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SIMULATION OF VIRAL INFECTION PROPAGATION THROUGH AIR TRAVEL

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EXECUTIVE SUMMARY

There is direct evidence for the spread of common infectious diseases during commercial air travel, including influenza, SARS (Severe Acute Respiratory Syndrome), tuberculosis, and measles. This has motivated calls for restrictions on air travel, for example during the 2014 Ebola outbreak. However, such restrictions carry considerable economic and human costs. Ideally, decision-makers ought to take steps to mitigate the likelihood of an epidemic without imposing the above costs. Thus, science-based policy analysis can yield useful insight to decision-makers.

The effectiveness of a policy depends on the human response to it. Given inherent uncertainties in human behavior, we simulate a variety of scenarios and identify the vulnerability of policies under these potential scenarios. Supercomputing is used to deal with the large number of scenarios and the need for a short response time in cases of national emergencies. Our results identify new boarding procedures that can result in a substantial reduction in the risk of the spread of Ebola and SARS.

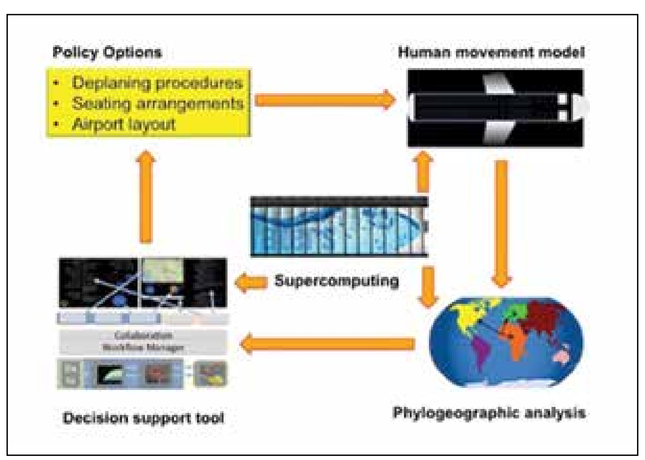

Figure 1: Schematic of the SPED fine-scale model combining pedestrian movement and infection dynamics.

RESEARCH CHALLENGE

Our goal is to develop models and a novel methodology that can provide insight to decision-makers on policies and procedures that will reduce the likelihood of infection spread during air travel. In addition, our research contributions promise major advances in the disciplinary areas of our expertise—pedestrian movement modeling, mathematics, epidemic modeling, computer science, and bioinformatics—with a consequent transformative effect on transportation infrastructure and management.

METHODS & CODES

We model the movement of pedestrians during air travel as particles based on a force-field approach proposed by [1]. Both the pedestrian density and speed of the immediate neighbor in a pedestrian line determine pedestrian speed and trajectory [2,3]. Our modifications incorporate these aspects into the pedestrian movement model. The pedestrian trajectory information is then integrated with a discrete-time stochastic Susceptible-Infected model for infection transmission that accounts for demographic stochasticity and variations in the susceptibility of the population. This approach (Fig. 1) provides insight into the consequences of policy choices that change passenger behavior at individual levels. We input this information to a global phylogeography model to assess the impact of these policies at a global scale.

Inherent uncertainties in human behavior and insufficient data during the initial stages of an epidemic make prediction difficult. Our approach is to parameterize the sources of uncertainty and evaluate vulnerability under different possible scenarios. We use the Blue Waters supercomputer to efficiently deal with the computational load that arises from a large parameter-space, and a low discrepancy parameter sweep to explore the space of uncertainties.

Phylogeography uses genetic mutation information and the geographic locations of viruses to model the spread of epidemics across large geographic scales. We used Blue Waters to analyze 264 full-genome Ebola sequences from Guinea, Liberia, Sierra Leone, Italy, the United Kingdom, and the United States. We used the BEAST [5] software installed on Blue Waters to implement the phylogeography model.

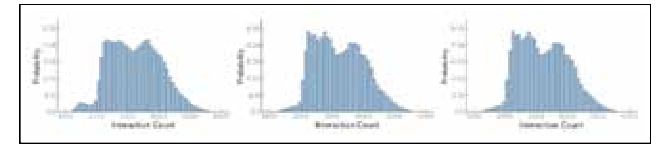

Figure 2: Comparison of the convergence of histograms for human contacts with different types of parameter sweep. (Left) Lattice with 1.4 million points. (Center) Low-discrepancy with 32,000 points. (Right) Accurate results.

RESULTS & IMPACT

In prior work, we used the above approach with Ebola. We studied the impact of different procedures for boarding, disembarkation, and seat assignment on infection spread. We showed that on a 182-passenger Boeing 757 airplane, random boarding can lead to substantial reduction in infection transmission compared with current zone-wise boarding. We have also obtained similar results showing the potential for changes in in-plane movement, deplaning procedure, seating arrangement, and plane sizes in reducing the likelihood of infection transmission. The improvements obtained for individual flights by these policy changes can be of substantial benefit over the course of an epidemic. Based on the transportation data from 2013, if unrestricted air travel were to have occurred during the 2014 Ebola epidemic, then the probability of generating 20 infections per month from air travel could have been reduced from 67% to 40% using better pedestrian movement strategies. This could further be reduced to 13% by exclusively using smaller 50-seat airplanes.

We have extended our approach to other directly transmitted diseases including SARS and influenza. This requires changes in approach that include aerosol and fomite transmission mechanisms, while pedestrian movement accounts for proximity among infectious and susceptible individuals. We have successfully extended the application to other high-density areas such as airport security-check areas and a generic airport gate. We also found effective strategies to mitigate spread by using temporary walls for queue management instead of ropes.

We developed a low-discrepancy parameter sweep that reduces by one to three orders of magnitude the number of parameter combinations that ought to be tried over the conventional lattice-based sweep (Fig. 2). We used number-theoretic properties of a low-discrepancy sequence to balance the load on the Blue Waters machine [4].

WHY BLUE WATERS

In a new emergency, due to lack of data, one usually needs to model for a variety of scenarios. This leads to a large parameter space of uncertainties, which requires a large computational effort. In addition, the models typically need fine-tuning, which leads to an iterative process where the model is repeatedly tuned based on results from its previous validation step. Consequently, rapid turn-around time is critical, which requires massive parallelism. Such parallelism becomes even more crucial during the course of a decision meeting, where results are typically needed in a short time. Toward that end, we obtained support from the Blue Waters team to optimize parallel I/O in our code to reduce simulation time by a factor of two.

PUBLICATIONS & DATA SETS

Srinivasan, A., C.D. Sudheer, and S. Namilae, Optimizing Massively Parallel Simulations of Infection Spread through Air-Travel for Policy Analysis. *Proceedings of the 16th IEEE/ACM International Symposium on Cluster, Cloud, and Grid Computing* (2016).

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Derjany, P., et al., Effect of Pedestrian movement on infection transmission during air travel: A modeling study. *Transportation Research Forum Proceedings* (2017).

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Namilae, S., A. Mubayi, and A. Srinivasan, Model based policy analysis for infection spread during air transportation. *International Conference of Transportation and Public Health* (2018).

Chunduri, S., et al., Parallel Low Discrepancy Parameter Sweep for Public Health Policy. *IEEE/ACM International Symposium on Cluster, Cloud, and Grid Computing* (2018).