INTELLIGENT AUTONOMY FOR MULTIPLE, COORDINATED UAVS

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Autonomously and Intelligently:

- Navigate and Search Large Areas
- Coordinate Sensor and Payload Capabilities
- Maintain Stealth
- Enable Communications
- Autonomously Reposition
- Avoid Threats and Maneuver
- Multi-Sensor Fusion
- Accomplish Mission Even if a Unit is Removed (robustness)
• What Control Architectures Enable Coordinated Ops?

• How is Collaboration Enabled Within the Architecture?

• How are Improvements Associated with Collaboration Measured?
UNMANNED TEST VEHICLES

AIR-FRAME

TAKE-OFF

LANDING
Changes made to the image are as follows:

- **Intelligent Control Architecture**
  - **Sensor Inputs**
    - Sensor 1
    - Sensor N
    - Messages
      - Contacts
      - In-Situ Environmental Data
      - Orders
      - Advice
  - **Payload Inputs**

- **Intelligent Controller**
  - **Perception**
    - Sensor Data Fusion
    - Information Integration
    - Inferencing and Interpretation
    - Situational Awareness
    - Incoming Missile
    - Mine field
    - Terrain Characterization
    - Obstacle
  - **Response**
    - Operational Assessment
    - Dynamic Planning and Replanning
    - Plan Execution
    - Launch Counter Missile
    - Monitor Situation
    - Survey Minefield
    - Environmental Path Planning
    - Avoid Obstacle
    - Configure Team

- **Messages**
  - Conventional Control Systems
  - Human Collaborator
  - Other Autonomous Controllers
CONTINUOUS INFERENC NETWORKS

Size
Range
Δ Speed
Δ Maneuvers
Deployed Decoys
Counterfire

CONFIDENCE FACTOR OF A THREAT TARGET
WEIGHTED FUZZY ANDs and ORs

• Two weighted clues, A and B, with weights \( w_A \) and \( w_B \), respectively, are merged with weighted fuzzy AND and fuzzy OR:

  Weighted Fuzzy AND:

  \[
  \text{AND}_w (A, w_A, B, w_B) = (1 - w_A + w_A\cdot A)(1 - w_B + w_B\cdot B)
  \]

  Weighted Fuzzy OR:

  \[
  \text{OR}_w (A, w_A, B, w_B) = 1 - (1 - w_A\cdot A)(1 – w_B\cdot B)
  \]

• These obey DeMorgan's laws and map to conventional Boolean logic when the logical values are 0 and 1 and the weights are 1.
C is the Node Connective Function (Continuous): \( I'' \rightarrow I, \ I = [0,1] \)

- \( W_i \) is a weight specifying relative significance of \( P_i \) to \( Q \)
- Relative significance may change over time (situation)
- Node output is the confidence factor for existence of \( Q \)
- \( C \) may be mathematical model of
  - Fuzzy “and” (necessity)
  - Fuzzy “or” (sufficiency)
  - Fuzzy “M-out-of-N”
  - Weighted Average
  - A Neural Network
  - Statistical Classifier
Fuzzy Logical Operator for "Similar"

\[ \text{Cf(Similar)} = u + (1 - u) \sin(\pi \left( \sqrt{\omega_6 \cdot \text{Cf(SA)}}^2 + (\omega_7 \cdot \text{Cf(SP)})^2 - (2u - \sqrt{2}) \right) / [2(\sqrt{2} - u) - 0.5]), \]

where \( u = \text{Max}\{\omega_6 \cdot \text{Cf(SA)}, \omega_7 \cdot \text{Cf(SP)}\} \)

and

\[ \text{Cf(SA)} = \{[1 - \omega_5 + \omega_5 \{0.5[b_{16} + b_{14} + (b_{16} - b_{14}) \sin(\pi ((DD - b_{13}) / (b_{15} - b_{13}) - 0.5)))]\}] \]

\[ \times [1 - \omega_4 + \omega_4 \{1 - \omega_3 + \omega_3 \{0.5 [b_{12} + b_{10} + (b_{12} - b_{10}) \sin(\pi ((DZ - b_9) / (b_{11} - b_9) - 0.5)))]\}] \]

\[ \times [1 - \omega_2 + \omega_2 \{0.5 [b_8 + b_6 + (b_8 - b_6) \sin(\pi ((DY - b_5) / (b_7 - b_5) - 0.5)))]\}] \]

\[ \times [1 - \omega_1 + \omega_1 \{0.5 [b_4 + b_2 + (b_4 - b_2) \sin(\pi ((DX - b_1) / (b_3 - b_1) - 0.5)))]\}] \]

\[ \times (0.1 + 0.9 \exp(-0.3(\omega_1 + \omega_2 + \omega_3 - 1))) \]

\[ \times (0.1 + 0.9 \exp(-0.3(\omega_4 + \omega_5 - 1))) \]

where \( b_1, \ldots, b_{16} \) and \( \omega_1, \ldots, \omega_7 \) are adaptation parameters.
Programs

- Target Anesthesia/Analgesia Control
- Neonatal Oxygenation Control
- Driver Warning Systems
- Human-In-The-Loop

Applications

- Information Overload
- Subtle Combinatorial Changes
MULTIPLE CONTROLLER INTERACTIONS

- Intelligent Controller #1
  - PERCEPTION
  - RESPONSE
  - Smart Sensor Data
  - Peer-to-Peer
  - Messages
  - Effector Commands

- Intelligent Controller #2
  - PERCEPTION
  - RESPONSE
  - Smart Sensor Data
  - Messages
  - Effector Commands

- Supervisor Intelligent Controller
  - PERCEPTION
  - RESPONSE
  - Smart Sensor Data
  - Messages
  - Effector Commands

- HUMAN GUI
  - Messages
  - Effector Commands
**SAMPLE SURVEILLANCE OPERATIONS**

**PERCEPTION**
- Smart Sensor Data
  - Radar 1 Detected
- Signal CINET
  - Target CINET Data Plus
  - Signal Level
  => Signal Strength Low
- Target CINET
  - Radar 1 Data
  - Data w/in Freq. Band
  - Data Associated w/ Target on List
  - PRF, Pulse Type, Pulse Width
  => High Confidence Target of Interest

**RESPONSE**
- MISSION MANAGER
  - Cycles Behaviors
  - No Obstacles
  => Maneuver OK
- OBSTACLE CINET
  => No Obstacles in Vicinity
- AUTOPILOT COMMAND
  - UAV Repositioned
- SIGNAL CINET
  - Target CINET Data Plus
  - Signal Level
  => Signal Strength Low
- MIANEUVER BEHAVIOR
  - Wants Control
  - To Get Higher Signal Strength

**Other ICs**
TARGET CINET ⇒ High Confidence Target of Interest

SIGNAL CINET ⇒ Signal Strength Good for Analysis

Smart Sensor Data - Radar 1 Detected From New UAV Position

COMMUNICATE BEHAVIOR - Requests and Receives Control to Send Messages

MESSAGES - Msg w/ UAV Posit Goes to Sup UAV and Other UAVs

MESSAGES - 2nd UAV Provides Its Posit to Sup UAV and other UAVs

= UAV #1 after maneuver

= UAV #2
Sup UAV Sensor Data
- UAV #1 and UAV#2 Posit Data

TARGET CINET
⇒ Cross Fix / Fusion of UAV#1 & UAV#2 Contact Data

MESSAGES
- Msg from Sup UAV to UAVs To Maintain Target Contact

COMMUNICATE BEHAVIOR
- Requests and Receives Control to Send Messages

= Sup UAV
MULTI-VEHICLE CONTROL DEMONSTRATION - 2
MEASURING COLLABORATIVE GAIN

• Multi-UAV Coordination Should Increase Likelihood of Mission Success Above the Base Capability

• Base Capability = Success of N Individual UAVs Accomplishing Their Missions (no coordination/collaboration)

• Collaborative Gain = Gain Above Base Capability and Results from
  • Communications
  • Information Exchange
  • Coordinated Mission Control

• Collaborative Gain is Not Automatic; It Is Possible to Design Systems Where Collaboration Results in Conflicts, Causing Deterioration in Overall Mission Success
• Collaborative Gain Can be Measured By

\[ CG = \sum_{i=1}^{M} \alpha_i \beta_i T_i \]

\( \alpha_i \) = weight reflecting importance of overall mission
\( \beta_i \) = success of task, \( 0 \leq \beta_i \leq 1 \)
\( T_i \) = \( i \)th of \( M \) mission tasks

Goal: Maximize \( CG \)
$M = 3$ (one for each UAV)

$\alpha_i = 1, \ i = 1, 2, 3$

$\beta_2 = 1, \ \beta_3 = 1$

<table>
<thead>
<tr>
<th></th>
<th>$\beta_1$</th>
<th>CG</th>
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</thead>
<tbody>
<tr>
<td>Base Capability</td>
<td>$\beta_1 = 0$</td>
<td>$CG = 2$</td>
</tr>
<tr>
<td>Partial Success Incorporated</td>
<td>$\beta_1 = 0.6$</td>
<td>$CG = 2.6$</td>
</tr>
<tr>
<td>UAVs Cooperate</td>
<td>$\beta_1 = 1$</td>
<td>$CG = 3$</td>
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</tbody>
</table>
$M = 5$ (one for each UAV)

$\alpha_i = 1, \ i = 1, \ldots, 5$

$\beta_2 = 1, \ \beta_5 = 1$

<table>
<thead>
<tr>
<th>Base Capability</th>
<th>$\beta_i = 0, \ i = 1, 3, 4$</th>
<th>CG = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Success Incorporated</td>
<td>$\beta_3 = 0.1, \ \beta_4 = 0.2$</td>
<td>CG = 2.3</td>
</tr>
<tr>
<td>UAVs Cooperate</td>
<td>$\beta_i = 1, \ i = 1, 3, 4$</td>
<td>CG = 5</td>
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### Measuring Collaborative Gain - 3

- **Base Capability**
  - $\beta_2 = 0$
  - $CG = 2$

- **Partial Success Incorporated**
  - $\beta_2 = 0.1$
  - $CG = 2.1$

- **UAVs Cooperate**
  - $\beta_2 = 1$
  - $CG = 3$

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$M = 3$ (one for each UAV)

$\alpha_i = 1, \ i = 1, \ldots, 3$

$\beta_1 = 1, \ \beta_3 = 1$
Multi-UAV Controller Architecture Supports

- **Fully Autonomous Vehicles**
  - Modular Open Architecture for Mission Control
  - Improved Situational Awareness
  - Dynamic Planning and Re-planning

- **Heterogeneous Vehicles w/ Disparate Payload Packages**
  - Interactions Between UAVs and Humans as Desired
  - Coordination Between UAV with Disparate Capabilities
  - Add or Remove Payloads w/out Affecting Controller Design
  - Control Software Akin to Middleware

- **Cooperative Capability For Complex Missions**
  - Hierarchical Control and Collaborative Control
  - Collaboration Measured by Collaborative Gain Index