Self-organized Control of Manned and Unmanned Vehicles in Space Colonies

Péter Molnár
Kameswara R. Namaduri
Lance M. Kaplan

Center for Theoretical Studies of Physical Systems
Clark Atlanta University

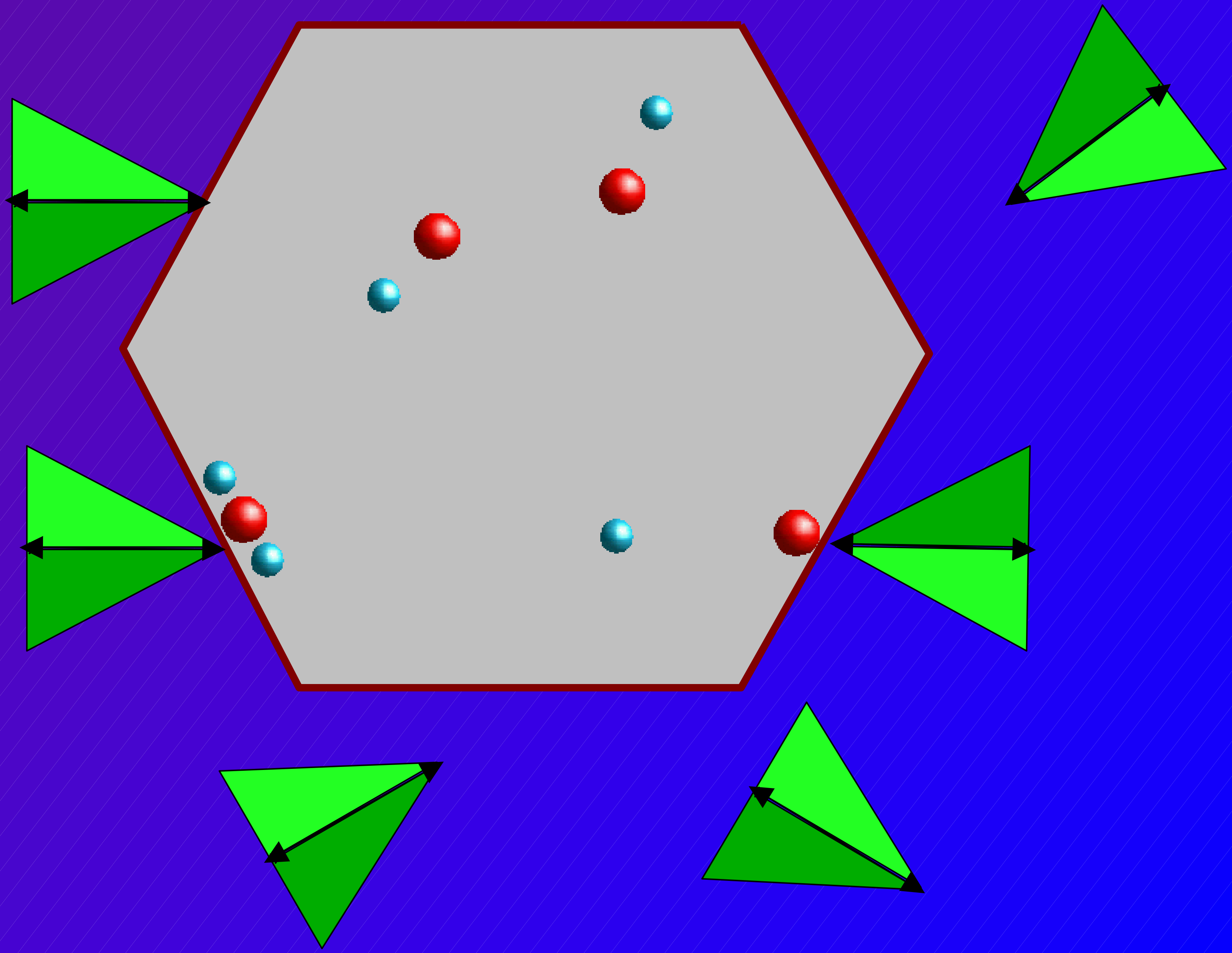
Outline

- Motivation
- Concept of distributed assignment problem solver
- Implementation and application
- Status & Goals

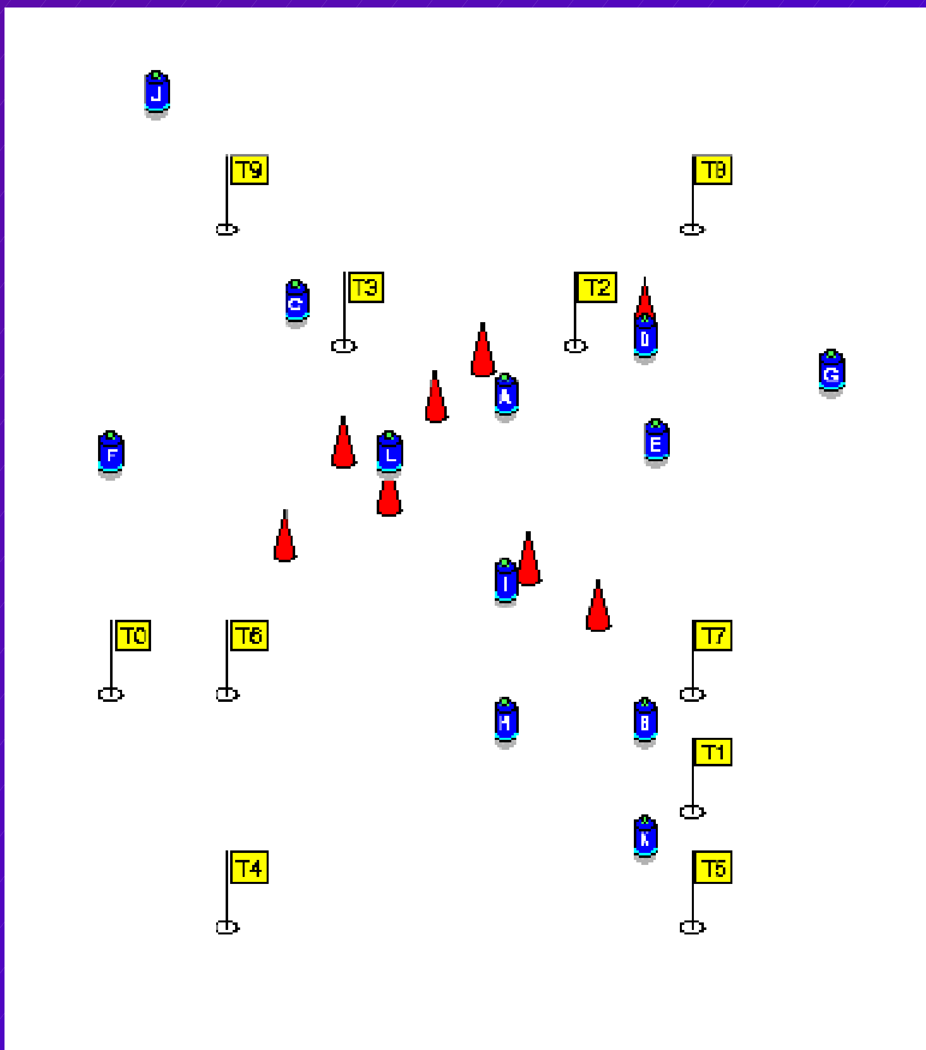
Motivation

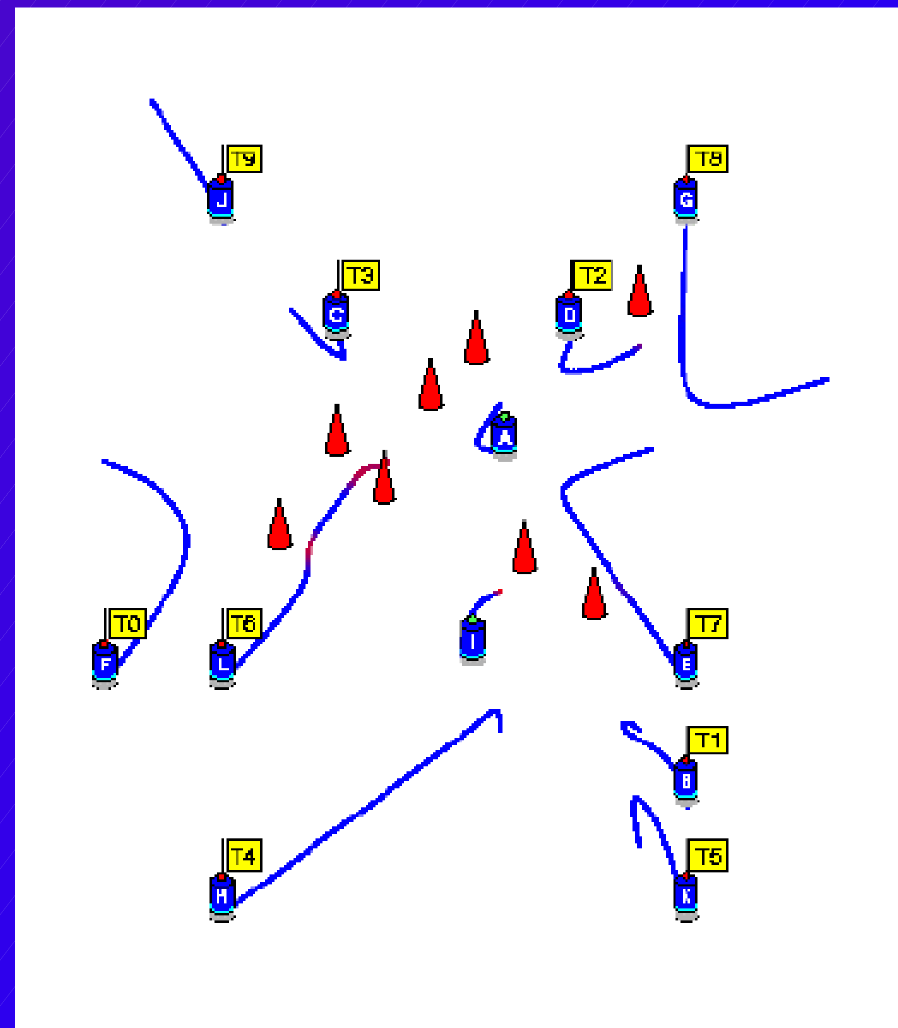
- Space Colonies will host a multitude of mobile entities vehicles
  - space ships: usually manned
  - service vehicles: pickup cargo and passengers, transport fuel and other supplies
  - maintenance and repair robots, etc.
- Navigation challenges
  - collision avoidance (basic navigation)
  - path planning: short travel distances, avoid congestion
- Assignment and scheduling problems: gate assignment, dispatcher for service robots.

Space Port



2D Assignment Problem



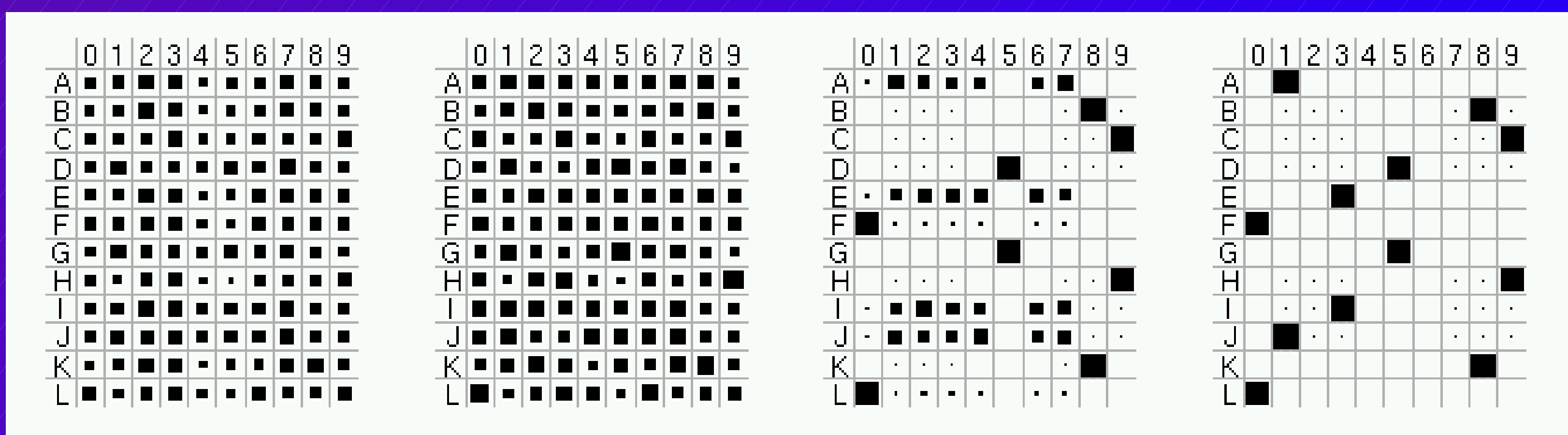


New Concept

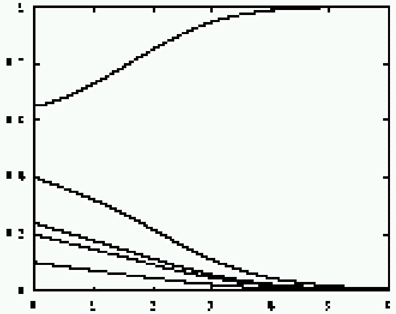
- Central Control
  - vehicles dispatched to individual destinations,
  - rigid schedule,
  - dependency on control center.
- Self-organization
  - vehicles select destinations,
  - schedule emerges,
  - adaptable to changes & use of spare vehicles,
  - inc. complexity and number of vehicles.

Distributed Assignment Problem Solver

- Robots create initial preferences (priority list), preferences will be exchanged via wireless communication.
- Robots update their preference based on the received information of other units.
- In the time limit the system always converges to a feasible solution.



Coupled Selection Equations



$$\dot{\xi}_{ij} = \kappa \xi_{ij} \left(1 - \xi_{ij}^2 - \beta \sum_{i' \neq i} \xi_{i'j}^2 - \beta \sum_{j' \neq j} \xi_{ij'}^2 \right)$$

- time scaling factor κ
- $\beta > 1/2 \Rightarrow (\xi_{ij}) \in \mathbb{R}^{n \times n}$ will always asymptotically end in a stable solution of permutation matrices (Starke 1997)
- surplus of robotic units $\Rightarrow$ there is not more than one target as destination for each of the robots
- performance of coupled selection equations for assignment problems in combinatorial optimization compares very well to other algorithms (Starke and Schanz 1998)
- proximity to targets used for the initial values $\xi_{ij}(0) = 1 - \frac{\|\mathbf{r}_i(0) - \mathbf{g}_j\|}{\max\limits_{i',j'} \left(\|\mathbf{r}_{i'}(0) - \mathbf{g}_{j'}\| \right)}$

Equation of Motion for the Robotic Units

$$\frac{d}{dt}\mathbf{v}_i(t) = \frac{1}{\tau}\left(v_i^0\mathbf{e}_i^0(t) - \mathbf{v}_i(t)\right) + \sum_{i'\neq i}\mathbf{f}_{ii'}^{\mathrm{r}}(\mathbf{r}_{i'} - \mathbf{r}_i) + \sum_k \mathbf{f}_{ik}^{\mathrm{o}}(\mathbf{x}_k - \mathbf{r}_i)$$

- $\mathbf{e}_i^0 = \mathbf{\Phi}_{\gamma\delta}\left(\sum_j \xi_{ij}\mathbf{\Phi}_{\gamma'\delta'}\left(\mathbf{g}_j - \mathbf{r}_i\right)\right)$ destination vector
- $\mathbf{\Phi}_{\gamma\delta}(\mathbf{x}) = \frac{1}{\|\mathbf{x}\|+1/(\gamma\|\mathbf{x}\|+\delta)} \cdot \mathbf{x}$ with $\gamma, \delta > 0$ normalization without singularity
- $v^0 \in \mathbb{R}$ is the normal operating speed of the robots
- force fields to avoid collisions:
  $$\mathbf{f}_{ii'}^{\mathrm{r,o}}(\mathbf{r}) = \begin{cases} -\left(\tan g(\tilde{r}) - g(\tilde{r})\right)\frac{\mathbf{r}}{\|\mathbf{r}\|} & \text{for} \quad 0 < \tilde{r} \leq \sigma^{\mathrm{r,o}} \\ 0 & \text{for} \quad \tilde{r} > \sigma^{\mathrm{r,o}} \end{cases}$$
  with $\tilde{r} = \|\mathbf{r}\| - d_i^{\mathrm{r}}/2 - d_{i'}^{\mathrm{r,o}}/2, \quad g(\tilde{r}) = \frac{\pi}{2}\left(\frac{\tilde{r}}{\sigma^{\mathrm{r,o}}} - 1\right)$
- to avoid the stagnancy near stationary points, small fluctuations are added to the eq. of motion

Features

- CSE's can solve NP-hard problems: multi-dimensional assignments.
- Distributed algorithm, system can be partitioned.
- Resistant to malfunctions of single units, ability to cover up with spare units.
- Insensitive to communication problems.

Implementation

- Vehicles require positioning system and wireless communication.
- Unmanned vehicles need navigation system, that ties in the assignment problem solver.
- Pilots receive instruction, similar to messages from a control tower.
- Development: Integrated device & communication protocol/language.

Applications

- Construction of space colonies.
- Operation: space port.
- Maintenance & first alert response.
- Use of versatile self-configurable and combinatorial robots.

Goals & Status

- Develop simulation program. ½ ✓
- Identify scenario(s) & design simulation(s).
- Test system for various conditions:
  - failure resistance (vehicles and communication)
  - performance w/ respect to complexity
  - number of vehicles