Where to Meet: A Context-Based Geoprocessing Framework to Find Optimal Spatiotemporal Interaction Corridor for Multiple Moving Objects

Song Gao[1], Yuan Zeng[2]

[1]STKO Lab, Department of Geography, University of California, Santa Barbara, CA 93106
Email: sgao@geog.ucsb.edu

[2]Environmental Systems Research Institute, 380 New York Street, Redlands, CA 92373
Email: mzeng@esri.com

1. Introduction

Human movements and interactions in space and time lay a foundation for supporting our economic and social activities. Especially with the increasingly development of location-based information communication technologies, people have access to rich information (e.g., real-time traffic) to support their decision makings. Giving different types of constraints in human life (Hägerstrand 1970, Schwanen and Kwan 2008), especially the space-time constraints, people need to make optimal decisions to satisfy their social activity participation and travel behaviors. By integrating time geography theory and GIS analysis capabilities, researchers have made great efforts and achievements on developing analytical foundations for studying accessibilities, human activities and interactions in both physical space and virtual space (Kim and Kwan 2003, Miller 2005, Shaw and Yu 2009). However, searching potential interaction areas for multiple moving objects or trajectories with space-time constraints is still a challenge. For example, how could friends driving from different working locations find an optimal intermediate meetup location for ride-sharing to a party place with limited parking capacity, or for handing over an important document before heading to different destinations? In addition, contextual information, such as traffic congestions, temporal barriers, points of interest (POI), weather and other environmental factors, also plays an important role in enabling and limiting movements (Buchin et al. 2012, Dodge et al. 2016, Siła-Nowicka et al. 2016).

In this research, we aim to formalize the problem of finding optimal spatiotemporal interaction corridor for multiple moving objects and introduce a context-based geoprocessing framework to solve this spatial optimization problem.

2. Methods

2.1 Problem Definition

Let M_i denote a moving object and there is a set of moving objects $\{M_1, M_2, \cdots, M_n\}$, and each of them has a pair of origin O_i and destination D_i. The departure time, arrival time, time budget, and a corresponding delay tolerance for M_i can be represented as T_{oi}, T_{di}, β_i, and τ_i respectively. Also, X denotes a meetup location; X_{Mi} represents accessible locations for M_i within a time budget; T_{xi} is the arrival time to X; T'_{xi} is the departure time from X; T'_{di} represents the updated arrival time to final destination D_i; ΔT_i represents the time difference between T'_{di} and T_{di}. The objective is to find an optimal intermediate location which supports multi-moving-objects to take a detour to meet while allowing them to arrive at their planned destinations on time or within their corresponding delay tolerances after rerouting. There are different definitions of “what is optimal" in different contexts. For example, it could be minimizing the total travel distance or total travel time for all objects, or minimizing the sum of time differences (Equation 1) such that objects don't deviate too much from their original plans. The latter definition has been taken in this study and can be formalized as follows:

Objective Function: $$\arg\min_x \sum_i^n \Delta T_i \qquad (1)$$

Subject to constraints:
$$\Delta T_i <= \tau_i \quad \forall i, \tau_i > 0 \qquad (2)$$
$$T'_{di} - T_{oi} <= \beta_i \quad \forall i, \beta_i > 0 \qquad (3)$$
$$X_{Mi} \cap X_{Mj} \neq \emptyset \quad \forall M_i, M_j \text{ and } i \neq j \qquad (4)$$
$$T'_{xi} > T_{xj} \quad \forall i, j \text{ and } i \neq j \qquad (5)$$
$$T'_{di} > T'_{xi} > T_{xi} > T_{oi} > 0 \quad \forall i \qquad (6)$$

Constraints (2) ensure that each object satisfies its time delay tolerance. Constraints (3) ensure that each object can arrive at original planned destination within its time budget after meeting and rerouting. Constraints (4) and (5) ensure that there is a common location and overlapped time period in which all moving objects have arrived this meetup location. Constraints (6) impose temporal sequence restrictions on departure, meetup and arrival time. Such spatial optimization problems are typically solved by linear programming methods (Tong and Murray 2012) in which a function of the variables is optimized subject to a set of equations that describe the constraints.

2.2 Geoprocessing Framework

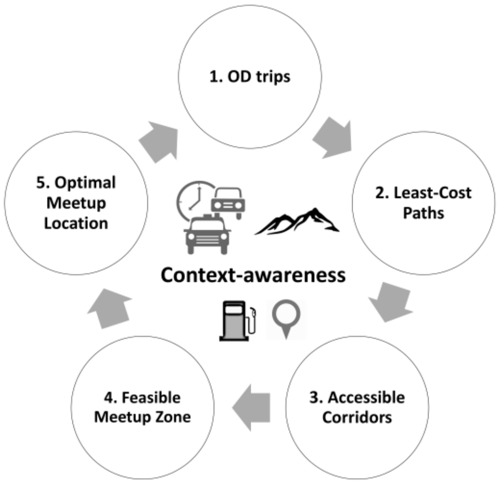
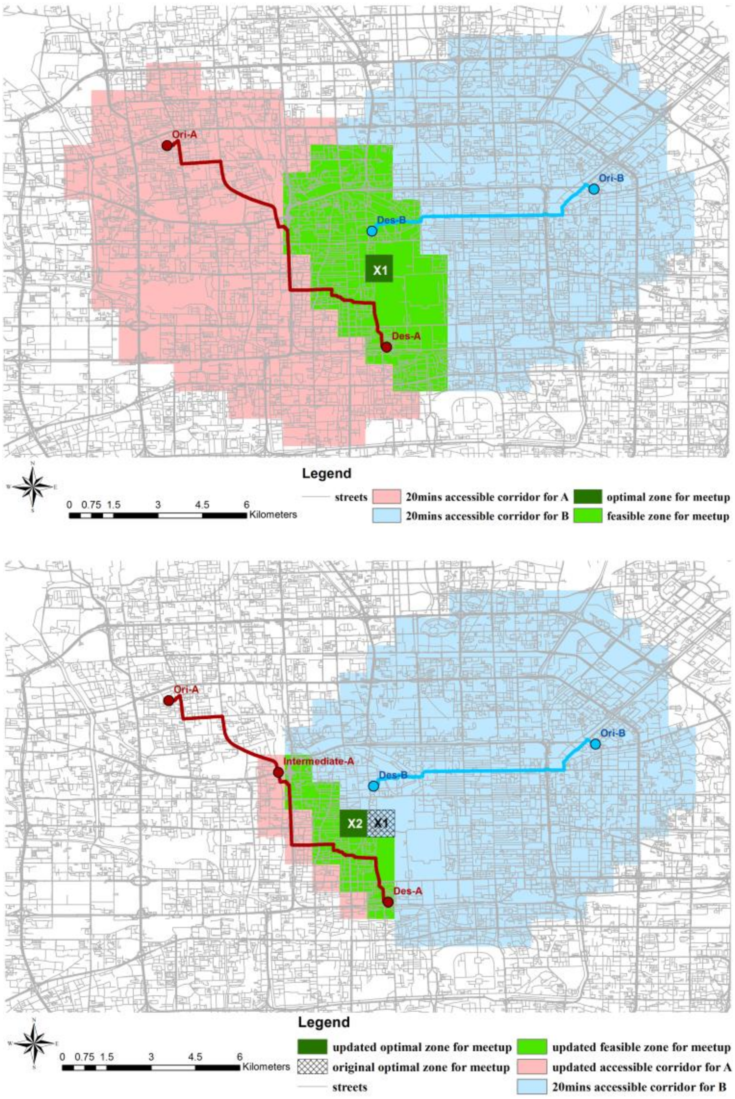


Figure 1. A context-based geoprocessing framework to find optimal spatiotemporal interaction corridor

As discussed above, in real-world analysis scenarios, we need to consider different kinds of contexts which further increase the computation complexity. Instead of using typical linear programming methods, we introduce a novel geoprocessing framework in GIS to solve this problem.

As shown in Figure 1, firstly, an input layer is the planned OD trips (with locations and time budget) for multiple moving objects. Secondly, the least-cost path (LCP) and estimated arrival time for every object can be computed based on either shortest distance or minimum travel time. The classic *Dijkstra or A** algorithm is used for searching shortest path between nodes in a graph if street networks are available otherwise visibility-graph-based approaches are typically used for deriving shortest path in continuous space (Hong and Murray 2013). If a meetup happens in the context of hiking in mountainous areas, accumulated cost surface with regard to both distance and slope, or viewshed analysis on digital elevation models (DEM) can be employed to compute LCP (Douglas 1994; Stucky 1998). Weighted lattice solutions have been frequently used to find LCP on raster-based tessellations. Thirdly, *accessible corridor locations* (AC) for each object are computed so that for each AC, the sum of accumulative time costs from origin to destination by passing through a corridor location is within the total time budget of each moving object. If additional contexts need to be considered, multi-objective corridor location models can be applied (Church et al. 1992) to compute AC. Fourthly, by spatially intersecting all accessible corridors derived from the previous step, we can find a common set of AC which forms a *feasible meetup zone* that satisfies all spatiotemporal interaction conditions. Fifthly, an optimal zone or a location can be further selected by considering Equations 1~6. Also, the existence of contextual information such as the availability of preferred POI type to meet can affect the final decision of selecting a meetup location. Such information can also be integrated in processing step 4 or 5. Last but not least, the planned OD trips for each individual may change by inserting the newly derived optimal intermediate meetup location.

3. Case Study



(a)

(b)

Figure 2. Finding optimal meetup location for two persons: (a) without traffic; (b) with traffic.

As shown in Figure 2, two persons (*A and B*) need to meet for handing over an important document before heading to separate destinations. They departure from different locations at the same time. *A* needs to take 15 minutes to his destination using the shortest path while *B* needs to take 12 minutes. Both of them have a 20-min budget. By applying the introduced geoprocessing framework, a feasible meetup zone and the optimal zone *X1* that satisfies all spatiotemporal conditions can be found.

However, person *A* encounters a 3-min traffic jam when he reaches an intermediate location. Under such a context, his accessible corridor locations within time budget need to be recalculated and another optimal zone *X2* will be derived accordingly. Note that we used 1km * 1km raster grids in this scenario and a preferred POI with an address inside this optimal zone will be chosen as the final meetup location.

4. Conclusion and Future Work

In this research, we formalize the problem of finding optimal spatiotemporal interaction corridor for multiple moving objects and introduce a context-based geoprocessing framework to solve this spatial optimization problem. A case study of finding two persons' meetup location with a time budget under traffic context is used to validate our computation framework. This framework is implemented in a GIS environment so that it is convenient for the integration with different contextual information, e.g., temporal barriers, POIs, and terrain surface when dynamically searching for optimal solutions. The proposed method can be applied in trip planning, carpooling services, and logistics and operations management, especially in the new era of sharing economy.

Another scenario for selecting multiple hikers' meetup location in mountainous areas will be included in an extended full paper. In addition, the computation efficiency in different scenarios and the impact of raster resolution will be evaluated in future work.

References

Buchin M, Dodge S, and Speckmann B, 2012, Context-aware similarity of trajectories. In *Geographic information science*, Springer Berlin Heidelberg, 43-56.

Church, RL, Loban SR, and Lombard K, 1992, An interface for exploring spatial alternatives for a corridor location problem, *Computers & Geosciences*, 18(8): 1095-1105.

Dodge S, Weibel R, Ahearn SC, Buchin M, and Miller JA, 2016, Analysis of movement data, *International Journal of Geographical Information Science*, 30 (5): 825-834.

Douglas DH, 1994, Least-cost path in GIS using an accumulated cost surface and slopelines. *Cartographica: International Journal for Geographic Information and Geovisualization*, 31(3): 37-51.

Hägerstrand T, 1970, What about people in regional science?, *Papers in regional science*, 24(1): 7-24.

Hong I and Murray AT, 2013, Efficient measurement of continuous space shortest distance around barriers, *International Journal of Geographical Information Science*, 27(12): 2302-2318.

Kim HM and Kwan MP, 2003, Space-time accessibility measures: A geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration, *Journal of Geographical Systems*, 5(1): 71-91.

Miller HJ, 2005, Necessary space-time conditions for human interaction, *Environment and Planning B: Planning and Design*, 32(3): 381-401.

Schwanen T and Kwan MP, 2008, The Internet, mobile phone and space-time constraints, *Geoforum*, 39(3): 1362-1377.

Shaw SL and Yu H, 2009, A GIS-based time-geographic approach of studying individual activities and interactions in a hybrid physical–virtual space, *Journal of Transport Geography*, 17(2): 141-149.

Siła-Nowicka, K., Vandrol, J., Oshan, T., Long, J. A., Demšar, U., & Fotheringham, A. S. (2016). Analysis of human mobility patterns from GPS trajectories and contextual information. *International Journal of Geographical Information Science*, 30 (5): 881-906.

Stucky, JLD, 1998, On applying viewshed analysis for determining least-cost paths on digital elevation models. *International Journal of Geographical Information Science*, 12(8): 891-905.

Tong D and Murray AT, 2012, Spatial optimization in geography, *Annals of the Association of American Geographers*, 102(6): 1290-1309.