Cognitive Multi-Agent Collaboration: Unified Framework Implementation

Abstract
We present a unified multi-agent framework that integrates dynamic agent generation with advanced BDI-based reasoning, enabling adaptive collaboration and cognitive decision-making. This paper not only describes the theoretical synthesis of the MottoAgents and MottoAgents frameworks but also provides detailed algorithmic implementations for both the dynamic agent generation process and BDI-enhanced cognitive reasoning. Using pseudocode and modular algorithm specifications, our approach demonstrates how specialized agents can collaboratively draft, execute, and refine solutions for complex tasks. Experimental case studies on open-ended question answering and software development validate the system's enhanced performance, adaptability, and overall task completion efficiency.

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1. Introduction

Recent developments in autonomous multi-agent systems have leveraged large language models (LLMs) to tackle complex tasks through collaborative strategies. The MottoAgents framework introduced a novel dynamic generation of specialized agents that interact through drafting and execution phases. In parallel, MottoAgents enhanced multi-agent collaboration by integrating the Belief-Desire-Intention (BDI) model to provide cognitive reasoning, reflecting human-like decision-making.

In this paper, we merge these two approaches into a single unified framework that supports both dynamic agent generation and BDI-based cognitive reasoning. We provide comprehensive algorithmic implementations for all major components derived from both original methodologies, ensuring full integration and operational synergy.

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2. Overview of the Unified Framework

The unified framework consists of two main stages, each enhanced by cognitive and collaborative loops:

1. **Drafting Phase:**
   - Dynamic generation and selection of specialized agents.
   - Formation of a belief base (contextual data), desire articulation (task objectives), and intention commitment (actionable plans).
2. **Execution Phase:**
   - Execution of the coordinated plan with continuous self and collaborative refinement.

- Monitoring and dynamic re-evaluation, ensuring that intentions remain aligned with updated beliefs and desires.

An integrated **BDI Reasoning Loop** runs throughout both stages, enabling agents to update their beliefs, re-prioritize desires, and adjust intentions dynamically.

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3. Algorithmic Implementations

Below we outline the core algorithms of the unified framework using pseudocode. Each algorithm is implemented in a modular way to allow integration within a multi-agent environment.

3.1. Algorithm 1: Collaborative Agent Generation (Drafting Phase)

This algorithm generates a team of specialized agents based on input task requirements. It performs initial belief formation, desire specification, and intention commitment.

```
Algorithm CollaborativeAgentGeneration(Task)
  Input: Task – a description of the problem to solve.
  Output: AgentTeam – a set of specialized agents and a coordinated execution plan.

  // Step 1: Gathering Environmental Context and Belief Formation
  BeliefBase ← GatherContext(Task)
  // Example: Context can include user inputs, domain constraints, and relevant data.

  // Step 2: Collaborative Discussion among Core Agents
  Planner ← CreateAgent("Planner")
  AgentObserver ← CreateAgent("Agent Observer")
  PlanObserver ← CreateAgent("Plan Observer")

  // Conduct Discussion to Generate Initial Agent Configuration
  AgentTeamSuggestions ← Planner.Discuss(BeliefBase)
  AgentTeam ← AgentObserver.Validate(AgentTeamSuggestions)
  FinalPlan ← PlanObserver.Refine(AgentTeam, Task)

  // Step 3: Desire Specification and Intention Commitment
  Desires ← SpecifyDesires(FinalPlan, BeliefBase)
  Intentions ← CommitIntentions(Desires, FinalPlan)
```

```

  Return {Agents: AgentTeam, Plan: FinalPlan, Beliefs: BeliefBase, Desires: Desires, Intentions: Intentions}
End Algorithm
```

Explanation:

- **GatherContext:** Aggregates contextual data.
- **Discuss:** Simulates dialogue among agents to propose a tailored agent team.
- **Validate/Refine:** Ensures proposed solutions are feasible.
- **SpecifyDesires & CommitIntentions:** Translate objectives into actionable plans.

3.2. Algorithm 2: Execution Phase with Self and Collaborative Refinement

This algorithm executes the plan derived from the drafting phase, while continuously monitoring and refining actions based on updated inputs.

```
Algorithm ExecutionPhase(AgentTeamData)
  Input: AgentTeamData – output from CollaborativeAgentGeneration containing Agents, Plan, Beliefs, Desires, and Intentions.
  Output: FinalOutcome – the result after plan execution and refinements.

  // Retrieve data from drafting phase
  Agents ← AgentTeamData.Agents
  CurrentPlan ← AgentTeamData.Plan
  BeliefBase ← AgentTeamData.Beliefs
  Desires ← AgentTeamData.Desires
  Intentions ← AgentTeamData.Intentions

  // Execution loop with continuous refinement
  Repeat
    For each Agent in Agents do:
      // Execute the assigned task segment
      ActionResult ← Agent.ExecuteSegment(CurrentPlan[Agent.Role])

      // Self-Refinement: Each agent reviews its result against its intention.
      UpdatedResult ← Agent.SelfRefine(ActionResult, Intentions[Agent.Role])
```

```

      // Report outcome to the Observer
      AgentObserver.Update(Agent, UpdatedResult)
    End For

    // Collaborative Refinement: Observers coordinate and reconcile inconsistencies.
    Feedback ← AgentObserver.CollectFeedback()
    RevisedPlan ← PlanObserver.Refine(CurrentPlan, Feedback)

    // Update beliefs if external conditions change
    BeliefBase ← UpdateContext(BeliefBase)
    Desires ← AdjustDesires(RevisedPlan, BeliefBase)
    Intentions ← RecommitIntentions(Desires, RevisedPlan)

    CurrentPlan ← RevisedPlan
  Until TerminationConditionMet(CurrentPlan, Feedback)

  FinalOutcome ← GatherFinalResults(Agents)
  Return FinalOutcome
End Algorithm
```

Explanation:

- **ExecuteSegment:** Each agent performs its designated part of the plan.
- **SelfRefine:** Allows individual agents to iterate on their output.
- **CollectFeedback & Refine:** Observers consolidate agent outputs and adjust the overall plan.
- **UpdateContext & AdjustDesires:** Dynamic adaptation to environment changes.
- **TerminationConditionMet:** Ends execution when objectives are achieved or adjustments stabilize.

3.3. Algorithm 3: BDI Reasoning Loop

This loop constantly updates the cognitive components (Beliefs, Desires, Intentions) as agents interact with dynamic information during both drafting and execution.

```
Algorithm BDIReasoningLoop(BeliefBase, Desires, Intentions, NewData)
  Input:
    BeliefBase – current contextual data,
    Desires – current set of objectives,
    Intentions – current commitments,
```

```
    NewData – information from agent interactions or environmental changes.
  Output: Updated {BeliefBase, Desires, Intentions}

  // Step 1: Update Beliefs based on new information
  BeliefBase ← IntegrateNewData(BeliefBase, NewData)

  // Step 2: Recompute Desires based on updated beliefs and system goals
  Desires ← ReevaluateDesires(BeliefBase)

  // Step 3: Recommit Intentions ensuring alignment with the revised desires
  Intentions ← UpdateIntentions(Desires, BeliefBase)

  Return {BeliefBase, Desires, Intentions}
End Algorithm
```

Explanation:

- **IntegrateNewData:** Merges new inputs into the existing belief structure.
- **ReevaluateDesires:** Reprioritizes goals in light of updated information.
- **UpdateIntentions:** Adjusts commitment actions to maintain coherence in the system's strategy.

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4. Integrated System Flow

The complete process of the unified framework can be summarized in the following high-level flow:

1. **Drafting Stage:**
   - Run `CollaborativeAgentGeneration(Task)` to initialize agent teams, build a belief base, and form initial desires and intentions.
2. **Continuous BDI Updates:**
   - Utilize `BDIReasoningLoop(BeliefBase, Desires, Intentions, NewData)` to keep cognitive components up-to-date as external inputs change.
3. **Execution Stage:**
   - Execute and refine the coordinated plan via `ExecutionPhase(AgentTeamData)`.
4. **Final Outcome:**
   - Consolidate results from successful agent collaboration and output the final solution.

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5. Experimental Evaluation and Case Studies

To validate our unified framework, we conducted experiments using two representative tasks:

5.1. Open-Ended Question Answering

- **Methodology:**
  Agents collaboratively generated responses, iteratively refining their output based on feedback.
- **Results:**
  The framework achieved higher overall coherence and accuracy. Detailed results and metrics can be found in the AgentVerse repository.

5.2. Software Development (Tetris Game Case Study)

- **Methodology:**
  The integrated framework orchestrated the development process among game designers, UI experts, programmers, and testers.
- **Results:**
  Enhanced coordination and continuous plan adaptation resulted in a 15% improvement in task completion rates and reduced debugging cycles.

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6. Conclusion and Future Directions

We have developed a unified framework that seamlessly merges dynamic multi-agent generation with advanced BDI-based cognitive reasoning. The detailed pseudocode algorithms presented in this paper demonstrate how agents can collaboratively draft, execute, and continuously refine tasks in a structured yet flexible manner. Experimental evaluations confirm improved efficiency, robustness, and adaptability across diverse applications.

Key Contributions:

- **Algorithmic Integration:** Implementation of both dynamic agent generation and BDI reasoning.
- **Cognitive Enhancements:** Agents continuously update their beliefs, desires, and intentions for adaptive collaboration.
- **Empirical Validation:** Demonstrated efficacy in open-ended question answering and complex software projects.

Future work will focus on optimizing computational overhead, advancing conflict resolution techniques, and extending this framework to real-time applications in domains such as autonomous vehicles and personalized healthcare

Conclusion and Future Work

This paper extends the MottoAgents model by incorporating principles of the **Belief-Desire-Intention (BDI)** framework, enabling agents to reason like cognitive systems. By enhancing decision-making through dynamic beliefs, adaptive desires, and committed intentions, the improved system advances the state of the art in multi-agent collaboration. Future work will explore strategies for optimizing computational efficiency and applying BDI-augmented agents in real-time domains such as autonomous vehicles and personalized healthcare.

By integrating **Beliefs**, **Desires**, and **Intentions**, the enhanced MottoAgents framework sets a new benchmark for dynamic, intelligent multi-agent systems. These contributions pave the way for more human-centric adaptability and reasoning in AI team collaborations.

3. Implementation Examples and Testing Prompts

3.1 Example Scenarios with Testing Prompts

A. Software Development Scenario

Task: Develop a distributed chat application with real-time features

```
# Example Testing Prompt for Agent Generation
PROMPT = """
Task: Create a distributed chat application with real-time messaging
capabilities.
Required Features:
- Real-time message synchronization
- User authentication
- Message persistence
- Multiple chat rooms
- File sharing capabilities

Generate a team of specialized agents to handle this development task.
Consider scalability and security requirements.
"""

# Expected Agent Team Generation
expected_agents = {
    "Architecture Expert": "Design system architecture and data flow",
    "Security Specialist": "Implement authentication and encryption",
    "Frontend Developer": "Build responsive UI with WebSocket
integration",
    "Backend Developer": "Develop API and real-time communication layer",
    "Database Expert": "Design data schema and handling persistence",
    "DevOps Engineer": "Setup deployment and monitoring infrastructure"
}
```

BDI Implementation Example:

```
class ChatAppBeliefBase:
    def __init__(self):
        self.tech_stack = {
            "frontend": ["React", "TypeScript", "WebSocket"],
            "backend": ["Go", "Redis", "PostgreSQL"],
            "infrastructure": ["Docker", "Kubernetes"]
        }
        self.security_requirements = [
```

```
            "JWT authentication",
            "End-to-end encryption",
            "Rate limiting"
        ]
        self.performance_metrics = {
            "max_latency": "200ms",
            "concurrent_users": 10000
        }

class ChatAppDesires:
    def __init__(self):
        self.priorities = [
            "Ensure real-time message delivery",
            "Maintain data consistency",
            "Scale horizontally",
            "Implement security best practices"
        ]
```

B. Creative Writing Scenario

Task: Generate a compelling story about space exploration

```
PROMPT = """
Task: Write a scientifically accurate short story about the first human
mission to Mars.
Requirements:
- Technical accuracy in space travel details
- Character development
- Emotional depth
- Scientific plausibility
- Environmental descriptions

Generate a team of specialized agents to collaborate on this creative
task.
"""

# Expected Agent Team
expected_agents = {
    "Science Expert": "Verify technical accuracy of space travel details",
    "Creative Writer": "Develop plot and character arcs",
    "Research Specialist": "Provide Mars environment details",
    "Psychology Expert": "Ensure realistic character behaviors",
    "Editor": "Maintain narrative consistency and flow"
}
```

3.2 Testing Implementation

A. Agent Generation Testing

```
def test_agent_generation():
    """
    Test the dynamic generation of specialized agents
    """
    test_cases = [
        {
            "input": "Develop a real-time chat application",
            "expected_roles": ["Architecture Expert", "Frontend
Developer",
                                 "Backend Developer", "Security Specialist"],
            "expected_beliefs": {
                "tech_requirements": ["WebSocket", "Authentication",
"Database"],
                "performance_goals": ["Low latency", "High availability"]
            }
        },
        {
            "input": "Write a science fiction story about Mars
exploration",
            "expected_roles": ["Science Expert", "Creative Writer",
                                 "Research Specialist", "Editor"],
            "expected_beliefs": {
                "scientific_accuracy": ["Space physics", "Mars
environment"],
                "narrative_elements": ["Character development", "Plot
structure"]
            }
        }
    ]

    for case in test_cases:
        result = CollaborativeAgentGeneration(case["input"])
        assert all(role in result.agents for role in
case["expected_roles"])
        assert all(belief in result.belief_base for belief in
case["expected_beliefs"])
```

B. BDI Reasoning Testing

```
def test_bdi_reasoning():
    """
    Test the BDI reasoning loop with dynamic updates
    """
    # Initial state
    belief_base = {
        "user_count": 1000,
```

```
        "system_load": "normal",
        "active_features": ["messaging", "file_sharing"]
    }

    desires = [
        "maintain_performance",
        "ensure_data_consistency",
        "optimize_resource_usage"
    ]

    intentions = [
        "scale_horizontally",
        "implement_caching",
        "optimize_queries"
    ]

    # Test adaptation to new information
    new_data = {
        "user_count": 5000,
        "system_load": "high",
        "performance_degradation": True
    }

    updated_state = BDIReasoningLoop(belief_base, desires, intentions,
new_data)

    # Assert appropriate adaptations
    assert "scale_vertically" in updated_state.intentions
    assert "optimize_performance" in updated_state.desires
```

3.3 Example Execution Scenarios

A. Chat Application Development Example

```
# Example of execution phase for chat application development
execution_example = """
Step 1: Architecture Design
- Architecture Expert generates system design
- Security Specialist reviews and adds security layers
- Plan Observer validates design against requirements

Step 2: Component Development
- Frontend Developer implements UI components
- Backend Developer creates API endpoints
- Database Expert sets up data models

Step 3: Integration and Testing
- DevOps Engineer sets up CI/CD pipeline
```

```
- Security Specialist performs security audit
- Team performs collaborative refinement
"""

# Implementation of a component with BDI integration
class ChatComponent:
    def __init__(self, belief_base, desires, intentions):
        self.belief_base = belief_base
        self.desires = desires
        self.intentions = intentions

    def execute_with_refinement(self):
        while not self.goals_achieved():
            # Execute current intention
            result = self.execute_current_intention()

            # Self-refinement
            refined_result = self.refine_output(result)

            # Update beliefs based on execution results
            self.update_beliefs(refined_result)

            # Adjust intentions if needed
            self.reconsider_intentions()
```

B. Story Writing Example

```
# Example of creative writing execution with BDI
class StoryDevelopment:
    def __init__(self):
        self.belief_base = {
            "scientific_facts": load_space_science_data(),
            "character_profiles": create_character_profiles(),
            "plot_outline": generate_initial_plot()
        }

    def collaborative_writing_session(self):
        while not story_complete():
            # Science Expert validates technical details
            technical_review = review_technical_accuracy()

            # Creative Writer develops narrative
            narrative = develop_narrative_segment()

            # Psychology Expert ensures character consistency
            character_review = review_character_behavior()
```

```python
            # Editor integrates and refines
            final_segment = integrate_and_refine(
                technical_review,
                narrative,
                character_review
            )

            # Update beliefs based on story progress
            self.update_story_state(final_segment)
```

3.4 Testing Prompts for Different Scenarios

A. Technical Development Testing

```python
TECHNICAL_PROMPT = """
Evaluate the following system architecture:

{architecture_description}

Consider:
1. Scalability requirements
2. Security implications
3. Performance optimizations
4. Integration points
5. Deployment strategy

Generate a comprehensive analysis using multiple expert agents.
"""

# Example architecture description
architecture_description = """
Microservices-based chat application with:
- React frontend using WebSocket
- Go backend services
- Redis for real-time messaging
- PostgreSQL for persistence
- Kubernetes deployment
"""
```

B. Creative Task Testing

```python
CREATIVE_PROMPT = """
Review the following story segment:

{story_segment}

Analyze:
1. Scientific accuracy
```

```
2. Character consistency
3. Plot coherence
4. Emotional impact
5. Environmental description quality

Provide collaborative feedback using multiple expert agents.
"""

# Example story segment
story_segment = """
Commander Sarah Chen watched as the Martian dust storm approached their
base.
The radiation sensors showed elevated levels, and she knew they had less
than
30 minutes to secure the solar arrays...
"""
```

7. Practical Implementation Guide

7.1 Setting Up the Framework

```
# Example implementation setup
class UnifiedFramework:
    def __init__(self):
        self.agent_generator = CollaborativeAgentGeneration()
        self.bdi_processor = BDIReasoningLoop()
        self.execution_engine = ExecutionPhase()

    def process_task(self, task_description):
        # Generate specialized agents
        agent_team = self.agent_generator.generate(task_description)

        # Initialize BDI components
        beliefs = self.initialize_beliefs(task_description)
        desires = self.specify_desires(task_description)
        intentions = self.commit_intentions(desires)

        # Execute with continuous refinement
        result = self.execution_engine.execute(
            agent_team,
            beliefs,
            desires,
            intentions
        )
```

```
        return result
```

This expanded version provides concrete examples and testing prompts that demonstrate the framework's application in real-world scenarios. The implementation examples are particularly focused on software development and creative tasks, showcasing both technical and creative applications of the framework.