A Methodology for Deploying the Max-Sum Algorithm and a Case Study on Unmanned Aerial Vehicles

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This talk is about deploying Max-Sum on a coordination system for disaster response

I. Motivation
   a. Situation Awareness for Disaster Response
   b. Unmanned Vehicles
   c. Decentralised Coordination using Max-Sum

II. Methodology + Case Study

III. Experiments
   a. Coordinated Behaviours
   b. Real Tests

IV. Conclusions and Future Work
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First Responders (FRs) at the scene of a disaster require accurate Situational Awareness.
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Situation Awareness [Endsley 2000]: The ability to make sense, and predict what is happening within an environment.
This information is necessary to prioritise intervention
Such information is necessary to prioritise intervention

More information will allow the first responders to discover (and save) more casualties
In our system, FRs request imagery using Personal Digital Assistants (PDAs)
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Unmanned Vehicles (UVs) can acquire accurate information. UVs can collect and process more information than humans.
Unmanned Vehicles (UVs) can acquire accurate information

UVs can reach places dangerous to humans
In our system, imagery is provided by a team of Unmanned Aerial Vehicles (UAVs)
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Within this setting, coordination is necessary to improve the performance.

By coordinating, the UAVs can explore more areas.
Within this setting, coordination is necessary to improve the performance. By coordinating, the UAVs can also decide to join forces in exploring a vast area.
In our system, the UAVs coordinate to attend the imagery tasks
This coordination should happen in a decentralised fashion
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This coordination should happen in a decentralised fashion.

A Decentralised System improves Scalability.
This coordination should happen in a decentralised fashion

A Decentralised System improves Robustness
This coordination should happen in a decentralised fashion.

A Decentralised System improves Robustness
No central point of failure
Hence, we study decentralised coordination algorithms:

- Negotiation Algorithms
  - Best Response (BR)
  - Market Based Allocation (MBA)
  - Auctions Techniques (AT)

![Graph showing the trade-off between Communication Cost and Optimality with Negotiation Algorithms as a central category.](image-url)
Multi-Agent System research focused on creating new methods

Iterative Algorithms
Distributed Stochastic Algorithm (DSA)
Maximum Gain Messaging (MGM)

Complete Algorithms
DPOP
OptAPO
ADOPT

Optimality

Communication Cost
Max-Sum appears as a good compromise between feasibility and solution’s quality.
Max-Sum has been applied to multiple Situational Awareness problems

- Monitoring Spatial Phenomena [Stranders, IJCAI’09]
- Patrolling / Pursuit Evasion [Stranders and Delle Fave, AAAI’ 10]
- Target Search [Delle Fave, AAMAS’ 10]
- Dynamic Task Assignment for UAVs [Delle Fave ICRA’ 12]
- Target Tracking [Rogers, AAMAS’ 08]
Max-Sum has been applied to multiple Situational Awareness problems

- Monitoring Spatial Phenomena [Stranders, IJCAI’09]
- Patrolling / Pursuit Evasion [Stranders and Delle Fave, AAAI’10]

However:
All this work has been tested only in simulation

- Target Search [Delle Fave, AAMAS’10]
- Dynamic Task Assignment for UAVs [Delle Fave ICRA’12]
- Target Tracking [Rogers, AAMAS’08]
Max-Sum has been applied to multiple Situational Awareness problems

• Monitoring Spatial Phenomena [Stranders, IJCAI’09]
• Patrolling / Pursuit Evasion [Stranders and Delle Fave, AAAI’10]

Moreover:
There exists no systematic methodology to apply max-sum to all these different problems.

• Dynamic Task Assignment for UAVs [Delle Fave ICRA’12]
• Target Tracking [Rogers, AAMAS’08]
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Max-Sum runs over a Factor Graph, a bipartite graph:

A factor graph contains two types of nodes: Variables and Function nodes.
2 types of messages are passed between the nodes

\[ Q_{n \rightarrow m}(x_n) = \sum_{m' \in M(n) \setminus m} R_{m' \rightarrow n}(x_n) \]
2 types of messages are passed between the nodes

\[ R_{m \rightarrow n}(x_n) = \max_{x_m \setminus n} \left( U_m(x_m) + \sum_{n' \in N(m) \setminus n} Q_{n' \rightarrow m}(x_{n'}) \right) \]
To deploy max-sum we propose a 5 steps methodology

STEP 1 / 2: **WHAT** are the nodes?

STEP 3: **WHO** controls the nodes?

STEP 4: **WHEN** are messages computed?

STEP 5: **HOW** do nodes know their neighbours?
STEP 1 / 2: WHAT are the nodes?

\[ U_a(X_a) \quad \text{and} \quad U_b(X_b) \]
STEP 1 / 2: **WHAT** are the nodes?

Tasks

- $x_1$
- $x_2$

Utilities of Tasks

$U_a(X_a)$

$U_b(X_b)$
STEP 3: **WHO** controls the nodes?

\[ U_a(X_a) \quad , \quad U_b(X_b) \]
STEP 3: WHO controls the nodes?

\[ U_a(X_a) \quad \text{UAVs} \quad x_1 \quad x_2 \quad U_b(X_b) \]
STEP 3: WHO controls the nodes?

UAVs

\[ U_a(X_a) \]

PDAs

\[ U_b(X_b) \]
STEP 4: **WHEN** are messages computed?
STEP 4: **WHEN** are messages computed?

Synchronised

WAIT
STEP 4: WHEN are messages computed?

Synchronised: WAIT

Reactive: When receive msg
STEP 4: WHEN are messages computed?

Synchronised

Periodical

Reactive

WAIT

Every T seconds

When receive msg
STEP 5: **HOW** do nodes know their neighbours?

\[ U_a(X_a) \]

\[ x_1 \quad x_2 \]
STEP 5: HOW do nodes know their neighbours?

UAVs broadcast their position

\[ U_a(X_a) \]
STEP 5: HOW do nodes know their neighbours?

Tasks broadcast their properties

$U_a(X_a) \quad U_b(X_b)$
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The task utility weights the problem’s constraints to improve the allocation

$$U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot \left[ 1 - e^{-\lambda_j \cdot (t_2 - t_1)} \right]$$
The Priority represents a task’s importance

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j \cdot (t_2 - t_1)}] \]
The Urgency prevents the tasks starvation

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j \cdot (t_2 - t_1)}] \]
The duration models the probability that the UAVs will complete the task

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j(t_2 - t_1)}] \]

Task Termination: Poisson Process
(details in the paper)
This probability allows to trade off between the UAVs that can attend the task

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot \left[ 1 - e^{-\lambda_j \cdot (t_2 - t_1)} \right] \]

Time span between the UAV with the highest battery life and the UAV closest to the task
The allocation varies depending on the UAVs capabilities

- Task 1 (LP, LU, LD)
- Task 2 (HP, LU, LD)
- UAV 1 (HB)
- UAV 2 (HB)

The UAVs can attend both the tasks
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t - t^0_j} \cdot [1 - e^{-\lambda_j(t_2 - t_1)}] \]

HB means that \( t_2 \) is very high for both the UAVs.
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j(t_2 - t_1)}] \]

HB means that \( t_2 \) is very high for both the UAVs

Each UAV can complete both the tasks
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [ 1 - e^{-\lambda_j \cdot (t_2 - t_1)} ] \]

Max-sum allocate each UAV to one different task so as to maximise the utility.
The allocation varies depending on the UAVs capabilities.

- **Task 1 (LP, LU, LD)**
- **Task 2 (HP, LU, LD)**
- **UAV 1 (LB)**
- **UAV 2 (LB)**

The UAVs may not be able to attend any task -> they join their forces.
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j(t_2 - t_1)}] \]

LB means that \( t_2 \) is very low for both the UAVs.
Why is this decision made?

$$U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j(t_2 - t_1)}]$$

LB means that $t_2$ is very low for both the UAVs.

The UAVs might not be able to complete one single task even working together.
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t-t^0_j} \cdot [1 - e^{-\lambda_j(t_2-t_1)}] \]

Max-sum allocate both the UAVs to the HP task so as to maximise the utility
The allocation varies depending on the UAVs capabilities.

- Task 1 (LP, LU, LD)
- Task 2 (HP, LU, LD)
- UAV 1 (HB)
- UAV 2 (LB)

The UAVs may be able to attend both the tasks -> they revise their decisions.
Why is this decision made?

$$U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j \cdot (t_2 - t_1)}]$$

HB for 1 UAV means that $t_2$ is very high for only 1 UAV
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t-t_j^0} \cdot \left[ 1 - e^{-\lambda_j(t_2-t_1)} \right] \]

HB for 1 UAV means that \( t_2 \) is very high for only 1 UAV

The UAVs will be able to complete the HP task if they work together.
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j \cdot (t_2 - t_1)}] \]

When they both reach the HP task, \( t_1 \) is the same for both the UAVs.
Why is this decision made?

\[ U_j(X_j) = p_j \cdot u_j^{t - t_j^0} \cdot [1 - e^{-\lambda_j(t_2 - t_1)}] \]

When they both reach the HP task, \( t_1 \) is the same for both the UAVs. One UAV hands over the HP task and goes to complete the LP one.
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VIDEOS legend

UAVs video

Factor Graph

Flight summary
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To Summarise

• We presented a Decentralised Coordination System for Disaster Response
  – FRs request imagery collection tasks to a team of UAVs.
  – The UAVs coordinate to complete the highest number of important tasks.
  – Max-Sum is used to coordinate the UAVs.
  – To use Max-Sum we present a detailed methodology.
  – We deploy our system on two real UAVs and deploy it on a number of flight tests.
To Summarise

- We presented a Decentralised Coordination System for Disaster Response.
  - FRs request imagery collection tasks to a team of UAVs.
  - The UAVs coordinate to complete the highest number of important tasks.
  - Max-Sum is used to coordinate the UAVs.
  - To use Max-Sum, we present a detailed methodology.
  - We deploy our system on two real UAVs and deploy it on a number of flight tests.

In conclusion:

The system performs well when confronted with the complexity of the real world:

- The methodology guided us to a successful deployment of max-sum.
- Max-sum performed well in the real world. It is a good candidate to coordinate real UVs on a number of flight tests.
Future Work

• This work is part of the ORCHID project (http://www.orchid.ac.uk/):
  – We are interested in applying the methodology to other Situational Awareness problems
    • Ex: Target – Search / Target Tracking
  – We are interested in verifying if the methodology can be extended to other domains
    • Ex: energy, traffic control
  – We wish to extend the system to consider
    • Heterogeneous vehicles (UAVs + UGVs)
    • Flexible autonomy