fig. 3. A plot of lnζ vs. lnN_r.

The search efficiency of rescuers depends on the number of missing persons. The distribution properties of θ is plotted in Fig. 4 for $N_r = 10$. Figure 4(a) shows how θ varies with N_t for $T = 1000$. Here θ is defined as N_f/N_t, which represents the probability of each missing person found. A number of measurements are made. The values of θ are obtained by averaging these measurements. In Fig. 4(a), it is obvious that the probability θ fluctuates around the average value $\bar{\theta}$. As N_t increases from 1 to 100, the fluctuation of θ tends to become small. In above simulations, only part of the missing persons is found. In this case, other missing persons are directly confronted with the threat of death. Increasing the search time T from 1000 to 8100, we record the average probability $\bar{\theta}$. The results are presented in Fig. 4(b). The data shown in Fig. 4(b) can be fitted by the mathematical function $\tanh(cT)$. Here c is approximately set to be 0.00058. The probability that each missing person is found is mainly affected by search time, especially in early search time.

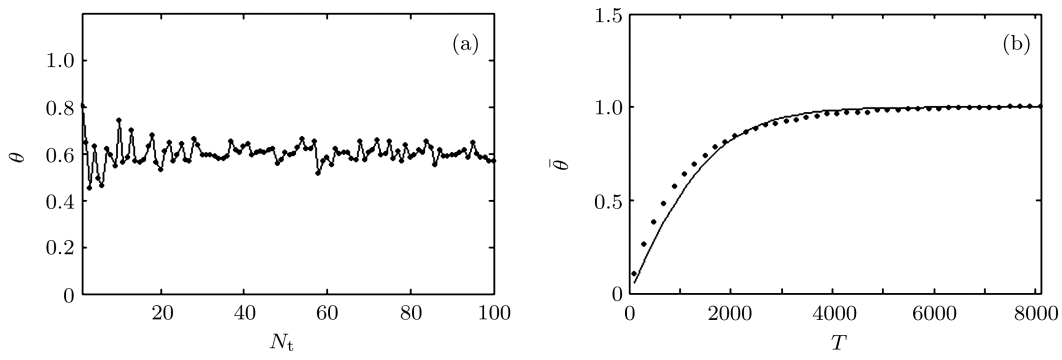


Fig. 4. (a) The relationship between the probability θ and the number N_t. (b) A plot of $\bar{\theta}$ vs. T.

Because of natural obstacles, some rescuers can not participate into collective cooperation. They search randomly. These rescuers are so-called defectors. Figure 5 shows the search efficiency of rescuers for $T = 2000$. In Fig. 5(a), solid line is the number of missing persons found by cooperators, and dash line is the result found by defectors. Here only half of rescuers participate into cooperation. The data shown in Fig. 5(a) indicate that the contribution of defectors is far less than that of cooperators. In Fig. 5(b), for a given vale of η, we make a number of tests, and then average the results of $N_{\rm f}$. Here η is the fraction of cooperators in the rescuers. In Fig. 5(b), as η increases, $N_{\rm f}$ increases. The results suggest that collective cooperation enhances search efficiency in the sense that rescuers have to carry out a high collective cooperative action.

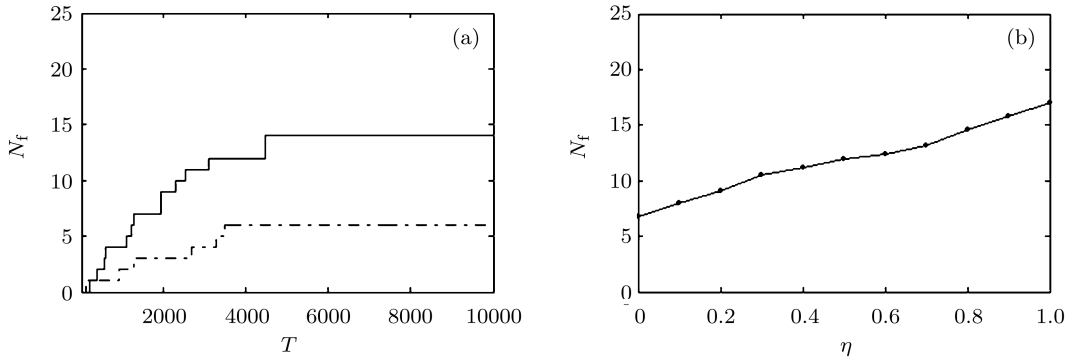


Fig. 5. (a) How $N_{\rm f}$ varies with search time T for $\eta = 0.5$. (b) A plot of $N_{\rm f}$ vs. η.

4. Conclusions

In conclusion, an improved Lévy walk model is proposed to simulate the collective movements of human. Here the cooperative behaviour is considered in search process. The simulation results indicate that the efficiency of large-scale search can be enhanced outstandingly by cooperation.

In our work, we consider a simple simulation situation. Actually, cooperative movements of human subject to some specified constraints (or regulating strategies), such as the natural and communication conditions. This leads that the simulations are simplified. In our future works, we will analyse and discuss these constraints in detail.

The general problem of cooperative search represents a scientifically important issue in human society and biology system. Our findings could prove useful in the foraging processes by diverse animal species, the oil recovery from mature reservoirs and the automated computer searches of registers in high-capacity databases.

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