BRINGING SOCIAL DISTANCING TO LIGHT: CROWD MANAGEMENT USING AI AND INTERACTIVE FLOOR PROJECTION

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Abstract

With the spread of COVID-19, social distancing has become an integral part of our everyday lives. Worldwide, efforts are focused on identifying ways to reopen public spaces, restart businesses, and reintroduce physical togetherness. We believe that architecture plays a key role in the return to a healthy public life by providing a means for controlling distances between people.

Making use of computational processing power and data accessibility, we propose a multi-pronged approach that will promote healthy and efficient movement through public space. Our approach must also be dynamic to easily accommodate developing requirements and programmatic changes within these spaces. The goal of our research is to develop: 1. a computational tool which utilizes machine learning to predict people's movement in existing spaces and provides suggestions for adapting existing spaces through local physical interventions and 2. a physical intervention system based on light projections that provides direct real-time information about safe trajectories and movement behavior for pedestrians.

The computational tool will use existing visual data from target case-study spaces, identifying movement patterns and translating those into behavior rules. This data will be combined with swarm behavior knowledge from natural systems to provide an initial movement prediction. At the same time, the installation of the camera-projection system will allow us to evaluate the efficiency of the proposed measures, monitor flow and inform the predictive model.

Ultimately we expect to identify strategies for efficient trajectory planning and repurposing of public space, while continually learning from their direct implementation. As such, we hope to identify novel spatial typologies pertaining to improved public health, resulting in planning rules that will reshape the built environment from the inside out.

Background

Social distancing has proven to be an effective measure in slowing the spread of infectious disease (1). Although it is unknown how long these preventative measures must remain in effect, we are confident that the reverberations of the current pandemic will echo across all aspects of life well into the future. More importantly, experts warn that the rate of arrival of new pandemics is likely higher due to the world's large population and its increasing globalization. Consequently, we need to explore not just short-term strategies for social distancing in response to the ongoing COVID-19 pandemic, but also lasting, long-term ones, that would either prevent or alleviate future pandemics.

Historically there is precedent for pandemics to transform the built environment (2, 3, 4). Today, the response to coronavirus is uniquely poised to make use of powerful computational tools, permitting swift action not just at the frontlines at the molecular scale, but also in everyday life on the architectural scale. Acute need for spatial intervention, both immediate and longer-term, is felt in our densely populated urban and suburban areas. Thus, the architectural response to the COVID-19 crisis will ultimately be a spatial one, where existing infrastructure originally designed for comfort, safety, and efficiency (5) with the aim of bringing people together will be forced to realign with vastly different ideals concerning public health. Swift action is needed to address this challenge, particularly in urban environments where sheer population density swells against a relative gridlock of existing spatial occupancy.

Access to increased computational power, data collection, and data processing ushers in the possibility to better predict and react to the spatial needs of such crises. Precedent projects have used AI to identify if social distancing guidelines are being met (6), however, no solution exists for implementing changes—immediate or long-term—that will alter behavior for the better. Drawing on collective dynamics and self-organization work in humans and animals, we plan to develop computational tools for optimizing the arrangement and movement of people in enclosed spaces, in particular in public areas such as transit stations and stores. By collecting and processing anonymized data on people's movement in public spaces, such as transit stations, we will train our simulation model to recognize behavioral patterns, eventually identifying necessary measures and improving its prediction over time. While computational methods for simulating people's movement have been employed in architectural and urban studies (7), the uniqueness of our approach lies in a rapid implementation beginning with an initial predictive simulation that is continuously informed and improved through data collection.

Our model will then be put to use by influencing people's behavior in crowded public spaces via architectural interventions. As a short-term response to improving social distancing efforts in public spaces, we will utilize existing sensing and light projection technology to generate visual cues for people moving through crowded environments. PI Parascho has employed visual capturing systems in architectural robotics projects to identify objects and reconstruct unknown geometries (in progress). Our visual cue system will be revolutionary in its ability to offer dynamic, real-time crowd control where existing distancing measures such as static floor markings and physical barriers currently fall short, including in the following scenarios:

- Crowds are larger than predicted
- Spaces are too small to accommodate longer queues
- Staffing is not available to monitor queues and crowds

- Queues form spontaneously in a public space such as in narrow passageways or checkpoints
- Queues do not take a linear form, such as on train platforms, queues intersect with other queues and pathways
- Individuals are unaware of, unaccustomed to, or simply forgetful of social distancing protocols

By providing a means for the public to visualize social distancing, we not only offer a quick, low-cost, and safe avenue for implementing new policy, but also raise awareness of the underlying issues.

While such short-term solutions address the urgency of the current situation, proactive solutions for future public health emergencies must rely on physical modifications to the built environment that promote and facilitate a sustainable level of social distancing. We do not believe it is overstated to assume that virtually all public and semi-public architectural interiors will need to conform to new standards based on safe and efficient distancing between people—standards for which they were not initially designed. An intelligent computational tool that can model, predict and recommend changes to spaces based on interior geometry, use, and traffic will be imperative to city planners, architects, business owners, and city officials worldwide.

Methods

To address different levels of urgency, we aim to impact social distancing in public space on two levels: through a computational planning tool and physical interventions. The two topics will be developed in parallel and inform each other to achieve maximum impact. We will apply the developed tools and physical interventions in a series of case studies to be monitored beyond the duration of the project. Experimental results from our case studies will be used in a continuous feedback loop to improve our simulation model. This way, we can both evaluate the efficiency of our tools and continuously improve them.

1. **Computational tool**

The core of our approach is a computational tool that is used to predict people's movements under various social distancing situations. Informed by swarm behavior algorithms and strengthened by machine learning, the tool will input site-specific data and will output simulations of crowds as they move through target spaces. In a second step, building on the simulation data, the tool will output recommendations that serve to streamline pedestrian movement in a given scenario.

1.1 Analysis and simulation

First, by collecting and processing camera data from video surveillance systems using open-source computer vision tools (8) alongside interior geometric data obtained via a handheld mapping sensor, we will track the movement of people passing through target public spaces. We will analyze how these movements may be affected by not only the geometric configuration of a space but also by programmatic features such as checkpoints and service stations. We will study how movement patterns may fluctuate not only in volume but also in quality throughout a given day.

These behaviors will be incorporated into a computational model based on swarm behavior. We will use models of collective animal behaviour to generate an initial model for pedestrian movement simulation. In a next step, we will inform it with rules identified from collecting on-site data. We will use computer vision and machine-learning-based pedestrian detection to extract people's position in space and time and identify their trajectories. We will identify different clusters of behavioral patterns by means of unsupervised learning. These clusters will inform the adjustment of the initially defined agents that will populate our tool. A machine learning model trained on all the collected data will then be able to make more sound predictions on longer-term motion from a local input.

The collected data will be anonymized and only contain a spatial location and a time tag for each identified person. Privacy concerns related to e.g. contact tracing applications that also need to uniquely identify individual persons would not apply.

1.2 Adjustments for social distancing

Second, we will expand the computational tool to include increased distancing requirements. By learning from the rules developed for the initial simulation, we can identify necessary local changes in the layout of a given space to allow for the required distancing measures.

One simple example is to increase the length of routes within a space to enable more people to cross it at the same time while keeping larger distances between them. Initially, the tool will make suggestions for motion path adjustments based on purely geometric constraints. Whenever the distance between two detected pedestrians falls below the prescribed minimum in the deskewed and rectified camera footage, the tool will suggest possible local path corrections. The collected observations of crowds' movement through space become the input for training in the next machine learning model. Trained on all the collected data, it will be able to make more sound predictions on probable future motion through space from only a local observation. This will allow us to make more foresighted suggestions on path adaptations and to coordinate crowds' motion with less discomfort.

Other measures will include identifying hard threshold points where the number of people passing is controlled at all times forming spontaneous queues, or by closing off areas to avoid close contact and improve flow. The resulting outputs will be new movement routes (figure 1), points where additional signals are needed to limit people's distances, safe trajectories for people to follow, and ways of easily adjusting existing spaces, such as rearranging mobile spatial elements. The goal is to provide a flexible computational design tool that can react to different distancing requirements and quickly give feedback about how an interior space could be adjusted to enable distancing measures.

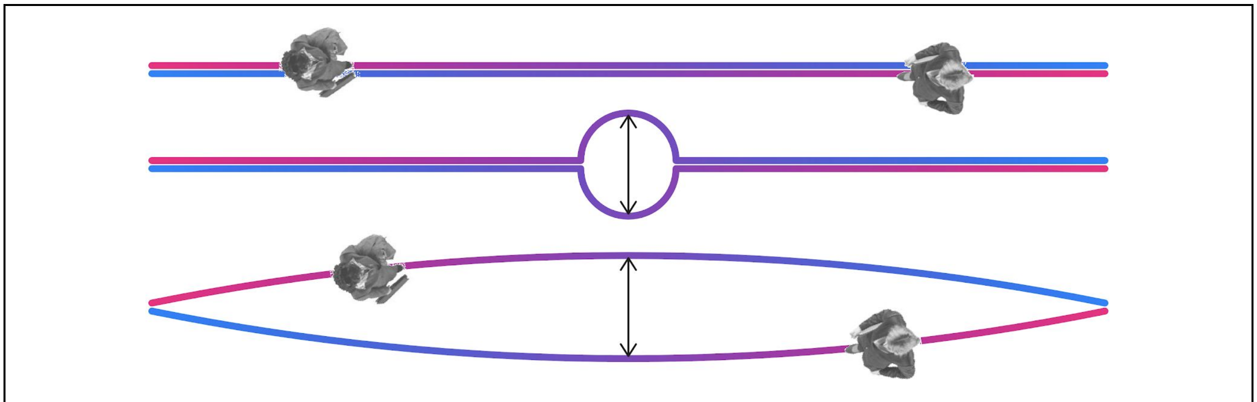

Fig. 1: Example of trajectory suggestion: two people walking from red to blue, crossing halfway; top: straight line shortest path, center: suggested local detour to maintain minimal social distance (5.7 % longer), bottom: learned predictive detour (only 0.7% longer than shortest path)

2. Applying the model: short- and long-term interventions

Our approach is designed to provide both rapid response to the current public health crisis and longer-term solutions to those to come. We propose two strategies: physical interventions designed to remediate specific challenges we are experiencing now and the analysis of the interventions' impact to identify how these new guidelines might affect architectural and urban planning in the long term.

2.1 Projected visual cues

Rapid interventions require simple and economical solutions that can be easily employed on-site. We propose to use digital projectors designed specifically for floor projection in varying light conditions. These projected-light interventions can be employed without complex preparations, and thus should be available to distribute to potential partners quickly. Possible direct applications are described in the case studies section below. Each projector will be matched with low-cost 3d cameras (e.g., Intel RealSense D435) to detect the number and movement of people below them. The following types of information will be conveyed by the projections:

- If the number of people in a space does not exceed a certain density, light projections will mark safe areas of movement around each person in the space. When these areas become too small, the recommendation tool will suggest possible local path corrections for each person and display these using visual cues, such as arrows, color changes, and animations (figure 1).

- If the number of people in a space exceeds a certain density, projectors will mark which people can enter a space or move further, so that not every person moves towards the same areas at the same time. This will also be used for queueing, such as at check-points, cashier points, or when entering public transport. Projector displays will be informed by our computational tool, which will determine safe trajectories and waiting points.

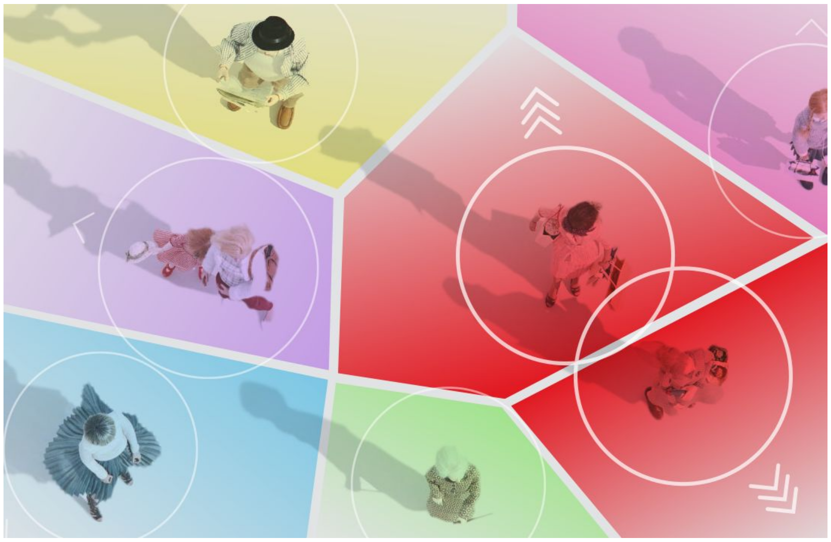

Fig.2: Visualization of potential projections to indicate safe movement areas and directions.

2.2 Recommendations for long-term change: while such short-term solutions are valuable, they rely on people's already heightened awareness of, and likelier compliance with, the need for social distancing. However, long-term implementation of distancing measures that can prevent or diminish the future spread of viruses must rely on modifications to the built environment that promote and facilitate a sustainable level of social distancing. Through cross-analysis of our computational model with experimental data collected from the projected light interventions, we will be able to identify more permanent adaptations of the built environment (e.g., readjusting interior walls, adding new separation elements or changing the access points into a space). Furthermore, we will identify common patterns for change, which can inform future building codes and best practices. Such adjustments will eventually lead to typological changes in architectural design—meaning that the fundamental spatial sequences and organizations of buildings may change. Anticipatory design speculations based on the altered codes and metrics will be critical to proposing successful long term/permanent solutions.

For the duration of our study we will analyze experimental results obtained from our case studies, concluding in the publication of a report of these findings to serve as a basis for new policy. The report will be publicly accessible on a GitHub repository, along with the source code for the tools developed as part of the research and anonymized collected movement data.

3. Case-studies

Public transit, especially subway travel in the New York metropolitan area, remains one of the more difficult areas for proper social distancing due to the important role it plays in providing transport to people who are still required to go to work. While a healthier passenger environment can be achieved onboard by limiting total passengers, leaving empty seats, and frequent sanitization of equipment, we seek to address the passenger experience in stations, including the choreography of boarding and deboarding under social distancing guidelines. We plan to develop interventions targeted at public transit stations using indicative projections at access points, in waiting areas, and on platforms as passengers exit and enter trains and buses. We intend to partner with New Jersey Transit to consult on social distancing strategies and implement our prototypes. In addition, we want to address large public transit areas, such as rail, bus and airport terminals by computing and visualizing safe transit trajectories, and by addressing queue formation and waiting areas through semi-permanent physical interventions.

Grocery stores, pharmacies, and other essential businesses, like public transit, must continue to fulfill their roles even during a public health crisis. Stores present a particular challenge for social distancing due to a general lack of excess space inside. Queue management has been an issue for many of these businesses even before the COVID-19 crisis. Many stores have adopted their own ad-hoc means for enforcing social distancing, such as installing temporary floor markers, hiring queue marshals, and preventing too many customers from entering at once. The result is that it's common to wait for long periods of time outside of a store—weather and physical stamina notwithstanding. Our vision is that through the use of projections, safe distancing between customers can be maintained, movement streamlined throughout, and thus more customers will be allowed to enter at a single time. Employees currently tasked at managing queues could be reassigned to operations that expedite bottlenecks, such as checkout. We aim to partner with local brick-and-mortar essential businesses to implement our projection system.

Expansion of Case-studies. While we identified transit and essential businesses as urgent action areas, we are aware that the United States is struggling to ensure people's health and safety in many other public areas. In discussions with state authorities, we hope to identify urgent and suitable applications for both the computational planning tool and physical implementations. For example, we envision utilizing the planning tool for re-planning and arranging hospital reception areas.

Collaborative Strategy

Stefana Parascho develops computational design methods and digital fabrication techniques for architectural construction. She will draw on her research in simulating agent-based systems (10) to develop the computational tool and on her experience in employing existing technologies in architectural applications and full-scale prototyping to develop and implement the physical light-interventions proposed. She is currently working with sensing hardware and 3d cameras to scan and identify objects to be handled in construction (11). Processing camera data (2D or 3D) to identify moving targets will be combined with developing visuals to be used in the light projections.

Corina Tarnita employs theoretical and computational tools to study self-organization and collective dynamics across natural systems. She will draw on her existing research to inform the computational model and its outputs for short-/long-term interventions. Animals compete for resources and partition space to minimize competition (zone of repulsion) while maximizing resource use (12). Animal systems have evolved to adjust their zones of repulsion dynamically. This can potentially be applied to humans moving in public areas, that also "compete" for the available space. Social distancing measures are akin to readjusting individuals' zones of repulsion. In addition, she has conducted research on termite mounds showing that their distribution influences the organization and function of the rest of the ecosystem (13, 14). Insights from this type of work would inform the use of the computational model for predicting long-term interventions to the built environment.

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List of collaborators

Stefana Parascho - Assistant Professor Princeton University, School of Architecture

Stefana Parascho is an architect with a focus on computational design and robotic fabrication. Prior to joining Princeton University in 2019, she obtained her PhD from ETH Zurich, in 2019. She received her Diploma in Architectural Engineering in 2012 from the University of Stuttgart and has worked with DesignToProduction Stuttgart and Knippers Helbig Advanced Engineering. Throughout her research she has explored existing computational design methods and their potential role for architectural construction, ranging from agent-based models to mathematical optimization. Her goal is to strengthen the connection between design, structure and fabrication and the interdisciplinary nature of architectural design through the development of accessible computational tools.

https://soa.princeton.edu/content/stefana-parascho

https://scholar.google.ch/citations?user=xLkdhCUAAAAJ&hl=en

Corina Tarnita - Associate Professor, Princeton University, Ecology and Evolutionary Biology

Corina joined the Princeton faculty in February 2013. Previously she was a Junior Fellow at the Harvard Society of Fellows (2010-2012) and a postdoctoral researcher with the Program for Evolutionary Dynamics, Harvard University (2009-2010). She obtained her B.A.('06), M.A.('08) and PhD ('09) in Mathematics from Harvard University. She is an ESA Early Career Fellow, a Kavli Frontiers of Science Fellow of the National Academy of Sciences and an Alfred P. Sloan Research Fellow. Her work is centered around the emergence of complex behavior out of simple interactions, across spatial and temporal scales.

https://soa.princeton.edu/content/stefana-parascho

https://scholar.google.ch/citations?user=xLkdhCUAAAAJ&hl=en

Budget

Our budget includes:

(a) Material supplies costs for setting up 2 full prototypes, (b) funding for travel and on-site visits for case studies, and (c) research personnel: two external research assistants with expertise knowledge who will work during the first 3 months on quickly developing hardware prototypes and speed up developments in the initial phase, stipend support for an Architecture PhD student who will develop and refine the computational design tool, funding for a graduate student assistant, who will work with Parascho on identifying and implementing new architectural typologies and design tools, summer salary for Tarnita who will work together with the PhD student to develop the computational model and summer salary for Parascho who will lead the development of the project. The budget will be supplemented by funding additional research personnel (not listed below: two PhD students for additional 6 months) by Princeton University.

(a) Material Supplies:

  20 x projector; 20 x cameras; 4 x mini computers; installation material ($15.000)

(b) Travel:

  Site-visits, meetings ($2.000)
  Dissemination travel ($3,000)

(c) Research Personnel:

  2 research assistants 3 months – 50% ($20,400)
  1 graduate student assistant architecture – 40h/month - 12 months ($9,600)
  1 summer stipend phd student ($6,000)
  ½ year – 50% PhD funding ($20,000)
  ¾ month summer salary for Tarnita ($12,000)
  1 month summer salary for Parascho ($12,000)

Total: $100,000