Real-time Motion Planning of Multiple Formations in Virtual Environments: Flexible Virtual Structures and Continuum Model

Yi Li & Kamal Gupta
Robotic Algorithms & Motion Planning (RAMP) Lab
School of Engineering Science
Simon Fraser University

Agenda

- Introduction
- Related work
- More on the Continuum Model
- Motion Planning of Multiple Formations
- Conclusion & Future Work

Introduction

Motions in Virtual Environments and Games

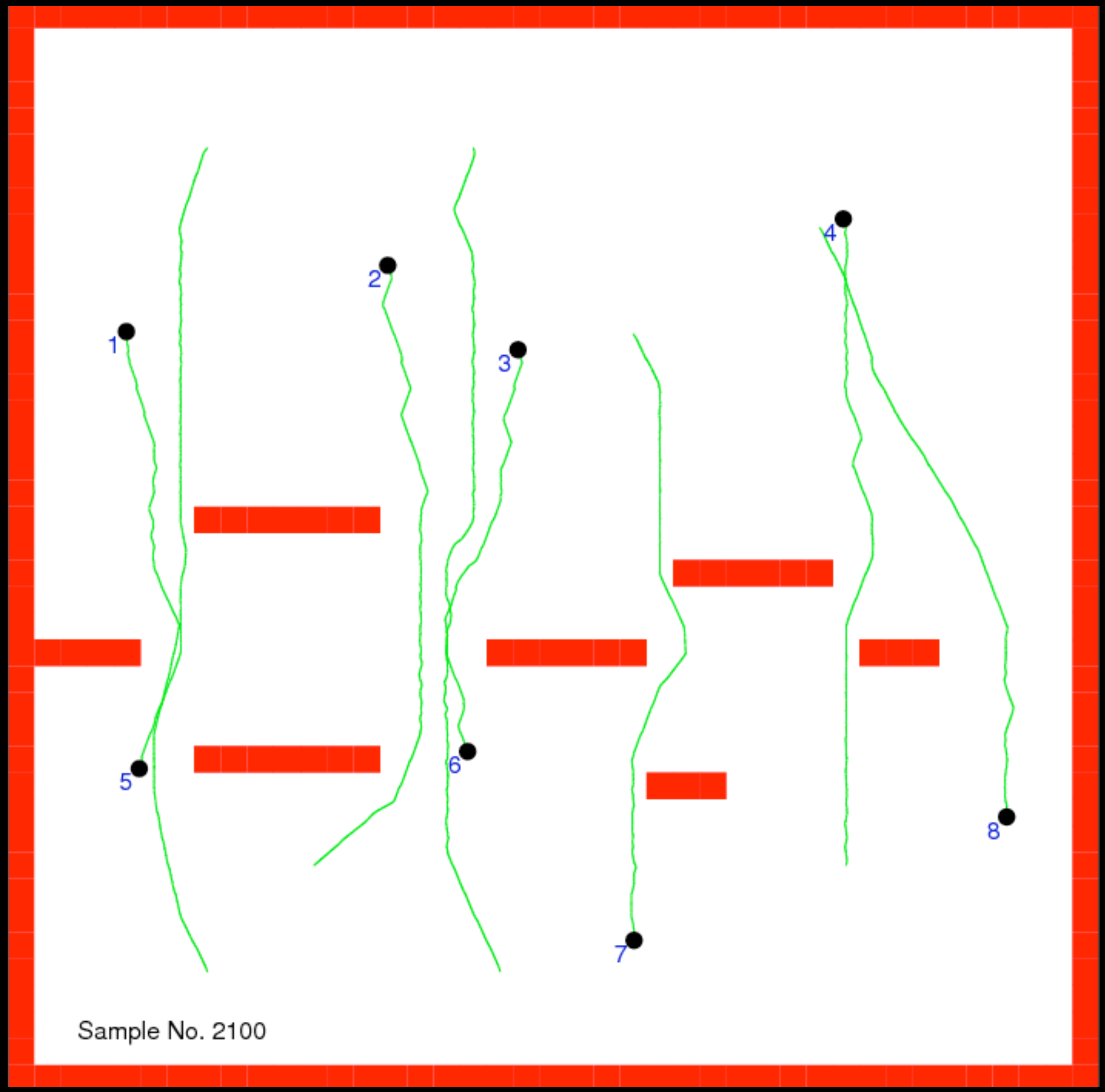
- Four different types of motions in virtual environments and games: **navigation**, **animation**, **manipulation**, and **camera**.
- We assume that there is **no uncertainty** in the agents' motions and virtual environments are given as **binary occupancy grids**. However, movements of dynamic obstacles are NOT given beforehand.

Real-time Tactical (RTT) Games

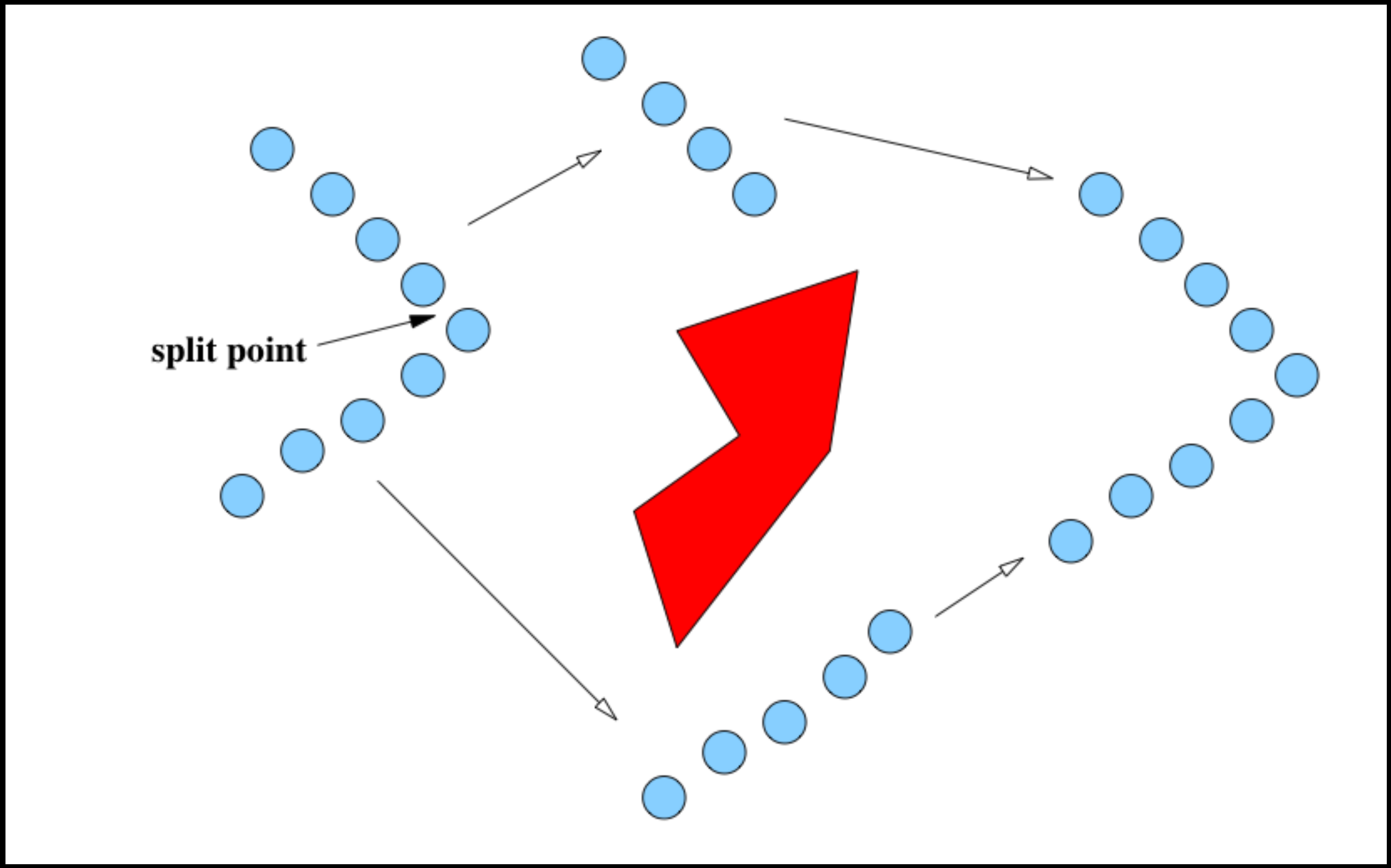
- Multiple Agents.
- Real-Time.
- Dynamic.
- Complexity.
- **Coherence (e.g., formations).**
- Inexpensive Pre-processing.

The Continuum Model

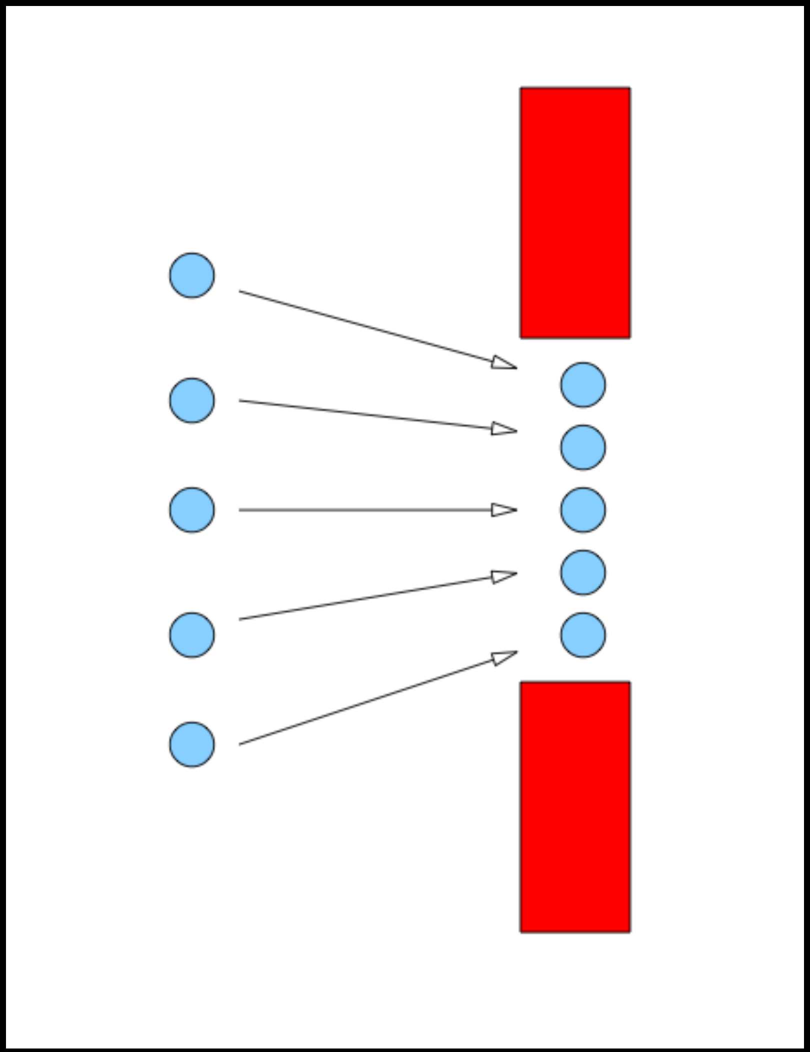
- A real-time crowd simulation framework based on the Fast Marching Method (FMM).
- It computes a set of potential fields (using the FMM) over the domain that guide all agents' motions simultaneously.
- It unifies global planning and local planning ➜ no conflicting requirements between global planning and local obstacle avoidance.



The Continuum Model.



Formation breaks and rejoins: not desirable at times.



Ordered obstacle avoidance while maintaining the formation.

Agenda

- Introduction
- Related work
- More on the Continuum Model
- Motion Planning of Multiple Formations
- Conclusion & Future Work

Related Work

Motion Planning of Multiple Agents

- **Centralized planning**: Considers all agents as one robotic system with many DOFs, and its time complexity is exponential in the dimension of the composite configuration space.
- **Decoupled planning**: Proceeds in a distributed manner and coordination is often handled by exploring a *coordination space*. Much faster, but not complete.

Motion Planning of Multiple Agents in Dynamic Environments

- The motions of the obstacles are given beforehand: The concept of the **configuration-time space** can be used to solve the planning problem.
- No prior information about the movements of the obstacles: **Path Modification** (e.g., elastic bands, elastic strips, the adaptive roadmap based algorithm) and **Replanning** (e.g., the D* deterministic planning algorithms, the multi-agent navigation graph (MaNG)).

Motion Planning of Multiple Agents as a Group

- In the continuum model, agents in each group share the same goal, but they do not stay together.
- Flocking / Several steering behaviors.
- Enclose a group by a deformable rectangle. The agents' total motions are given by combining the global motions of the group (PRM) and the local motions of the agents (group potential fields).
- Extend the backbone path for a single agent to a **corridor** using the clearance along the path. All agents must remain inside a group region (part of the corridor).

Motion Planning of Multiple Agents as a Formation

- **The leader-follower approach**: cannot maintain the formation if a follower is perturbed.
- **The behavior based approach**: inadequate when the formation shape needs to be changed.
- **The virtual structure approach**: no automatic reconfiguring strategy.

Agenda

- Introduction
- Related work
- More on the Continuum Model
- Motion Planning of Multiple Formations
- Conclusion & Future Work

More on the Continuum Model

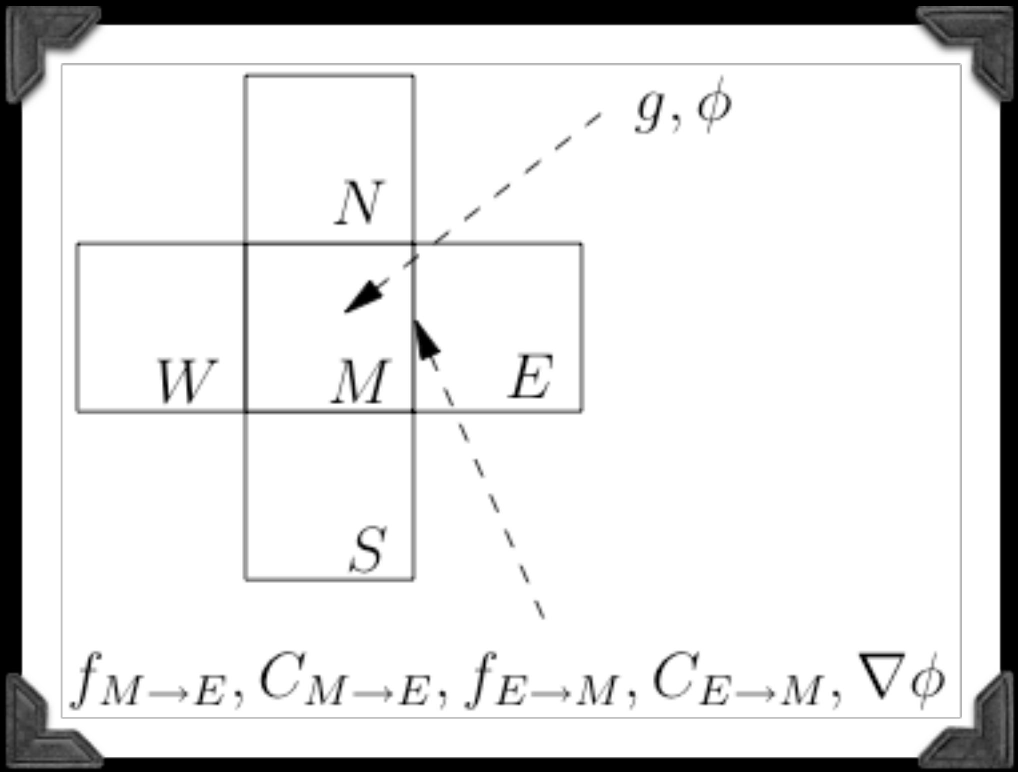
The Fast Marching Method

- John N. Tsitsiklis, *“Efficient algorithms for globally optimal trajectories,”* IEEE Transactions on Automatic Control 40(9), 1995.

The Fast Marching Method

$$\|\nabla \phi(\mathbf{x})\| = C$$
$$C > 0$$
$$\phi(g_b) = 0$$

The Fast Marching Method



$$\left(\frac{\phi_M - \phi_{m_x}}{C_{M\to m_x}}\right)^2 + \left(\frac{\phi_M - \phi_{m_y}}{C_{M\to m_y}}\right)^2 = 1$$

$$m_x = arg\,min_{i\in\{W,E\}}\{\phi_i + C_{M\to i}\}$$

$$m_y = arg\,min_{i\in\{N,S\}}\{\phi_i + C_{M\to i}\}$$

The Continuum Model

- A. Treuille, S. Cooper, and Z. Popovic, *"Continuum crowds,"* SIGGRAPH'06, 2006.

The Continuum Model

- Minimize a linear combination of the following terms:
  1) The length of the path;
  2) The amount of time to the goal;
  3) The discomfort felt, per unit time, along the path.

The Continuum Model

$$C = \alpha + \beta \frac{1}{f} + \gamma \frac{g}{f}$$

where

f is the speed field

g is the discomfort field

$$\dot{\mathbf{x}} = -f(\mathbf{x}, \theta) \frac{\nabla \phi(\mathbf{x})}{\|\nabla \phi(\mathbf{x})\|}$$

The Continuum Model

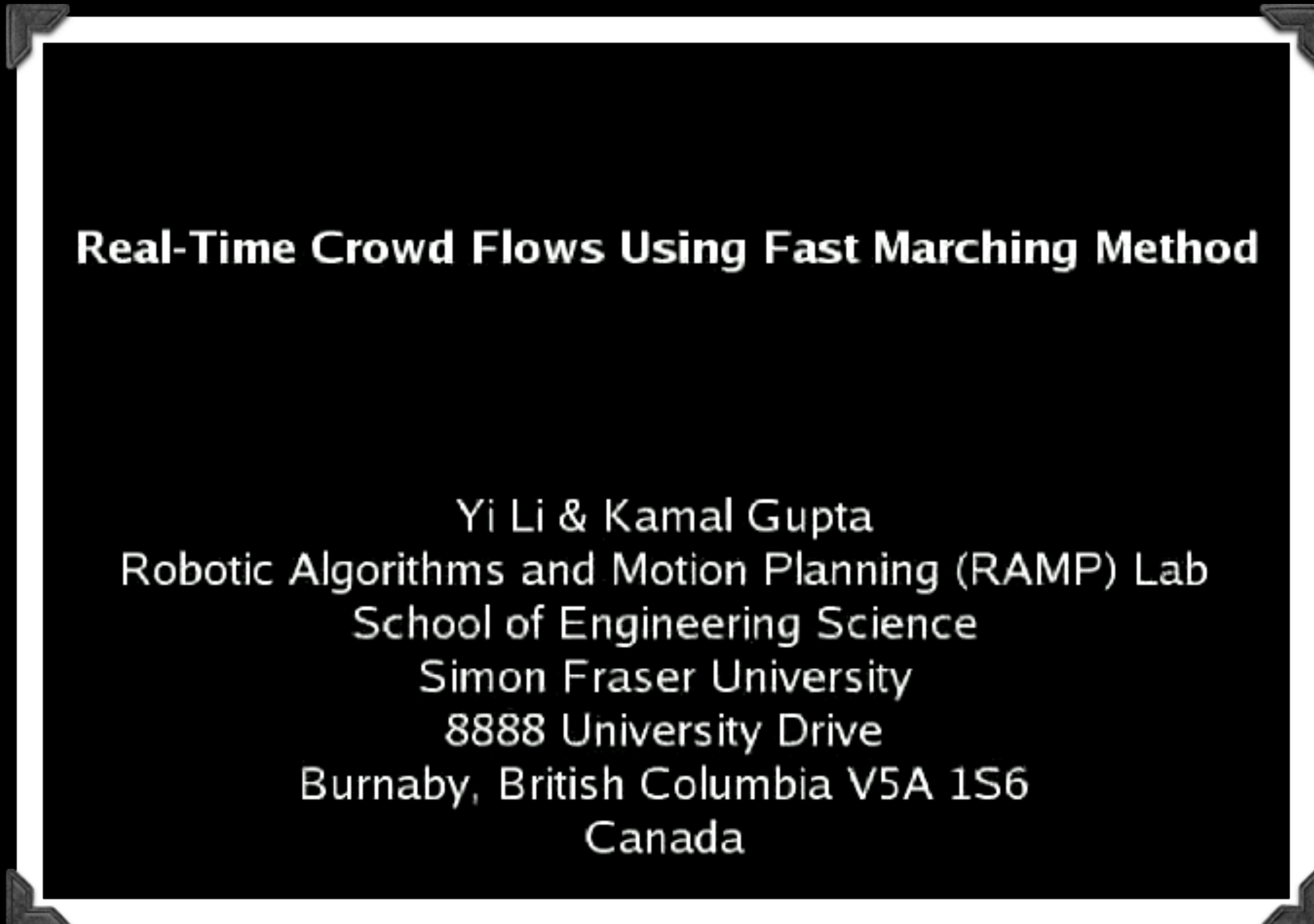
- Low crowd densities ➜ Speed is dominated by the terrain (constant on flat surfaces, but changing with the slope).
- High crowd densities ➜ Speed is dominated by the movements of nearby agents (e.g., movement is inhibited when trying to move against the flow).

The Continuum Model

- When two agents cross perpendicularly ➜ Add discomfort in front of each agent ➜ The agents anticipate each other.

```
foreach simulation cycle do
    Construct the density field;
    foreach group do
        Construct the unit cost field C;
        Construct the potential ϕ and its gradient ∇ϕ;
        Update agents' locations;
    end
    Enforce the minimum distance between the agents;
end
```

The Continuum Model.



Video: Continuum Crowds.

Agenda

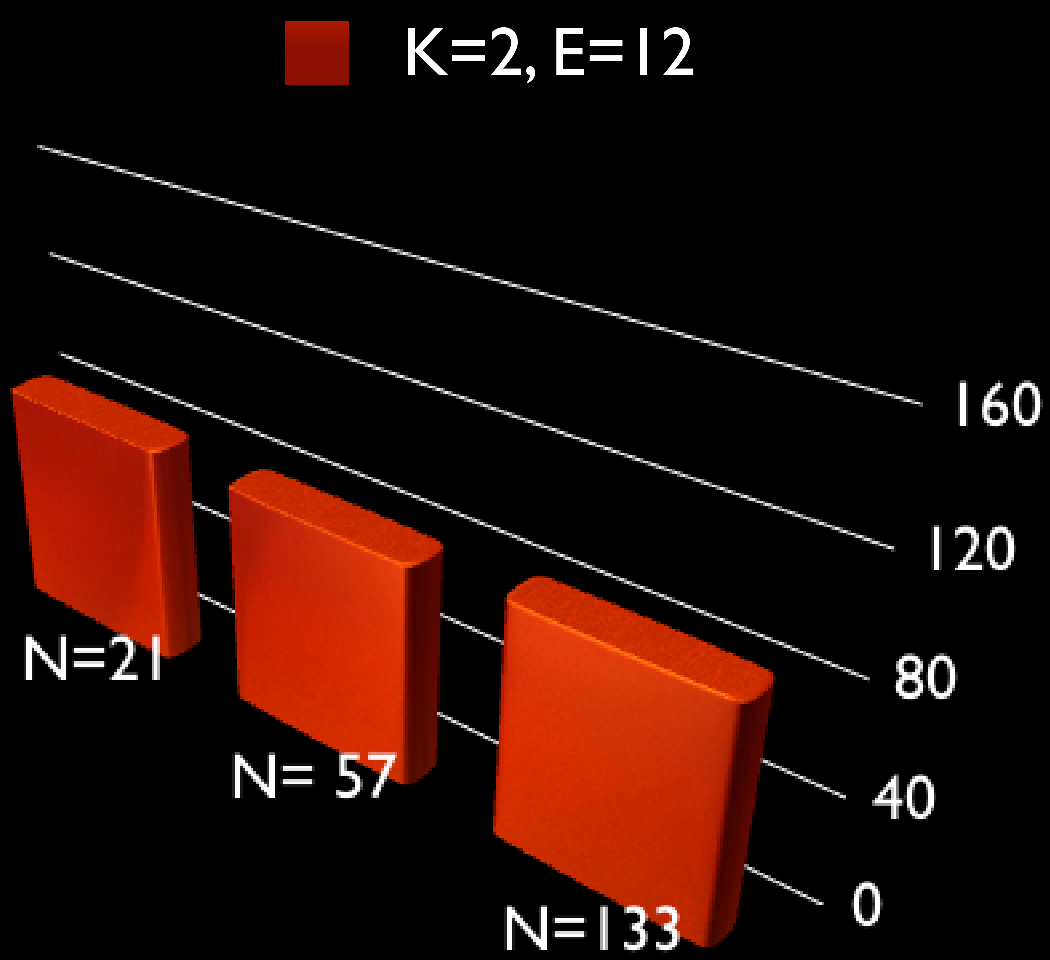
- Introduction
- Related work
- More on the Continuum Model
- Motion Planning of Multiple Formations
- Conclusion & Future Work

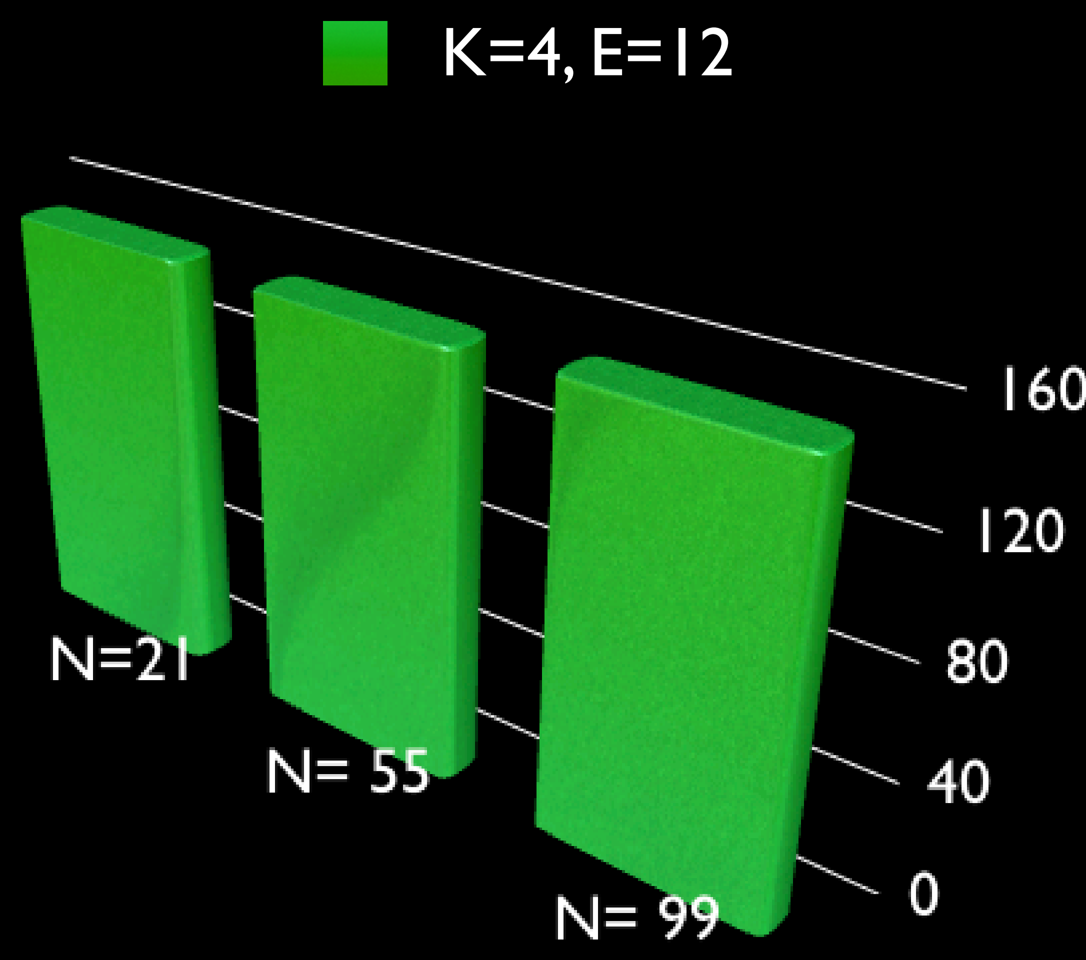
Motion Planning of Multiple Formations

Video: Motion Planning of Multiple Formations.

$$
\begin{aligned}
\mathbf{u} &= \mathbf{A}\mathbf{t} \\
\mathbf{u}_{int} &= \mathbf{G}_{int}\mathbf{t} - \mathbf{F}_{int}\mathbf{u} \\
\mathbf{u}_{ctrl_c} &= (\mathbf{G}_{ctrl} - \mathbf{F}_{ctrl}\mathbf{A})\mathbf{t} \\
E(\mathbf{t}) &= \|\mathbf{u}_{ctrl_d} - \mathbf{u}_{ctrl_c}\|
\end{aligned}
$$

Average computation time for one deformation in millisecond

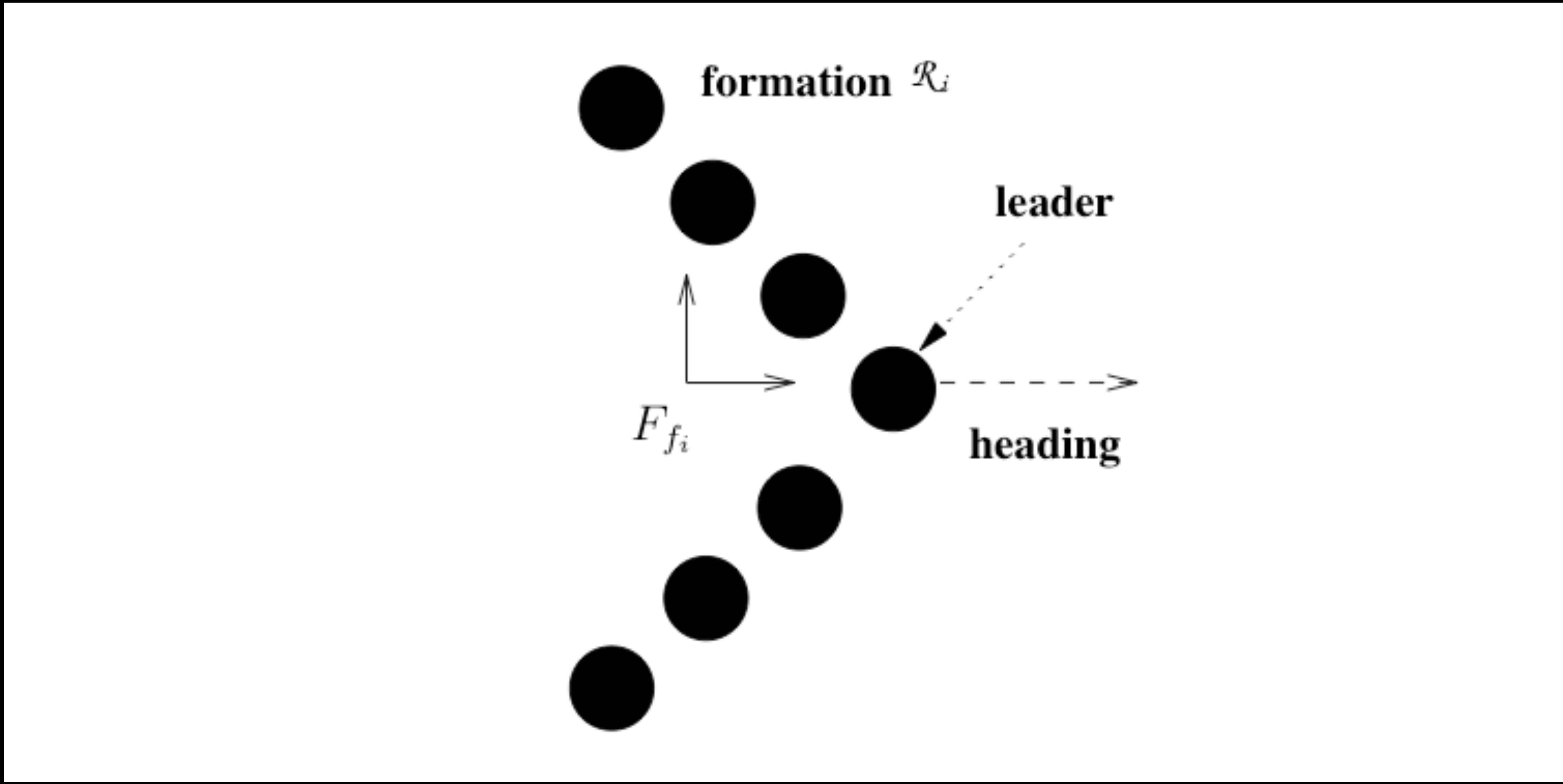




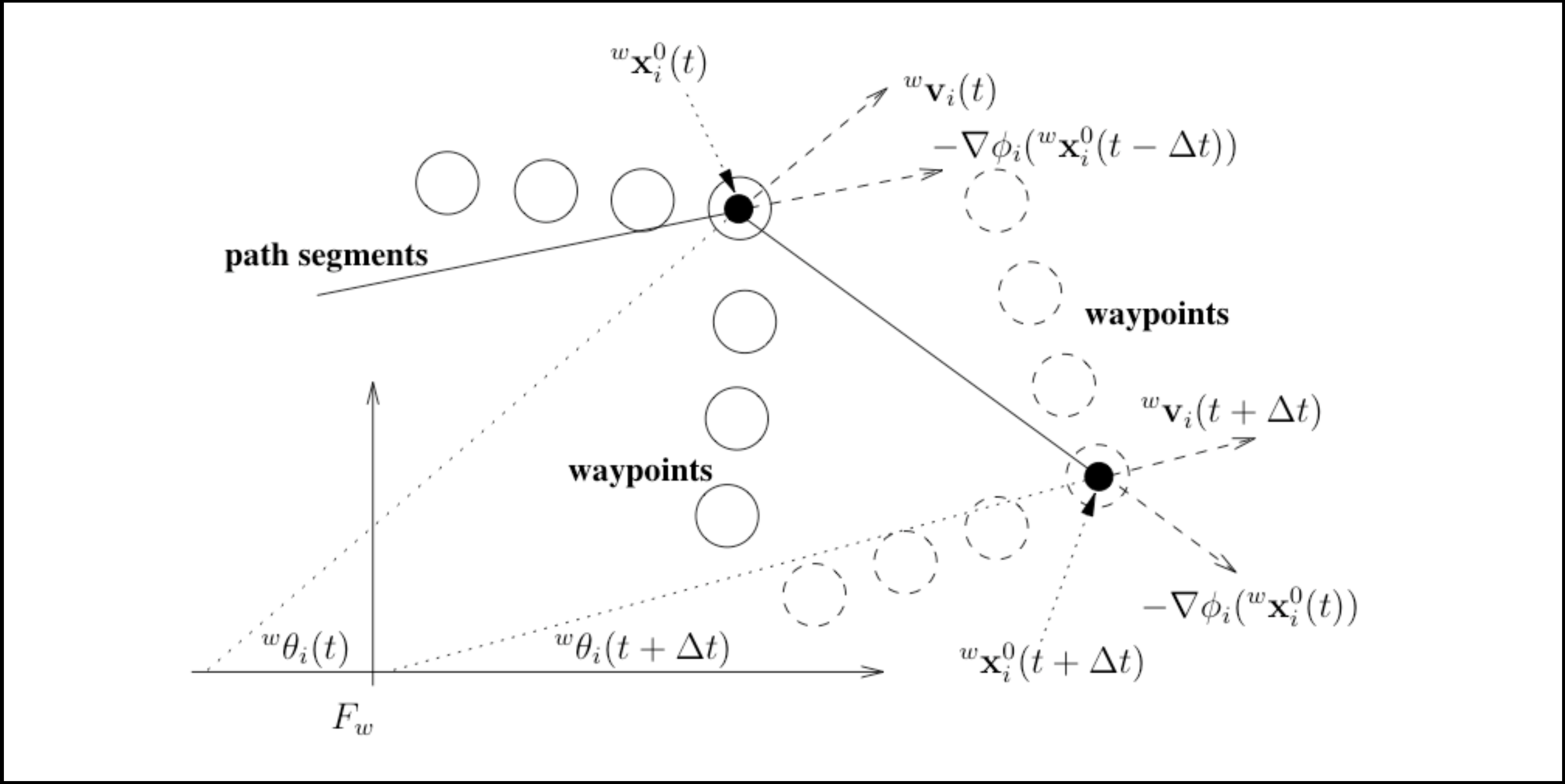
N is the number of agents.

K is the number of the control nodes.

E is the number quadratic elements (2E boundary nodes).



Formation Definition.



Formation Mapping.

Curvature Constrained Path Planning

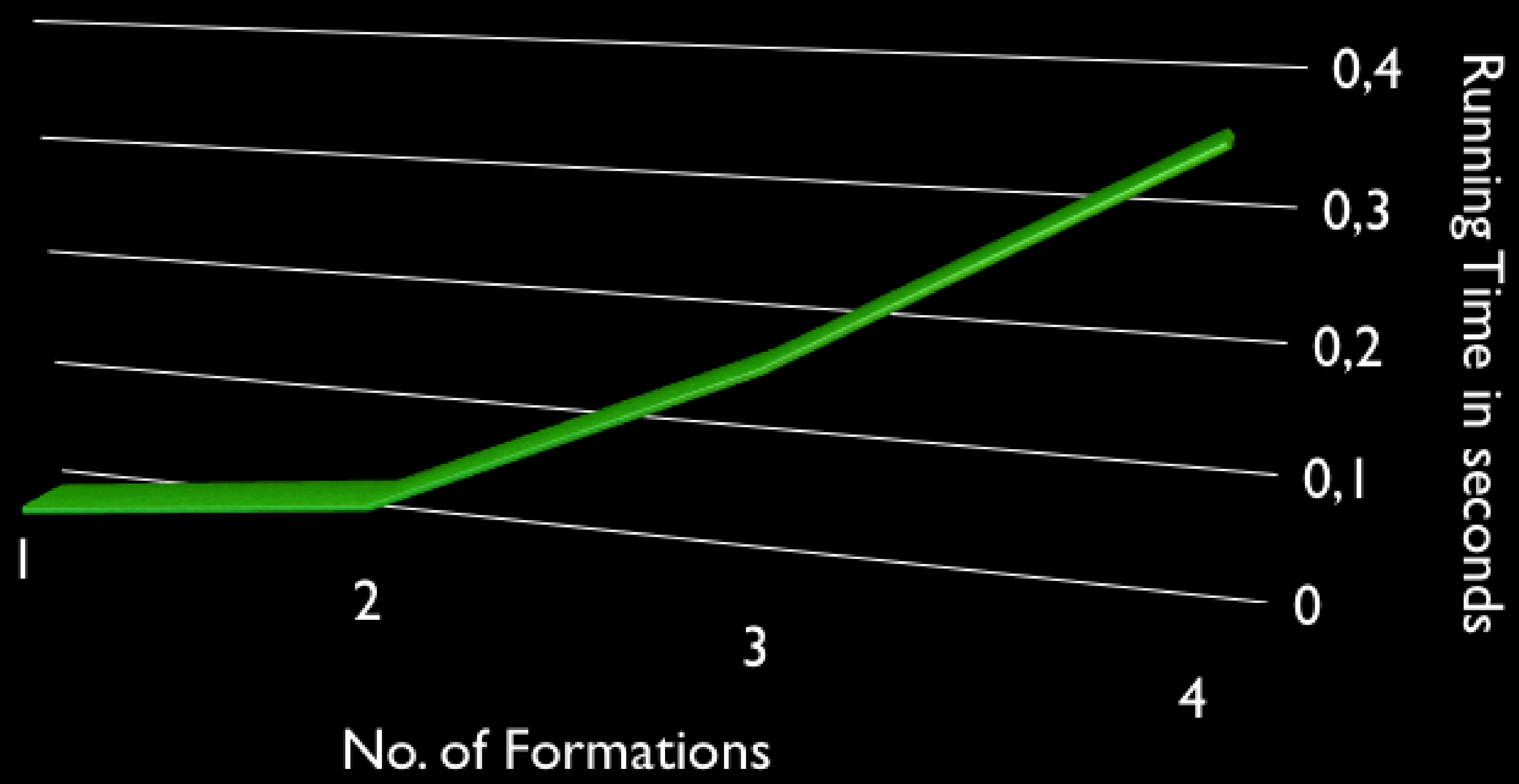
- Clément Pêtrès etc., *"Path Planning for Autonomous Underwater Vehicles,"* IEEE Transactions on Robotics, 23(2), 2007.
- Smooth the cost function ➜ Increase the lower bound of the curvature radius of an optimal path.
- Large grid: 1000 x 1000

foreach *simulation cycle* **do**
  foreach *formation* R_i **do**
    Construct f_i, g_i, and C_i;
    Compute ϕ_i and $\nabla\phi_i$ using the FMM;
    Construct waypoints for R_i;
    Update positions of R_i's agents using social potential fields;
    if ($\phi_i({}^{w}\mathbf{x}_i^0(t))$ *is very high* ***or*** *a command is given by the user*) **then**
      Deform R_i;
    end
  end
end

Motion Planning of Multiple Formations:

Apply the continuum model to formations. High potential ➜ Try a list of different deformations (pre-computed or compute in real-time).

Average Running Time of ONE Simulation Cycle (sec)



Minkowski sum computations between the formations is done naively (i.e., a formation, when planning its next move, takes all other formations into account).

Agenda

- Introduction
- Related work
- More on the Continuum Model
- Motion Planning of Multiple Formations
- Conclusion & Future Work

Conclusion and Future Work

Conclusion

- Proposed **flexible virtual structure** approach to model formations.
- Proposed a real-time motion planner for **multiple tightly controlled formations**.
- The motion planning algorithm for multiple formations is the first one that does not use ad-hoc and local approaches and hence **agents in a formation does not split easily from the formation**.

Future Work

- Plan motions of more formations in real-time.
- When planning for one formation, the agents may run into local minima (even though potentials generated by the FMM are free of local minima analytically).
- Partition the environments into unstructured meshes.
- Tune the three weights in the unit cost field automatically.

IVA

KUNGL. INGENJÖRSVETENSKAPSAKADEMIEN

Royal Swedish Academy of Engineering Sciences

A special thank you to *Dr. Kevin T. Chu* at Princeton University, *Prof. Shigeru Kuriyama* at Toyohashi University of Technology (TUT), and *Royal Swedish Academy of Engineering Sciences (IVA)*.