Evaluating Transformations of the Air Transportation System Through Agent-Based Modeling and Simulation

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A system composed of a large number of humans, machines and technical systems interacts with each other.

**Characteristics**
- Dynamic
- Interactive
- Emergent behavior

**System**
- Human
- Machine
Viewing Air Traffic System Behavior as Emergent

- “Emergent Behavior” – a behavior at one level of abstraction that can not be predicted from another level of abstraction
  - Needs simulation to predict!
- In this case, we view our agents as the individual humans and technologies in the air traffic system (a ‘low’, detailed level of abstraction)
- Out of their individually conducted (and motivated) actions emerge the higher-level system behaviors
Thought Experiments During Design

- Have we sufficiently determined what every one in an operational concept (con ops) is expected to do?
- If everyone in con ops does what they are supposed to, how well would the system work?
- If known, predictable aspects of human performance are ‘brought in’, how does that affect system performance?
- If the system runs as it ought, what will the humans be asked to do? Is this feasible? (Answer would provide early insight to the human factors community)
Agent-Based Modeling and Simulation

 Entities Are Modeled as *Agents*

- Heterogeneous agents may behave differently and interact with each other

 Agents then act and interact within a rich environment

- Generates individual behavior based on internal rules
- Produces emergent phenomena from local interactions
Concept of Agent

An ‘agent’ in ABMS may be defined as an simulated entity within a larger system with the following properties:

- Some Degree Of Autonomy: The Capability To Carry Out Some Set Of Operations (i.e. work meeting its own purpose)
  - Flexible (Reactive, Pro-Active, Social) Behavior
- Interactivity: The Ability To Interact With Other Agents To Accomplish Its Own Goals
  - Mutual influence (cooperative or competitive)

In our case, our agents:

- Have their own goals
- Reference their behavior to established procedures

Example: pilots, controllers, dispatchers, flow managers, schedulers, automated system
Known and Unknown During Design

- System-wide Behaviors
- Coordination Procedures
- Technological Functions
- Operating Procedures
- Human Performance to Meet Obligations in Context

Unknown (sought)
Environment Is Known
Unknown (sought)

Additional Inferences
Structure Preserving Representations

- Model maintains the form of reality
  - E.g., directly represent “knowns” in the world in same form as they are designed / implemented
  - Stream-lines all aspects of the process by minimizing translation and abstraction
    - Less model translation
    - Direct comparisons for validation
    - Direct applicability to implementation

- Thus, our model uses the structures used to describe:
  - Technological functions (e.g., aircraft dynamic models)
  - Information (e.g., same interfaces as used in reality)
  - Operational/ organizational factors (e.g., procedures specified to human and automated agents)
Agent Models of Human Performance

- Computational Agent Model With Cognitive Abilities
  - Observe and Sense Its Simulated Environment
  - Reasoning, Planning, and Problem Solving
  - Take Actions To Perform

- Why?
  - Humans are integral system components
  - Cost-effective, detailed simulation early in design
    - Consideration of human capabilities and limitations
  - Evaluation of changes of human behavior on safety and performance of the system at the system-level
    - Procedures, interfaces, new technologies
    - Sensitivity analyses (impacts of human errors)
RFS-WEA Simulation Architecture
RFS-WEA Framework

→ Built Upon Cognitive Engineering Principles
  ➢ Describes the work environment in a task-relevant, structure-preserving form
  ➢ Proactive Agents
  ➢ Dynamic Environmental Components

→ Declarative Models of System Components and Their Interrelations

→ Computational Models of The Complex, Dynamic Behaviors of Those Components
Agent-Based Simulation Architecture

- Easily Incorporates Different Types of Models
- Accepts Any Types of Agents with Varying Fidelity and Resolution
- Easily Added and Removed As Needed
- Easily Modified and Reused
- Easily Extendible and Sharable
- Computationally Efficient Timing Methods
Component-Based Architecture

- Abstraction of Simulation Components
  - Object-Oriented Framework (C++)
  - Interface Inheritance from Parent Class

- Modularity (Configurable, Robust, Sharable)
  - Implementation of Components Completely Isolated from the RFS Executable
  - Each Module is a Dynamically-Linked Library (dll)
  - Modules Configured Through Run-Time Interface and/or Scripts
Simulation Architecture
Interactions and Communications

- Most Interactions Between Agents Can Be Supported By Accessing Pointers To Other Agents

- Base Standard Interfaces Handle The Interactions and Communications Between Agents
  - Standard Event Messages (Creation and Removal of Agent)
  - Basic Attributes and Methods

- Additional Interfaces (Attributes and Methods) Can Be Provided By Using the Object Data/Methods Extensions (OD/ME) Protocol.
  - Allow to Share With Other Agents
  - Allow to Facilitate the Communications Between Agents
The Environmental Component

\[ \text{WE} = \langle \langle \text{C}_e \rangle, \langle \text{KD}_e \rangle \rangle \]

Environmental component (\( \text{C}_e \)): Any thing, physical or not, that affects work activities of workers, independent of any particular worker

- Internal Dynamics (\( \text{ID}_c \)): Any internal mechanism that governs the autonomous or responsive behavior of the \( \text{C}_e \)
  \textit{(Developed as separately-compiled software)}
- Properties (\( \langle \text{P}_c \rangle \)): The set of properties of the \( \text{C}_e \) that represents its state
- Usage Mechanisms (\( \langle \text{UM}_c \rangle \)): The set of mechanisms by which a \( \text{C}_e \) can be used

\[ \text{C}_e = \langle \text{ID}_c, \langle \text{P}_c \rangle, \langle \text{UM}_c \rangle \rangle \]
Dimensions and Relationships

**Functional Dimension**
- Avoid Conflict
- Vertical Separation Procedure
- MCF = Means, CAT = Work-process
- Lateral Separation Procedure
- Avoid Conflict
- Vertical Separation Procedure
- MCF = Means, CAT = Work-process

**Knowledge Dimension (Kd_e)**
- WE = <<C_e>, <KD_e>>
  - KD_e = <<R_d>>
  - R_d = <<C_e>, <P_r>>

**Contextual Dimension**
- ZLA-39 (Controller Workspace)
  - Radar Screen
  - Voice Radio Equipment
  - Lateral Separation Procedure
  - Vertical Separation Procedure

- ZLA-37 (Controller Workspace)
  - Radar Screen
  - Voice Radio Equipment
  - Lateral Separation Procedure
  - Vertical Separation Procedure
Component Aspects and Dimensions

- **Contextual Dimension**
  - ZLA-39
    - Radar Screen
    - Lateral Separation Procedure
    - Voice Radio Equipment
    - Vertical Separation Procedure

- **Lateral Separation Procedure**
  - Expression of applicability
  - Process specification
  - Situation assessment mechanism
  - Process following mechanism

- **Radar Equipment - 39**
  - Radar sweep every 12 seconds
  - Radar blips of all aircraft in sector
  - Coordinate read mechanism
  - Speed assessment mechanism

- **Dimension Relevant Interface**

Mathematical expressions:
- \( C_e = \{\text{id}_c, \{p_c\}, \{uM_c\}\} \)
- \( C_e = \{\text{id}_c, \{CA_c\}\} \)
- \( CA_c = \{\{p_c\}, \{uM_c\}\} \)
Agent Model of Worker
Worker Example – Air Traffic Controller

Air Traffic Controller

Proxy Scheduler
Active Elements
Activity Processor

Passive Elements
Basic Executive Skills
Basic Perceptual Skills
Basic Analytical Skills
Procedure Following Skills
Internal Representation
Internal Resources
Context Interface

Multidimensional Environment Model

Functional Dimension
Contextual Dimension
Environmental Components
MIT Spacing Proc.
Vertical Separation Proc.
Building a Computational Model of System

Conceptual Models of System Components

Conceptual Model of System

Computational Models of System Components

Computational Model of System

Designer

Computational Model Constructor
Constructing Models of Worker

Agent = \(<\text{Skill}_a>, \text{Capability}_a, \text{Processor}_a\>

- Ability to predict conflicts
- Ability to calculate distance b/w pts
- Ability to read the radar screen
- Ability to follow procedures
Putting The Models Together

Contextual Dimension

- ZLA-39
  - Radar screen
  - Lateral separation procedure
  - Voice radio equipment
  - Vertical separation procedure

Radar Equipment - 39

- Radar sweep every 12 seconds
- Radar screen
- Radar blips of all aircraft in sector
- Coordinate read mechanism
- Speed assessment mechanism

Air Traffic Controller

- Coordinate Reading Skill
- Context Understanding Skill
Demonstration

→ Model arrivals into Los Angeles International Airport (LAX) with the following procedures
  ➢ Conflict Avoidance (CA)
  ➢ Miles-In-Trail Metering (MIT)
  ➢ Time-Based-Metering (TBM)
Effect of Change in Procedures

# Violations

MIT + CA Procedures
MIT Procedures

SCT-FDR  ZLA19  ZLA20  ZLA37  ZLA39
Impact of Human Performance

Air Traffic Controller

Proxy Scheduler

Activity Processor

Active Aspects

Passive Aspects

Basic Executive Skills

Basic Perceptual Skills

Basic Analytical Skills

Procedure Following Skills

Internal Representation

Internal Resources

Context Interface

Improved Accuracy of Estimates

Unlimited Resources
Transformation in Air Traffic Controller

<table>
<thead>
<tr>
<th>Activity</th>
<th>Agent Type</th>
<th>Unlimited resources</th>
<th>Limited resources (Max Resources = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Source of Variability</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distribution</td>
<td>Accuracy</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Monitor Traffic for Conflicts</td>
<td>1</td>
<td>N/A</td>
<td>0.8</td>
</tr>
<tr>
<td>Monitor Traffic for MIT Spacing</td>
<td>1</td>
<td>N/A</td>
<td>0.8</td>
</tr>
<tr>
<td>Monitor Traffic for TBM Compliance</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Change Speed</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Change Heading</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Change Altitude</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Resume Course</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Resume Speed</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Monitor Sector Boundary Conformance</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Wait</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Follow Procedures</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Accuracy: Probability of detecting a conflict on each scan. That is, with a ‘prob’ of 0.8 there is 98.4% chance that the air traffic controller, would have detected the conflict by the End of the 3rd scan

ATM 2007 Seminar in Barcelona
Impact of Human Performance Variables

- Resource Limited Model
- Resource Unlimited Model

# Violations

- SCT-FDR
- ZLA19
- ZLA20
- ZLA37
- ZLA39
Summary of Results

- Modelled arrivals into Los Angeles International Airport (LAX) with the following procedures:
  - Conflict Avoidance (CA)
  - Miles-In-Trail Metering (MIT)
  - Time-Based-Metering (TBM)
- Constructed and compared design alternatives
- Explained emergent behavior that could not previously be explained
Overall Thoughts

Agent-based Simulation Can Examine Many Different Types of Operational Concepts Involving Interaction / Coordination of Agents

Measures / High-level Behaviors Examined can Include:
- Safety (‘emergent error’ as well as ‘emergent behavior’?)
- Efficiency / throughput
- Others? (Demand/scheduling...)

Translation Between ‘Micro’ and ‘Macro’ Viewpoints
Summary

<table>
<thead>
<tr>
<th>Ideal</th>
<th>RFS-Agent Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictive</td>
<td>Based on known properties of physics and cognition, in response to proposed procedures and technologies</td>
</tr>
<tr>
<td>Detailed</td>
<td>As detailed as standard operating procedures and technology specifications</td>
</tr>
<tr>
<td>Broad Scope</td>
<td>Several sectors / center no problem. Wider is possible</td>
</tr>
<tr>
<td>Available</td>
<td>Yes, immediately</td>
</tr>
<tr>
<td>Easy to Configure</td>
<td>Airborne aircraft and ‘standard’ controllers already in place. Most other behaviors easily scripted into place</td>
</tr>
<tr>
<td>Fast to Run</td>
<td>On small compute cluster (11 machine) recently ran almost 1 million aircraft arrivals into LAX</td>
</tr>
<tr>
<td>Relevant to Design</td>
<td>Uses same language as procedure design and technology requirements</td>
</tr>
</tbody>
</table>
Discussion
Contextual Dimension

- Sector (SCT-FDR)
- Sector (ZLA19)
- Sector (ZLA20)
- Sector (ZLA37)
- Sector (ZLA39)

  - Surveillance
  - Voice Radio
  - Flight Strips
  - Wind Measurement

  *AC₁*

1. Latitude,
2. Longitude,
3. Altitude,
4. Ground speed,
5. Vertical speed,
6. Heading,
7. Flight Path Angle

*AC₂*

1. Change speed,
2. Change altitude with vertical speed,
3. Fly to heading,
4. Resume course,
5. Resume speed
Functional Dimension
Summary of Conceptual Framework

\[ WE = \langle \langle C_e \rangle, \langle KD_e \rangle \rangle \quad \text{Work-environment} \]

\[ KD_e = \langle \langle R_d \rangle \rangle \quad \text{Knowledge Dimensions} \]

\[ R_d = \langle [C_e], \langle P_r \rangle \rangle \quad \text{Work-relevant Relationship} \]

\[ C_e = \langle \langle ID_e \rangle, \langle P_c \rangle, \langle UM_c \rangle \rangle \quad \text{Environmental Component} \]

\[ C_e = \langle \langle ID_e \rangle, \langle CA_c \rangle \rangle \quad \text{Dimension-oriented Representation of the Component} \]

\[ CA_c = \langle [P_c], [UM_c] \rangle \quad \text{Aspect of a Component} \]

\[ \text{Agent} = \langle \langle \text{Skill}_a \rangle, \langle \text{Capability}_a \rangle, \langle \text{Processor}_a \rangle \rangle \quad \text{Agent} \]
Contextual Structure

- Is radar screen available?
- What is the latitude of aircraft?
- Is command equipment available?
- Command aircraft to resume course
Constructing The Situational Dimension - XML

```xml
<WEAObject Name="ZLA39" ClassID="WEAObject"
DLL="."\modules\WEA\WEAObject.dll">
  <Initialization><![CDATA[
  <Dimension type="SituationalDimension">
    <SituationalAspect Name="ZLA39"/>
  </Dimension>
  ]]></Initialization>

  <WEAAspects>
    <WEAAspect Name="ZLA39" ClassID="WEASituationalAspect"
DLL="."\modules\WEA\WEASituationalAspect.dll">
      <Initialization><![CDATA[
      <ParentContext Name="//"/>
      ]]></Initialization>
    </WEAAspect>
  </WEAAspects>
</WEAObject>
```
XML Representation of Air Traffic Controller

<WEAObject Name="ATC39" DLL="\modules\WEA\WEAATC-RL.dll"
    ClassID="BaseWEAObject">

<WEAAAspects>
    <WEAAspect Name="ATCDATA" DLL="\modules\WEA\WEAATC-RL.dll"
        ClassID="ATCDATA">
        <Initialization><![CDATA[
            <Initialization>
                <SectorID Value="39"></SectorID>
                </Initialization>
            ]]>]]></Initializa
</WEAAspect>

<WEAAspect Name="SectorRadar"
    DLL="\modules\WEA\WEASituation_accessor.dll">
    <Initialization><![CDATA[
        <WEASituation_accessor_initData>
            <CurrentContext ObjectName="Radar39" AspectName="RadarData"/>
        </WEASituation_accessor_initData>
    ]]>]]></Initializat
</WEAAspect>
<WEAAAspect Name="ActivityProcessor"
    DLL="\modules\WEA\WEAATC-RL.dll" ClassID="ActivityProcessor">
    <Initialization><![CDATA[
        <ActivityLogFile Value="..../Simulation Outputs/PhaseIII
                         /ActivityLog/ActivityLog_MIT_1205_030804.csv"/>
    ]]></Initialization>
</WEAAAspect>

<WEAAAspect Name="ProcedureProcessor"
    DLL="\modules\WEA\WEATestProcessor.dll"
    ClassID="WEAProcedureProcessor">
    <Initialization><![CDATA[
        <DefaultContextAspect AspectName="/ZLA39"/>
        <StartProcedure ProcedureName="MonitorTraffic"/>
    ]]></Initialization>
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<WEAAspect Name="PerceptualCapabilities"
   DLL=".\modules\WEA\WEAATC-RL.dll"
   ClassID="CBasicPerceptualCapabilities">
   <Initialization><![CDATA[
       <DefaultAccessor Value="SectorRadar"/>
   </Initialization>]]>
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<WEAAspect Name="AnalyticalCapabilities"
   DLL=".\modules\WEA\WEAATC-RL.dll"
   ClassID="CBasicAnalyticalCapabilities">
   <Initialization><![CDATA[
       <ATCDataAspect Value="ATCData"/>
       <CBasicPerceptualCapabilities Value="PerceptualCapabilities"/>
   </Initialization>]]>
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<WEAAspect Name="ResourceProvider"
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   </Initialization>]]>
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<WEAAspect Name="ExecutionCapabilities"
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    ClassID="CBasicExecutionCapabilities">
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        <ATCDATAAspect Value="ATCData"/>
        <ATCControlAspect Value="SectorChannel"/>
        <BasicAnalyticalCapabilities Value="AnalyticalCapabilities"/>
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</WEAAspects>

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