Modeling and Simulation of Digital Humans:
From Individuals to Crowds

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Digital Humans

ViCrow

]

Virtual Iraq [ICT/USC 06]

Disaster Response [ICT/USC]

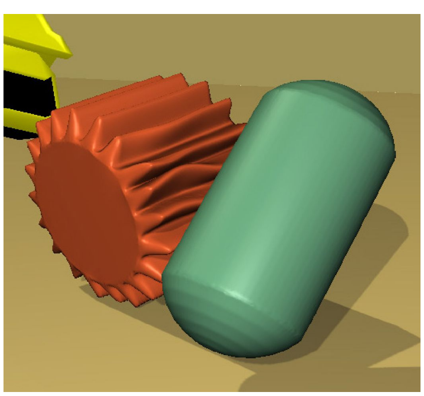
Applications

(a) Games (b) Crowds (c) Movie

(d) Robot (e) CAD/Human factor (f) ergonomics

Motivation

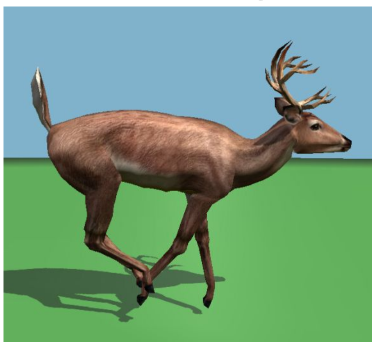
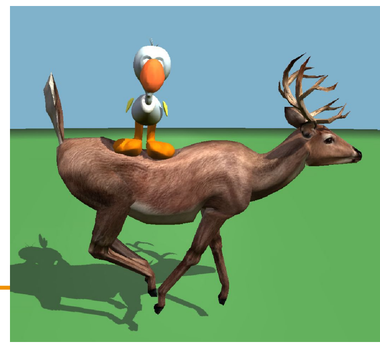
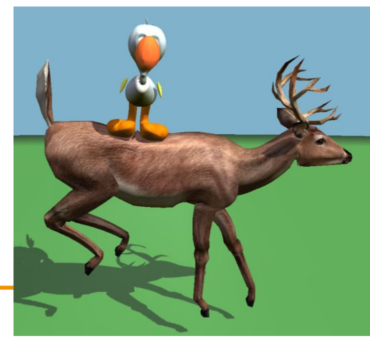
- Dynamic simulation of deformable solids
- Highly detailed surface geometry
- Large contact area: objects bounce, roll, slide,…



[Galoppo et al; Eurographics 2007]

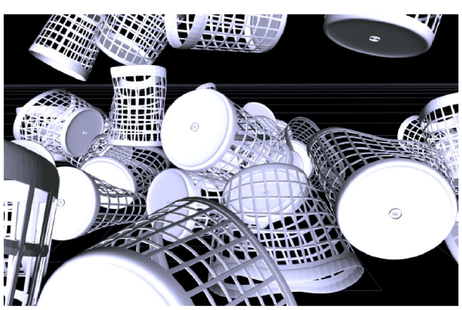
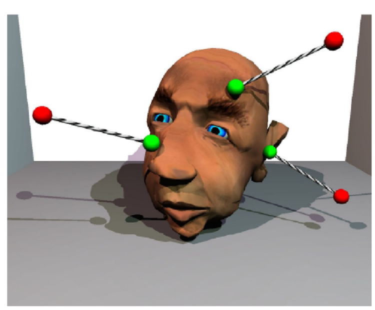
Motivation: Layered Models

- Detailed, small-scale deformations
- Global (skeletal) deformations
- Dynamic interplay between skeletal motion and surface deformation during contact

Modeling Soft Articulated Bodies in Contact Using Dynamic Deformation Textures

Global deformations ⟷ Detailed deformations

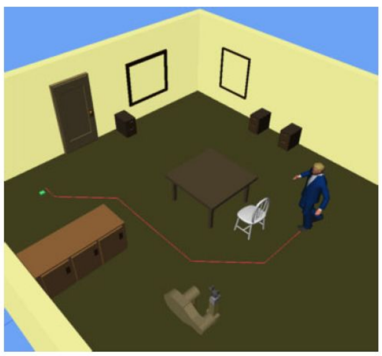




[Galoppo et al; SCA 2006]

Motivation

- Human-like characters are widely used in computer animation and virtual environments
- Synthesize natural-looking human motion
  - Key-frame animation methods are tedious and need considerable input from the animators
  - Current automated tools are open limited to simple or open environments

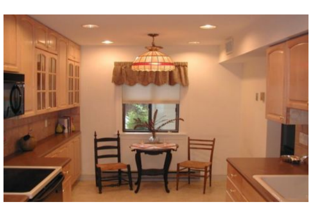
Open environment



Constrained environment

Motivation: Goal-Oriented

Automated tools for natural human generation in constrained environments



Natural Human Motion

Constrained Environments

Crowd Simulation

- Simulating movement of a large number of agents to replicate collective behavior

Agents in Games

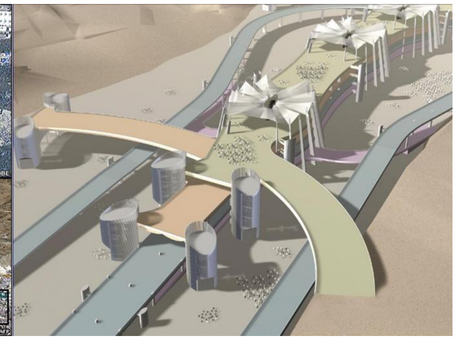
Interactive simulation of virtual agents

Assas

Spore

Planning & Architectural design

- Stampedes at Hajj
- Improvements to the Jamarat Bridge

Large, Dense Crowds

- Commonplace occurrences
- Greater safety risks
  - Crowd panic


(Top) Iraq war protest: Broadway
(Bottom) Presidential swearing in
©MSNBC

Challenges

- Realistic human locomotion behaviors
- Simulating very *large, dense* crowd
- *Control* and *direct* crowd flows
- Modeling the interaction with and due to *traffic* flows & vehicles

Outline: Crowd Simulations

- "Principle of Least Efforts" Navigation
- Modeling of Dense Crowd
- Control and Direction Crowds

Outline: Crowd Simulations

- **"Principle of Least Efforts" Navigation**
- Modeling of Dense Crowd
- Control and Direction Crowds

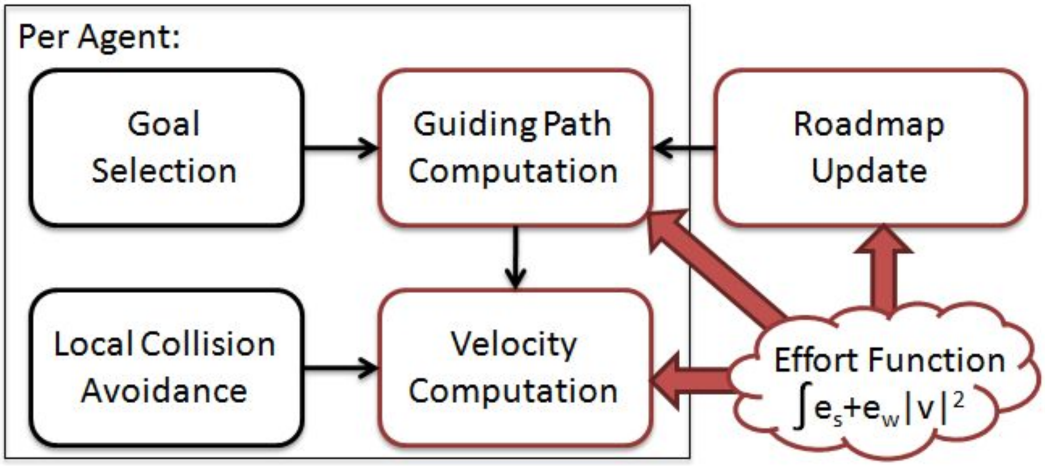
Principle of Least Efforts

- Our hypothesis: Effort = Biomechanical Energy
- Imperially measured as function of speed [Whittle, 2007]
  - $E = m\int(e_s + e_w|v|^2)dt$
    - e_s – energy when still
    - e_w – energy at speed

which we seek to minimize

Algorithm Overview

1. Determine goal position
2. Find permissible (non-colliding) velocities (PV)
3. Choose velocity ∈ PV with minimum energy



Optimal Reciprocal Collision Avoidance (ORCA) [ISRR2009]

- A new algorithm for collision avoidance
- A linear programming based formulation
- Scalable approach to collision avoidance
  - From two agents to thousands of agents
- Extends Velocity Obstacle concepts
  - *Decentralized* planning
  - Decisions are made *independently*, with no communication nor assumptions of the motion
  - *Sufficient* conditions for avoiding collisions

Problem Overview

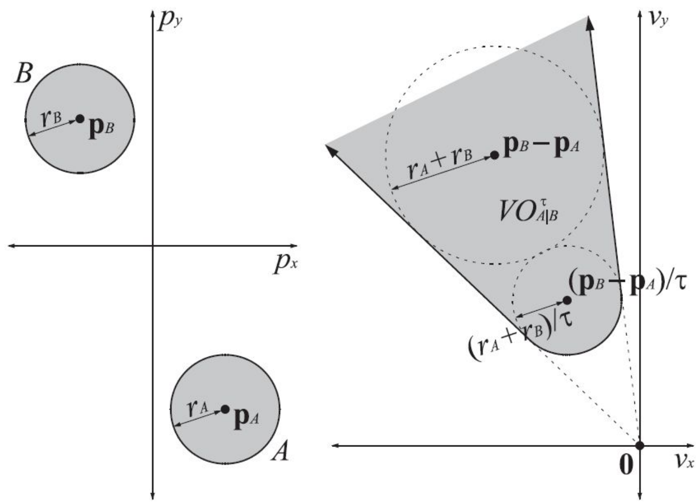
- Inputs:
  - Independent Agents
  - Current Velocity of all
  - Own Desired Velocity (V^{pref})
- Outputs:
  - New n-way collision-free velocity (V^{out})
- Description – Each Agent:
  - Determines permitted (collision free) velocities
  - Chooses velocity closest to V^{pref} which is permitted

Velocity Space & Forbidden Regions

- Forbidden Regions
  - Potentially Colliding Velocities
  - An "obstacle" in velocity space
- VO: Velocity Obstacle [Fiorini & Shillier 98]
  - Assumes other agent is unresponsive
  - Appropriate for static & unresponsive obstacles
- RVO: Reciprocal VO [Berg et al., 08]
  - Assumes other agent is mutually cooperating

Time Horizon

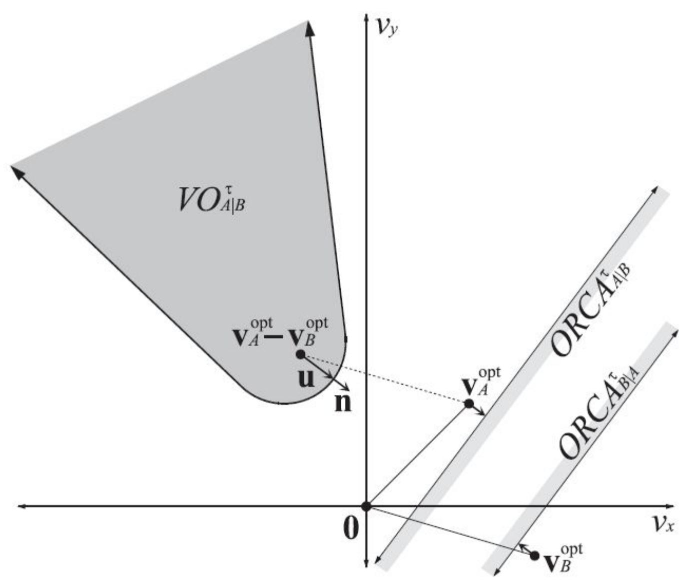
- Ignore collisions more than τ seconds away
- Diagram of τ adjusted VO – $VO^{\tau}_{A|B}$



(a) (b)

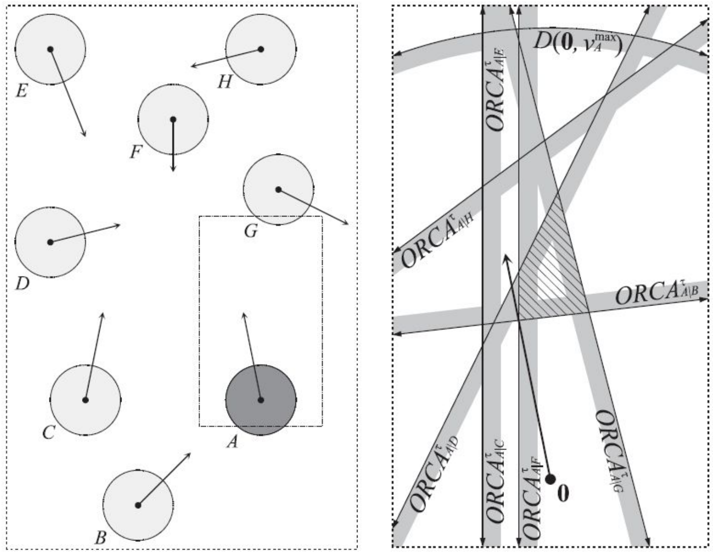
ORCA

- u – Vector which escapes $VO^{\tau}_{A|B}$
  - Each robot is responsible for ½u
- $ORCA^{\tau}_{A|B}$
  - The set of Velocities allow to A
  - Sufficient condition for collision avoidance if B chooses from $ORCA^{\tau}_{A|B}$



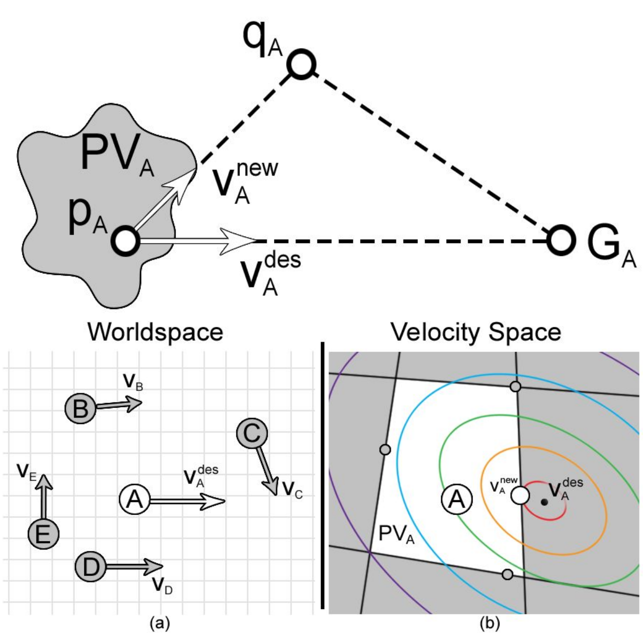
Multi-Robot Navigation

- Choose a velocity inside ALL pair-wise ORCAs
- Efficient O(n) implementation w/ Linear Programming



Estimating Least Effort

- Evaluate potential paths based on least effort
- Approximate total effort in a greedy piecewise fashion
- Compute optimum in velocity space using linear programming



Results: Evaluation & Comparison

Video Demonstration

[Guy et al; SCA 2010]

Summary

- Powerful and simple (easy to implement) navigation method for multi-agent simulations
- Allows for easy integration with global planning, kinodynamic constraints, visibility constraints, etc.
- *Scalable with number of agents and number of cores used*
- Application to Behavior Modeling & Crowd Simulation

Outline: Crowd Simulations

- "Principle of Least Efforts" navigation
- **Modeling of Dense Crowd**
- Control and Direction Crowds

Dense Crowds

(Top): Obama campaign rally © The Telegraph
(Bottom): Subway Station, Beijing © ABC

(Top): Al-Masjid Al-Haram, Mecca © SacredSites
(Bottom): Carnivale, Milan © Dan, Picasa

Challenges

- Human behavior is complex
  - Avoid other people
- Complex emergent behavior

©Ellen Isaacs, World of Stock

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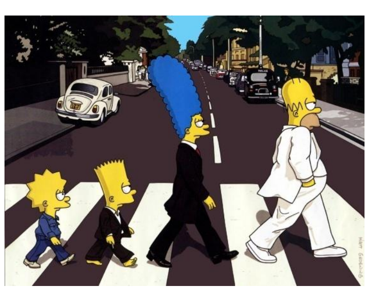
Challenges

- Parameters
  - Scene complexity
  - Crowd distribution
- Density dependent behaviors

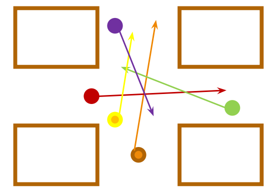
http://bobscrafts.com/bobstuff/maze.htm



Shibuya crossing © NextStop

Large, Dense Crowds

- Per-agent Local navigation expensive
  - Large number of possible collisions
  - Continuous collisions



- Becomes computational bottleneck
- Infeasible to simulate large crowds

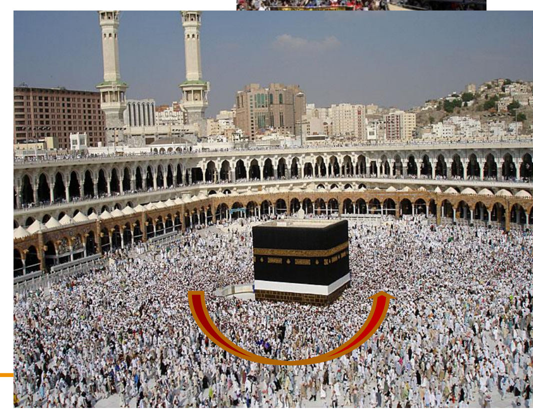
Density-dependent Behavior

- Low density
  - Similar to gases
- Medium density
  - Fluid flow
- High density
  - Granular flow

[Sud et al. 2007]

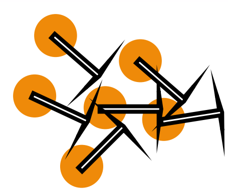
Intuition

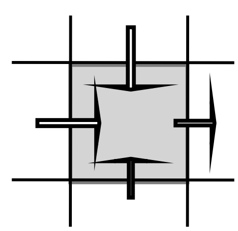
- Crowd behaves as an aggregate at medium-high densities
- Reduced individual freedom of movement



Key Ideas

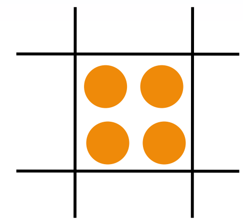
- Model crowd as hybrid of
  - Discrete agents
  - Continuum based crowd
- Collision avoidance ↔ Minimum separation





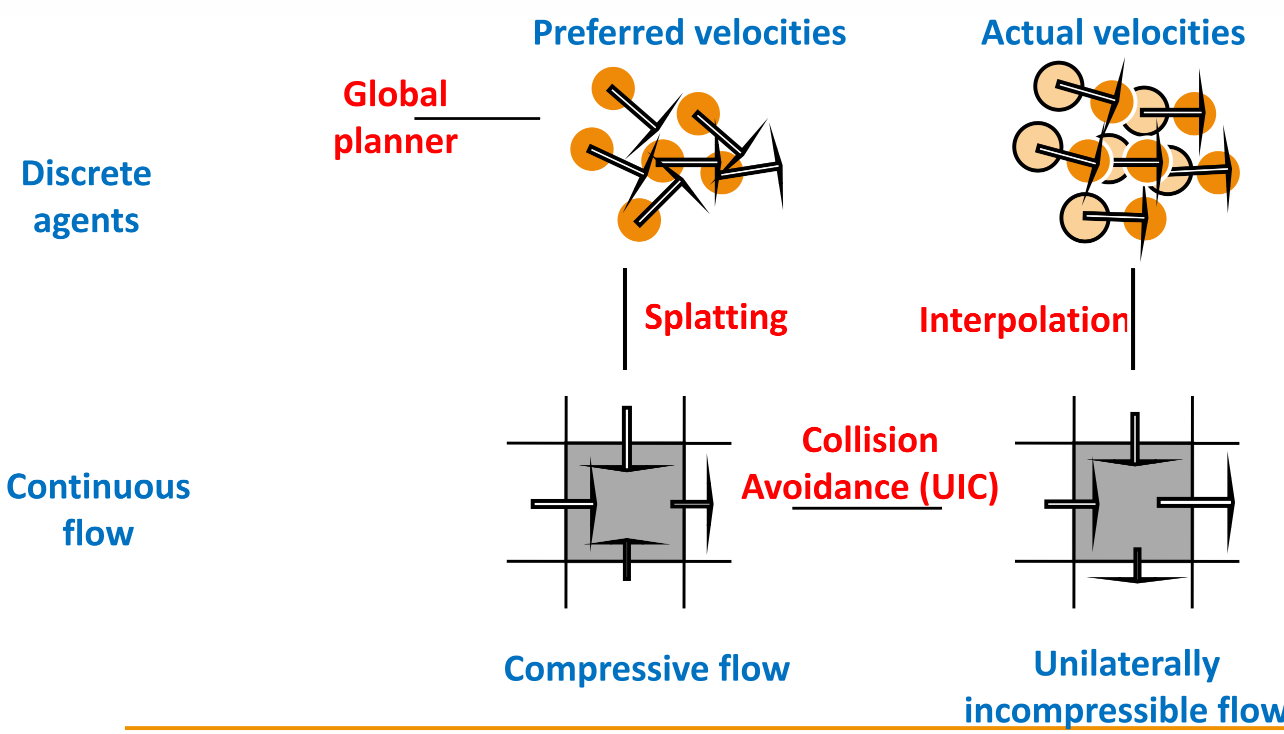
Key Ideas (2)

- Minimum separation
- Density must be below a maximum
- Inequality constraint on density
- Unilateral Incompressibility Constraint (UIC)



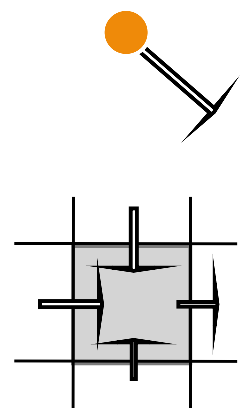
[Narain et al; SIGGRAPH Asia 2009]

System Overview



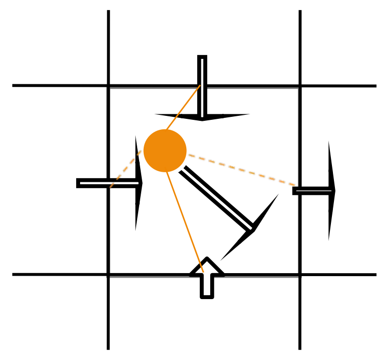
System Overview

- System
  - Agents *i*
    - **Mass (m_i)**
    - **Velocity (v_i)**
  - Crowd continuum
    - **Density (ρ)**
    - **Velocity(*v*)**
- UIC: $\rho < \rho_{\max}$



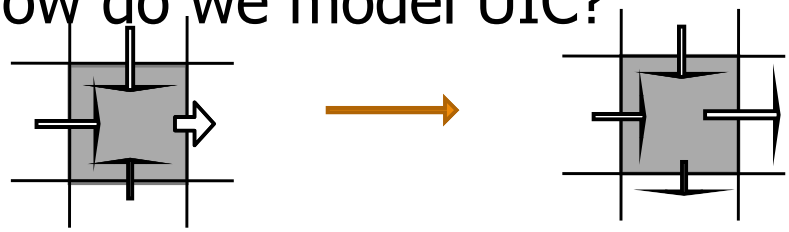
Building Crowd Continuum

- Accumulate
  - Agent velocity
  - Agent mass
- Bilinear interpolation weights



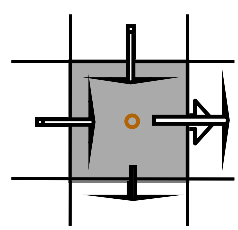
Collision Avoidance (UIC)

- How do we model UIC?



- If density is high
  - Apply some force to prevent agents from coming closer
- Else, leave cell as it is
- Solve this constraint as LCP

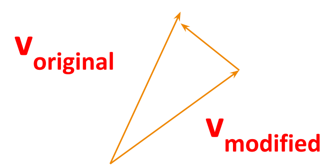
Collision Avoidance (UIC)



- What should this force be?
  - Isotropic
- Any analogues?
  - Pressure (fluids)
- Pressure force only acts when density is high

Collision Avoidance (UIC)

- Pressure modifies velocities
- What is the pressure force, and thus the new velocity field?
- Modified velocity should make maximum possible progress to goal
  - Maximize $\int \rho v_{original} \cdot v_{modified}$



Collision Avoidance (UIC)

- Move with maximum speed possible in the direction of modified velocity

$$v^{n+1} = v_{\max} \frac{v^n - \nabla p}{\left\| v^n - \nabla p \right\|}$$

$$\rho < \rho_{\max} \Rightarrow p = 0$$

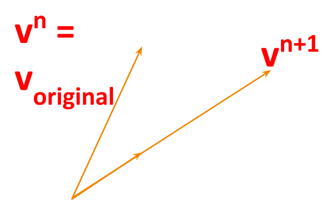
$$p > 0 \Rightarrow \nabla \cdot v = 0$$

Steady state
Conservation of
Modified velocity mass

- This is a non-linear formulation
- Approximate iterative solution?

Collision Avoidance (UIC)

- Split into 2 parts
  - Pressure solve $psolve(v^n) = v^n - \nabla p$
  - Velocity renormalization $renorm(\hat{v}) = v_{\max} \frac{\hat{v}}{\|\hat{v}\|}$
- Iteratively solve using these 2 primitives $v^{n+1} = psolve(renorm(psolve(v^n)))$
- In practice we use:



- How to do the pressure solve?

$$\frac{\hat{v}}{\|\hat{v}\|}$$

Collision avoidance (UIC)

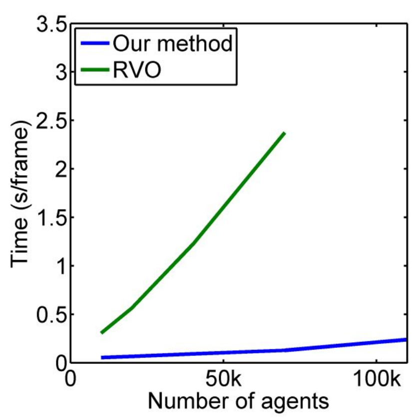
- Discretize conservation of mass equation with
  - Density
  - Modified velocity
- Linear Complimentarity problem
- Efficient solvers exist

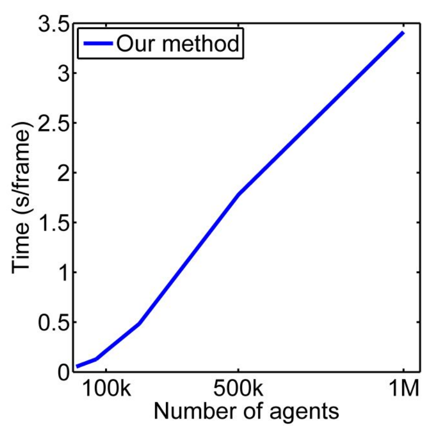
Collision Avoidance

- Getting collision-free velocities for each agent
  - Interpolate between agent velocity and grid velocity
- There may be some collisions still
  - Push apart intersecting agents
  - Sufficient: only 0.12% agents approach closer than minimum separation

Advantages

- Gross collision avoidance independent of number of agents
- Makes large dense crowds feasible





System Demonstration

Outline: Crowd Simulations

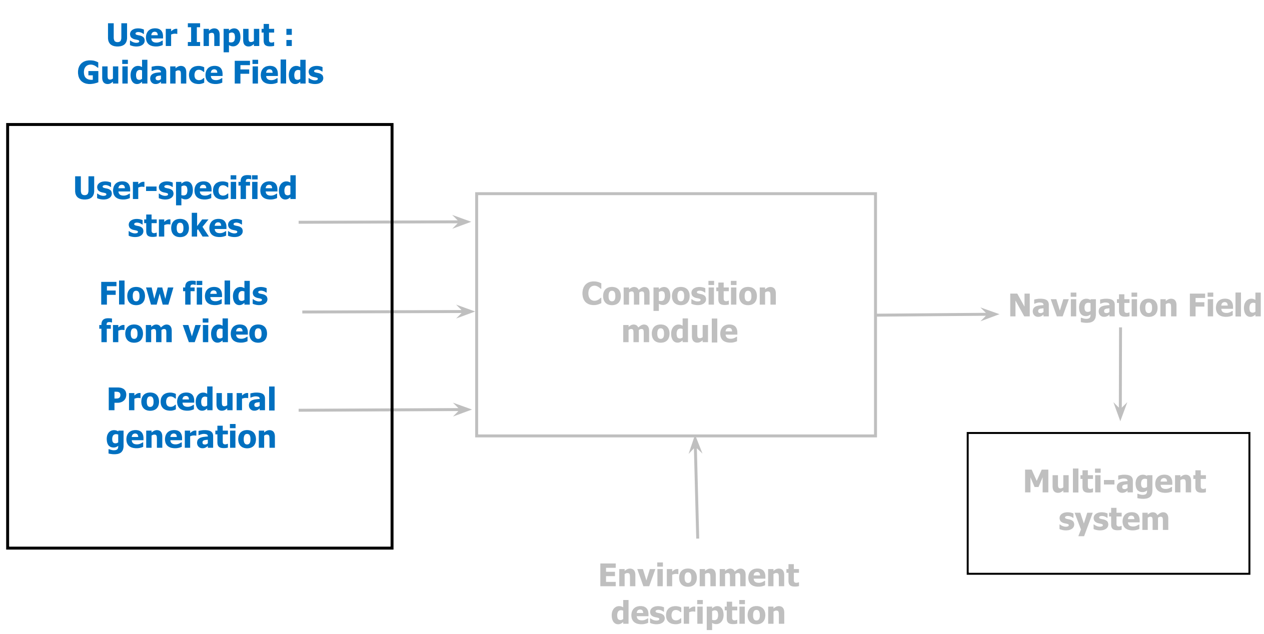
- "Principle of Least Efforts" navigation
- Modeling of Dense Crowd
- **Control and Direction Crowds**

Approach

- Our method allows the user to 'direct' the flow of agents in an ongoing simulation
- Salient features:
  - Interactive scheme to direct virtual crowds
  - Novel formulation for compositing arbitrary user input into navigation fields
  - Importing data from real video

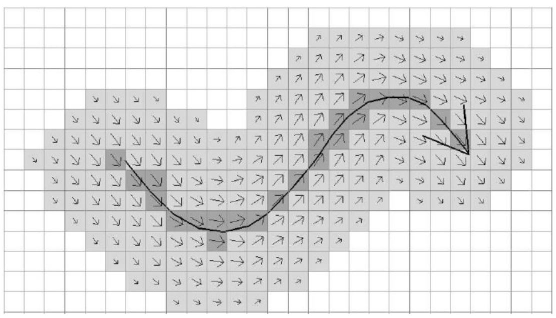
[Patil et al; TVCG 2010]

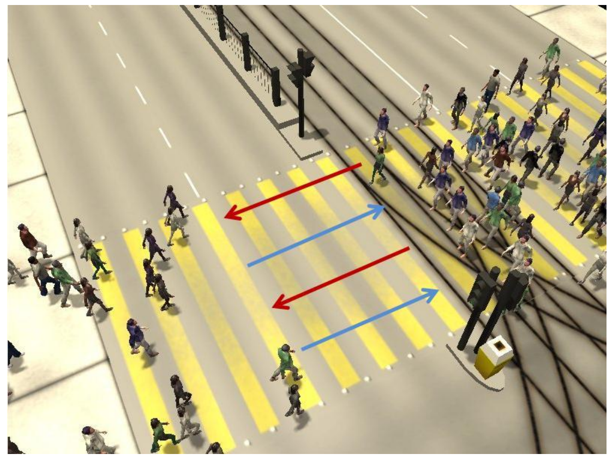
Framework



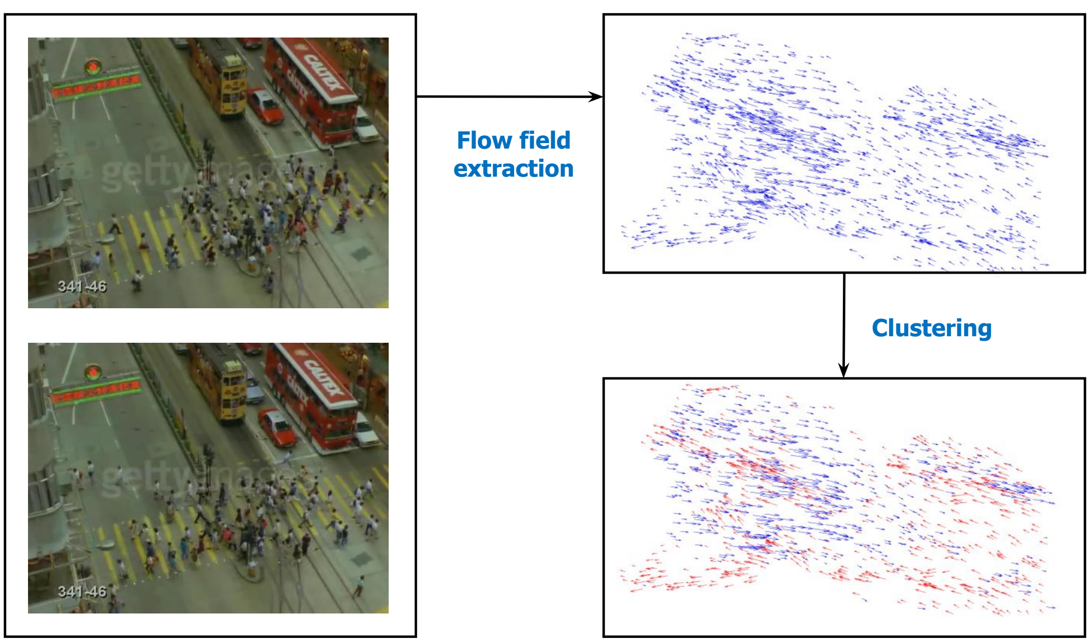
Specifying User Input

- Stroke based interface



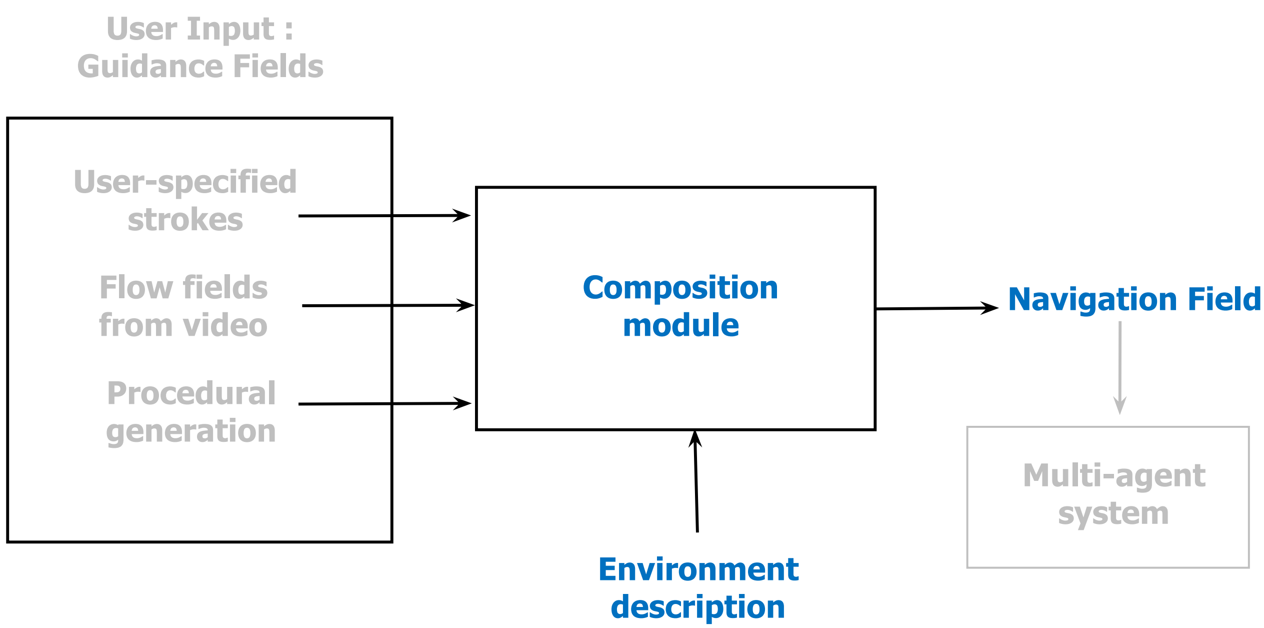


Importing Guidance Fields From Video



Individual Guidance Fields

Framework

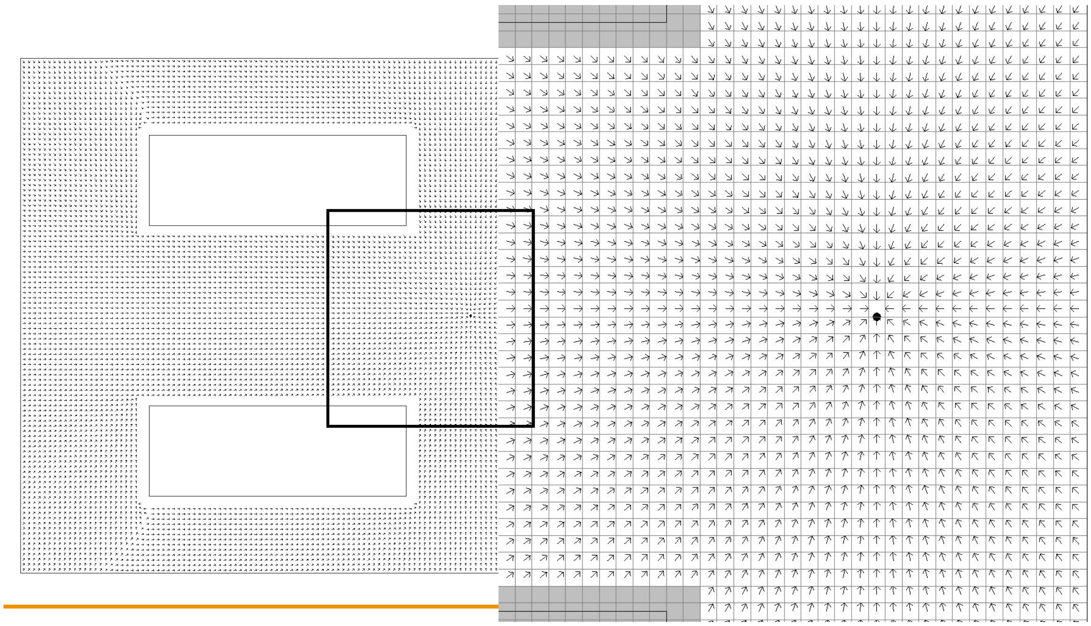


Navigation Fields

- Key Features
  - Goal-directed
  - Encodes paths of least effort (minimum cost)
  - Singularity-free (except for minima at goal positions)

Navigation Fields

- Store gradient at each grid-cell



Analysis

- Computes discrete approximation of following static Hamilton-Bellman-Jacobi PDE:

$$\max_{\mathbf{a}\in S^1}\{(-\nabla T(X)\cdot\mathbf{a})s(X,\mathbf{a})\}=1$$

  - Necessary and sufficient condition for cost-optimal paths under an *anisotropic* speed function

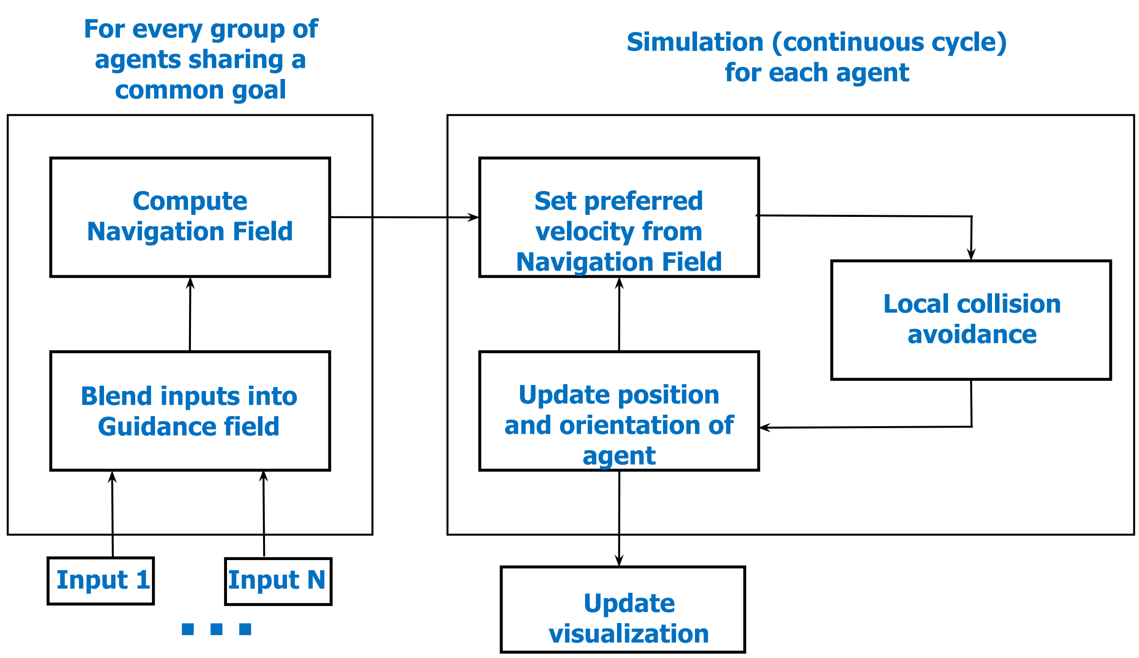
Performance

Scene	#Agents	Grid Dimension (m x n)	NF compute time* (ms)	Local Collision Avoidance	Average sim time* (ms/frame)
4 Blocks	100	100 x 100	5.0	RVO	2.0
Crossing	640	100 x 100	5.0	Helbing	1.1
Crosswalk	145	225 x 100	13.0	Helbing	0.4
Subway	435	200 x 200	22.0	RVO	5.5

- Complexity: O(m·n log (m·n))

* All times measured on single Intel Xeon 2.66 GHz processor

Overall System



System Demonstration

- *Directing Crowds*
- *Animating Crowds in Blender*

Reconstructing Traffic

- Virtualized Traffic
  [van den Berg et al. VR2009; TVCG2010]
- Continuum Traffic Simulation
  [Sewall et al. Eurographics 2010; CGF2010]

Summary

- Modeling & simulation of digital humans present many new computational challenges
- New techniques for motion synthesis for virtual humans from individuals to crowds
  - Layer Representation for accelerated collision detection & Dynamics
  - Motion Planning with high degrees of freedom and constraints
  - Multi-Agent Planning and Collision Avoidance
- Map well to new Moore's Law

Future Research Challenges

- Investigate issues associated with adaptive algorithms that use hierarchical structures (e.g. multigrids, pedestrian level of detail, etc.)
- Hybrid models (physics+AI, data-driven+physcis, etc.)
- Incorporation of behaviors and variety
- Integration of locomotion and foot-step planning
- Integrated crowd & traffic simulations in virtual cities
- Parallel algorithms for solving real-world problems (e.g. emergency response, entertainment, shopping, e-commerce, travel)